Laminar-turbulent Transition Modelling in the DLR *TAU* Code

Transition Prescription and Transition Prediction

Andreas Krumbein
German Aerospace Center
Institute of Aerodynamics and Flow Technology, Numerical Methods

DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

Outline

- Introduction
- Transition Prescription
- Transition Prediction
- Transition Prediction Coupling Structure
- Computational Results
- Example input file
- Stability boundary
- Conclusion and Outlook

Introduction

- Background of considering transition in RANS-based CFD tools
  - Better numerical simulation results
    - Capturing of physical phenomena, which were discounted otherwise
    - Quantitatively, sometimes even qualitatively the results can differ significantly w/o transition
    - At first, main focus:
      - Influence on lift and drag, pressure and skin friction distributions
      - 2D multi-element airfoil configurations
  - Long term requirement from research organisations and industry
    - Transition prescription
    - Some kind of transitional flow modelling
    - Transition prediction
    - Automatically & autonomously
  - First, in DLR *FLOWer* code, later in DLR *TAU* code

Introduction

- Further configurations and current application areas:
  - 3D multi-element wing configurations
  - Micro Air Vehicles (MAV): very low Re numbers, leading edge laminar separation bubble or long laminar lengths
  - Performance of sailplanes: transition at fuselage highly relevant, laminar length up to 20% of fuselage length
  - Design of high-lift systems (Airbus): to get the suction peaks at the nose, interaction of transition and separation, long laminar lengths possible (also on pressure side) → EUROLIFT I & II
  - Determination of critical N factors: free flight, wind tunnels, e.g. ETW → TELFONA
- Future → Flight at the borders of the flight envelope
  - Separation stronger → interaction of transition and separation becomes a key issue
  - Transition is unsteady
  - Using the full potential of advanced turbulence models

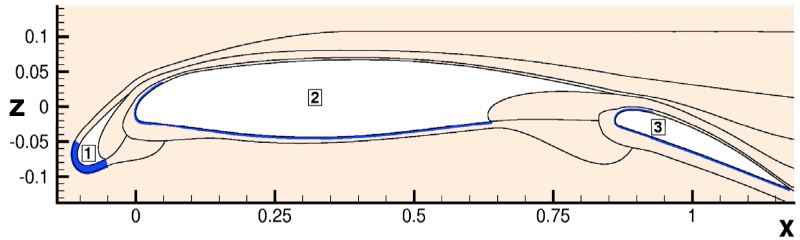
Introduction

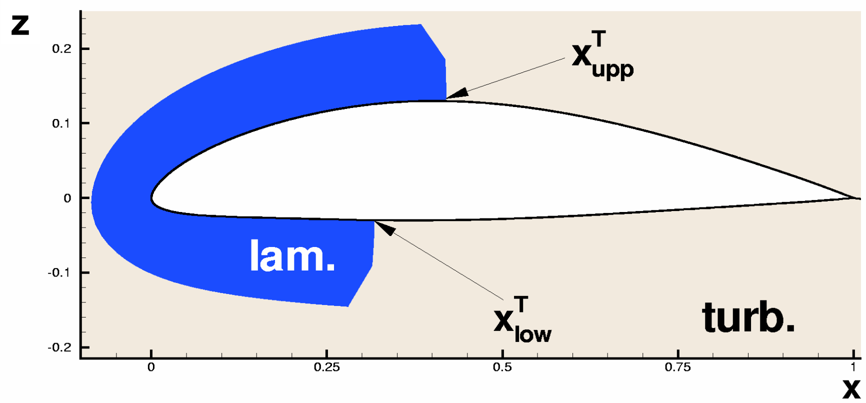
- **Transition Prescription:**
  - fixing of transition locations known *a priori*
  - prescription of polygonial lines on (or near) geometry surfaces
  - multi-element configurations
  - wings, fuselage, nacelle
  - high level of generality

- **Transition Prediction:**
  - determination of transition locations not known *a priori*
  - fixing the determined transition points using transition prescription
    - → pre<u>scrip</u>tion is a technical prerequisite for pre<u>dic</u>tion
  - automatic: no intervention by the code user
  - autonomous: as little additional information as possible
  - high level of generality

Transition Prescription

- automatic partitioning of flow field into laminar and turbulent regions
- individual laminar zone for each element

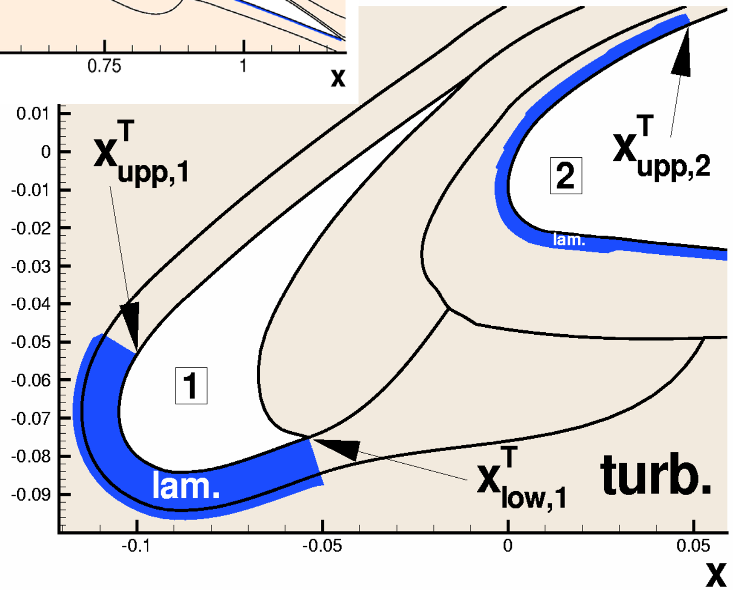


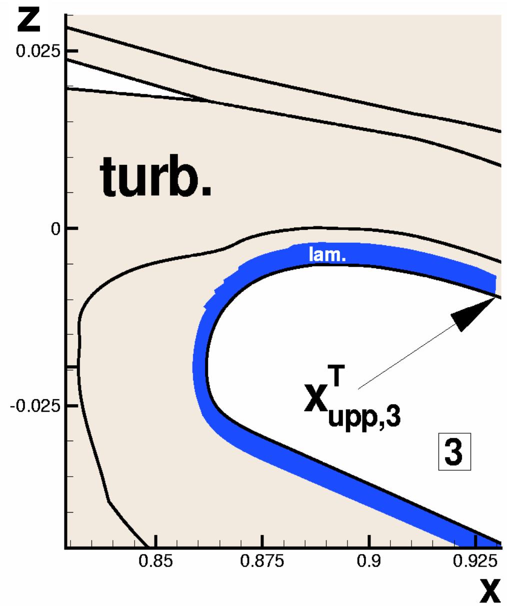


- different numerical treatment of laminar and turbulent grid points

  laminar:

  control of TM's source terms





- transition line on ONERA M6 wing
  4 points on upper and lower side in a structured grid

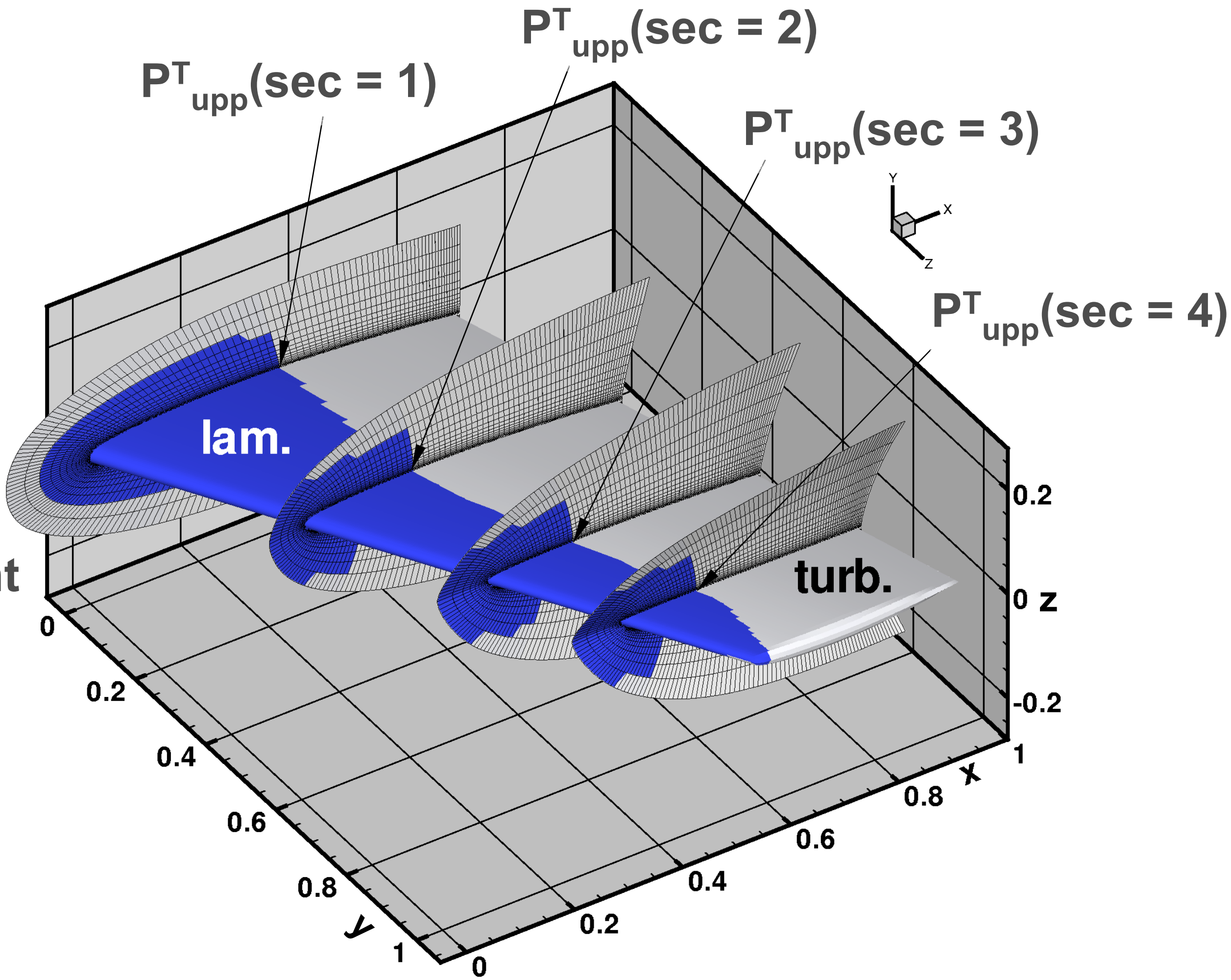
necessary input data:

1.) x,y,z coordinate sets for each transition point → polygonial line

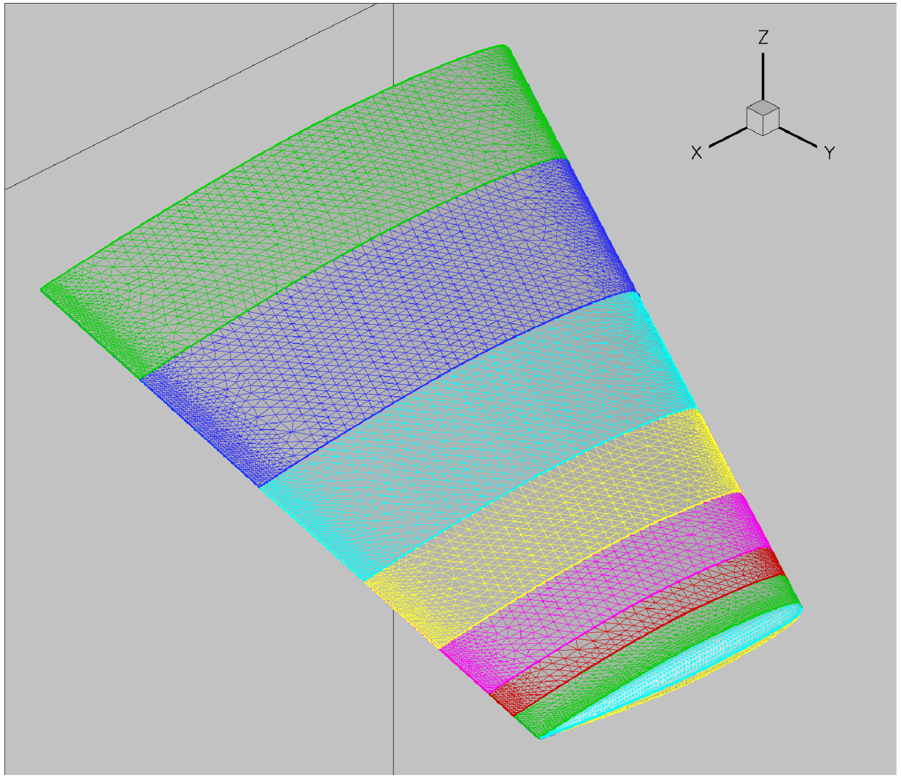
2.) polygonial line for upper and lower side

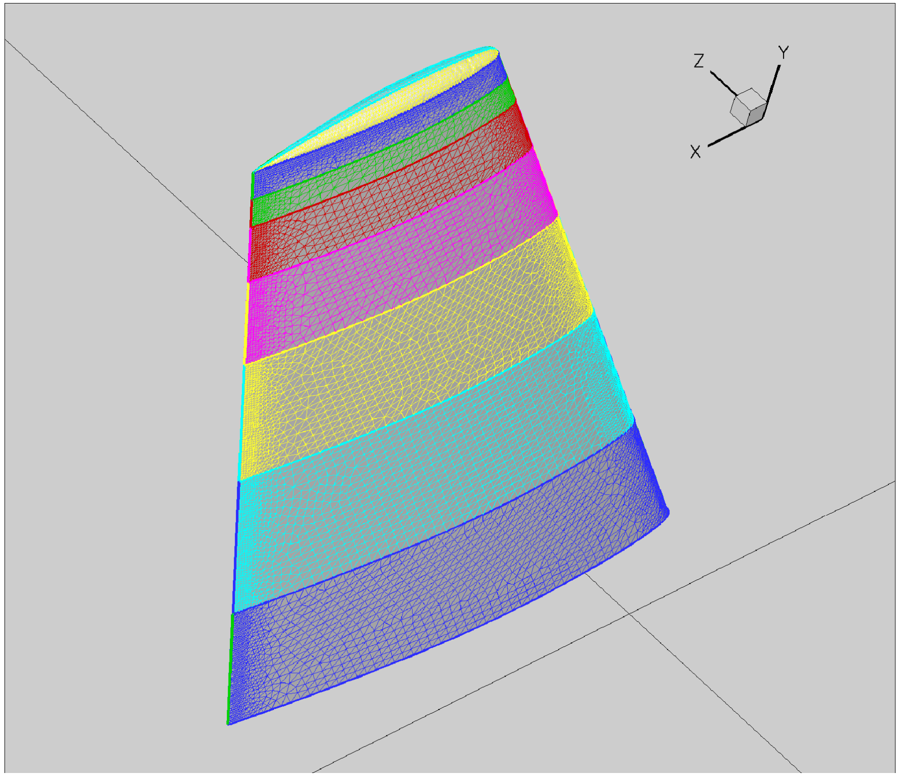
3.) for each wing element

4.) wall normal distance for each wing element



- transition line on ONERA M6 wing
  3 points on upper and lower side in an unstructured grid





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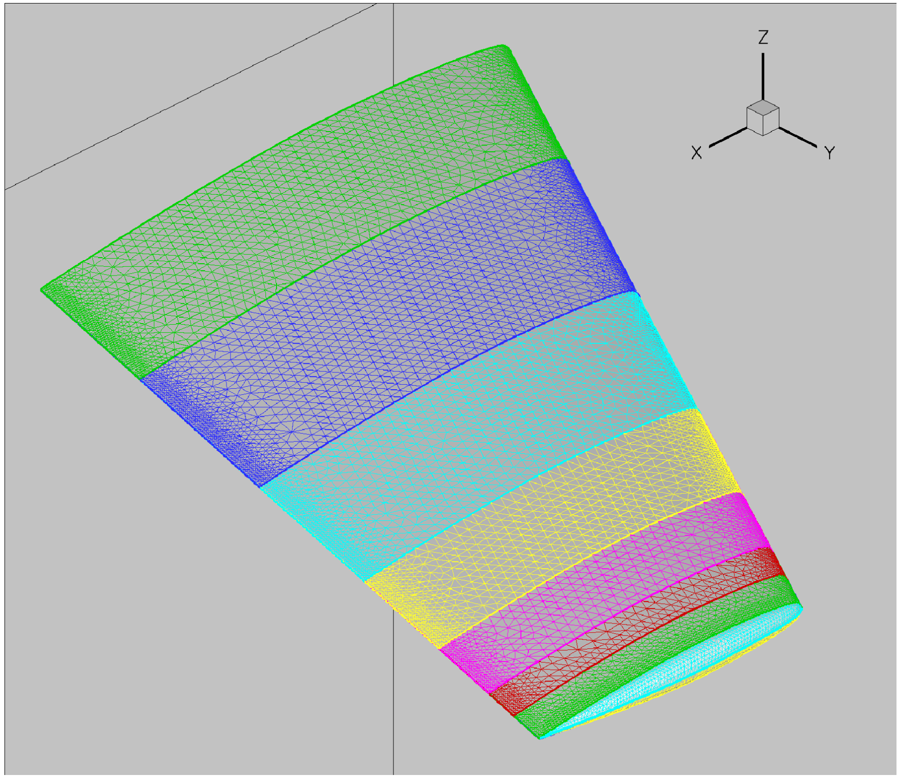

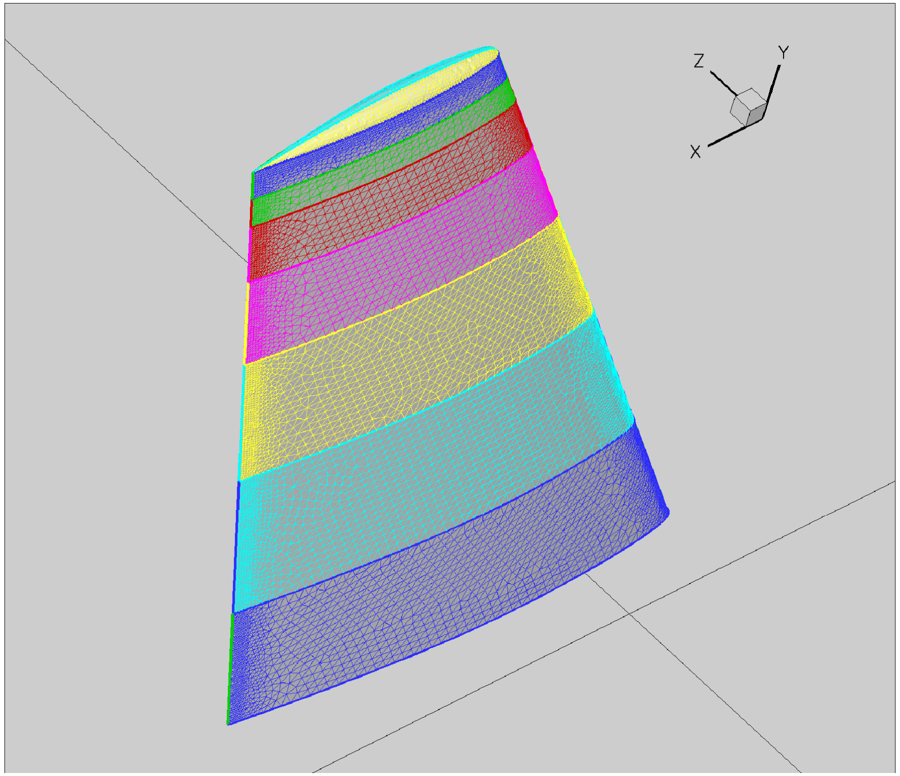

- grid has 22 ‘boundary markers’ → 22 faces bound the grid
- 16 faces compose the solid surface of the wing: markers 1-16

- transition line on ONERA M6 wing
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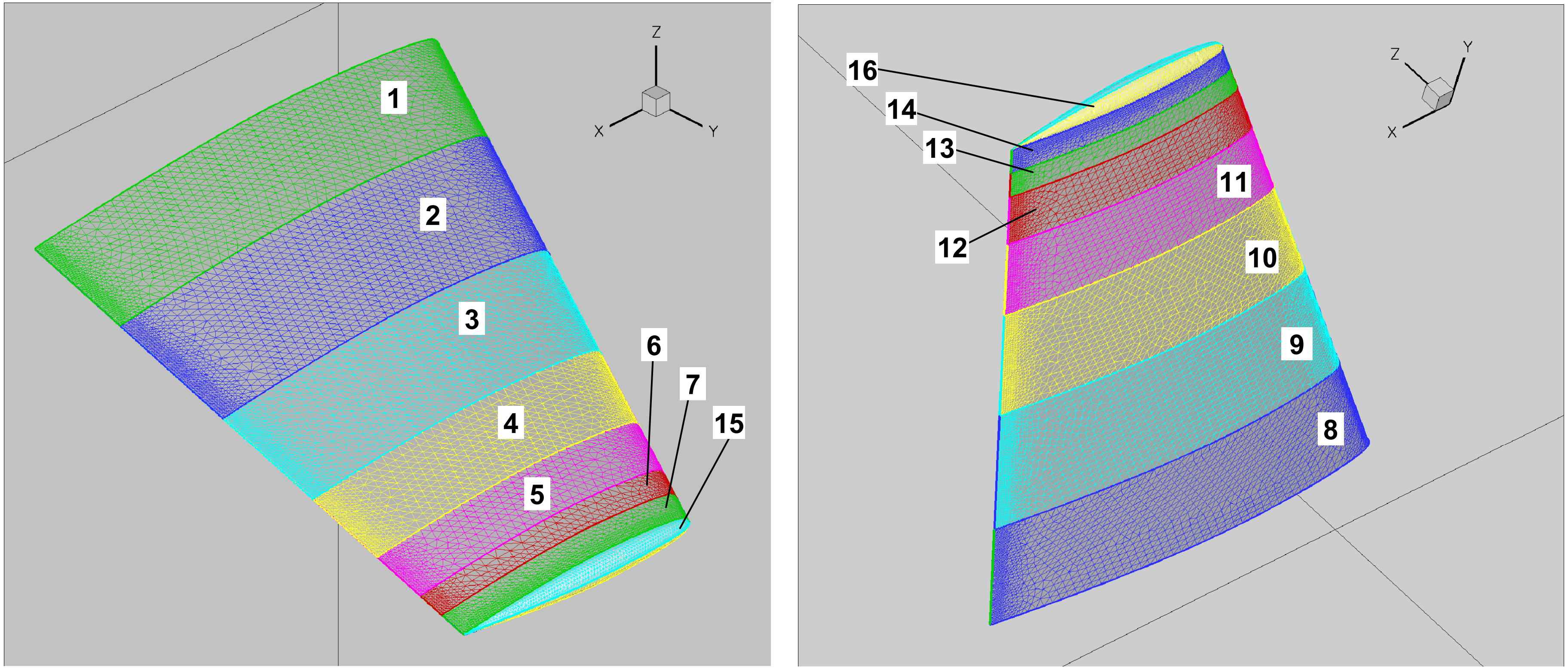

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- 16 faces compose the solid surface of the wing: markers 1-16

- transition line on ONERA M6 wing
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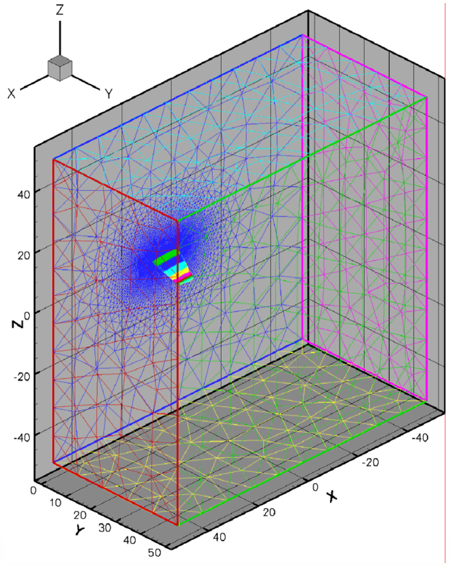
```
Markers: 1-16
   Type: viscous wall
Subtype: laminar
block end

Markers: 17,18,19,20,22
   Type: farfield
block end

Markers: 21
   Type: symmetry plane
block end
```




```
Markers: 1-7
   Type: viscous wall
 Subtype: transition
    Name: wing_upper
block end

Markers: 15,16
   Type: viscous wall
Subtype: turbulent
block end

Markers: 8-14
   Type: viscous wall
Subtype: transition
   Name: wing_lower
block end

Markers: 17,18,19,20,22
   Type: farfield
block end

 Markers: 21
    Type: symmetry plane
block end
```

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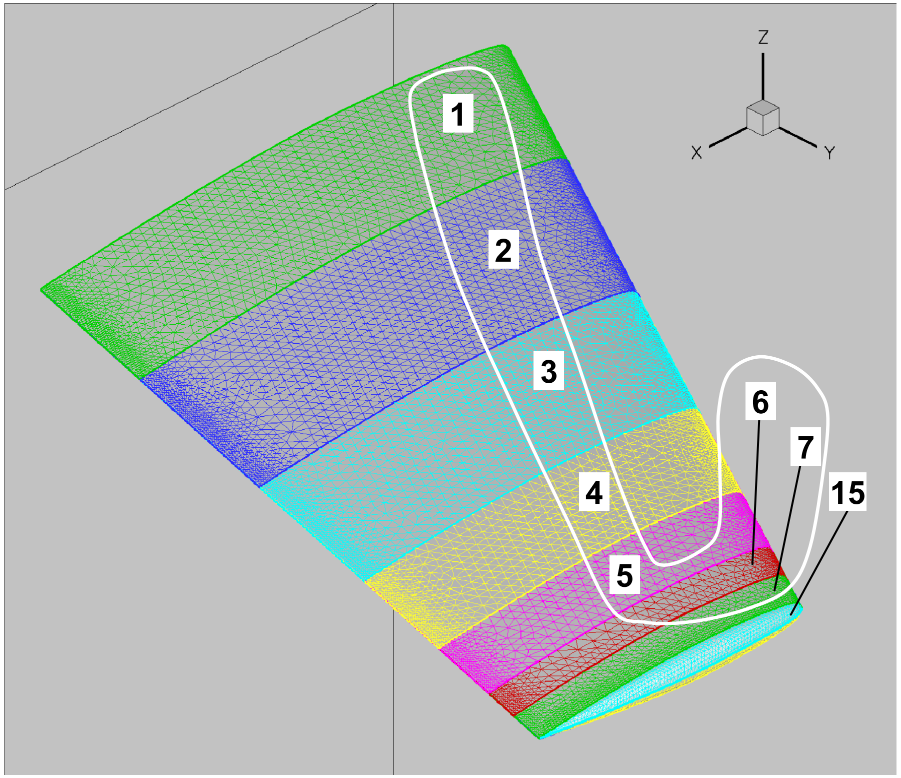
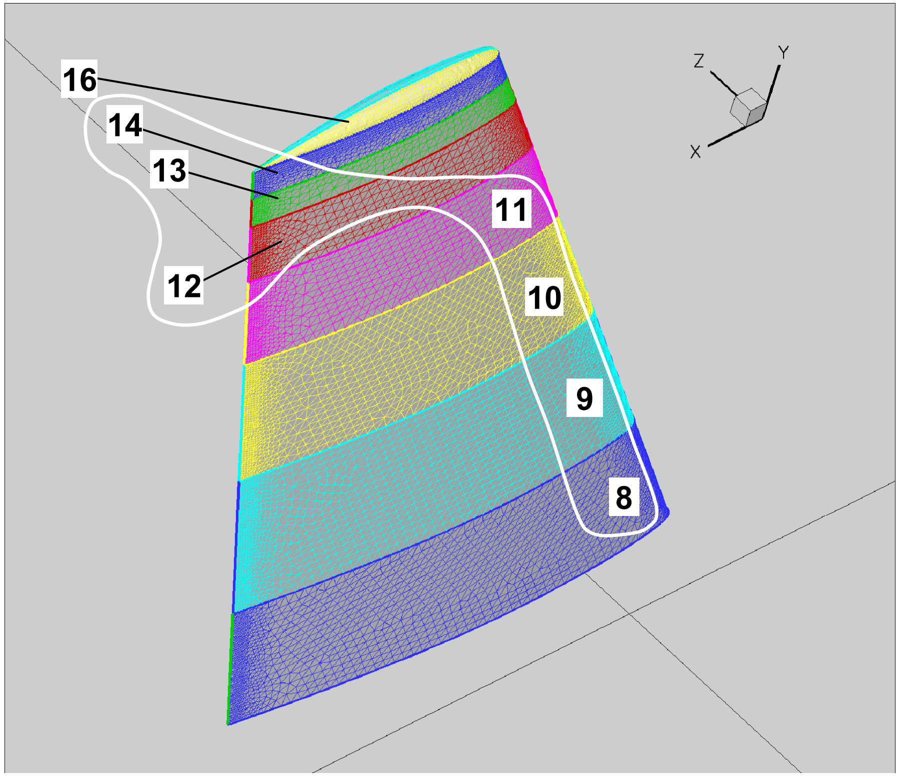
3 points on upper and lower side in an unstructured grid





- markers 1 - 7 are grouped and form ‘wing_upper’
  → marker segment ‘wing_upper’ associated with upper side transition line
- markers 8 - 14 are grouped and form ‘wing_lower’
  → marker segment ‘wing_lower’ associated with lower side transition line

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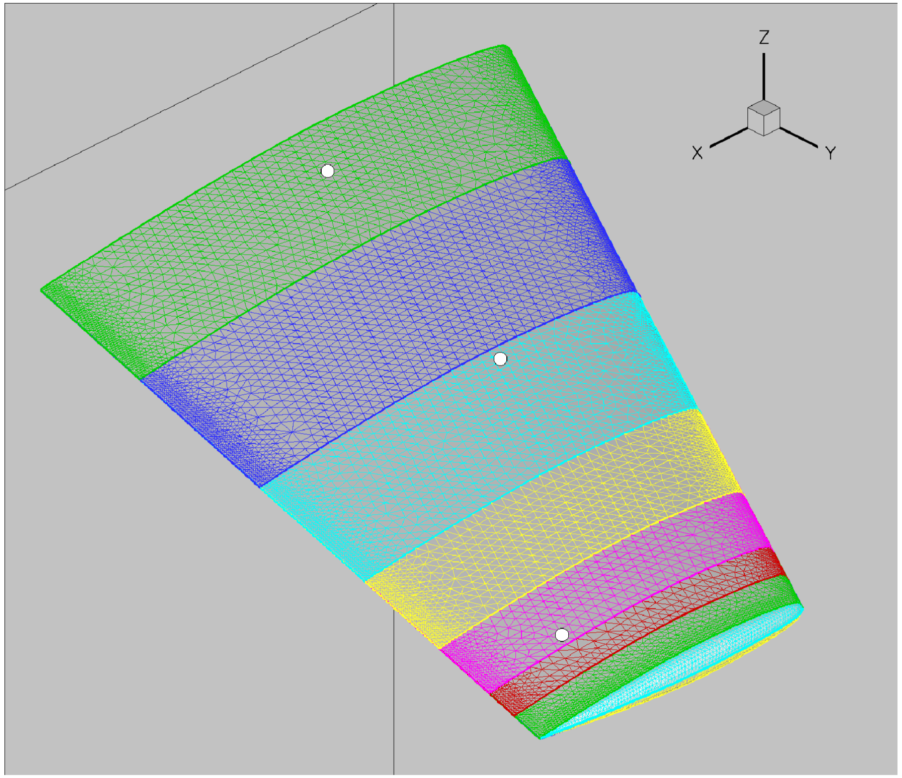

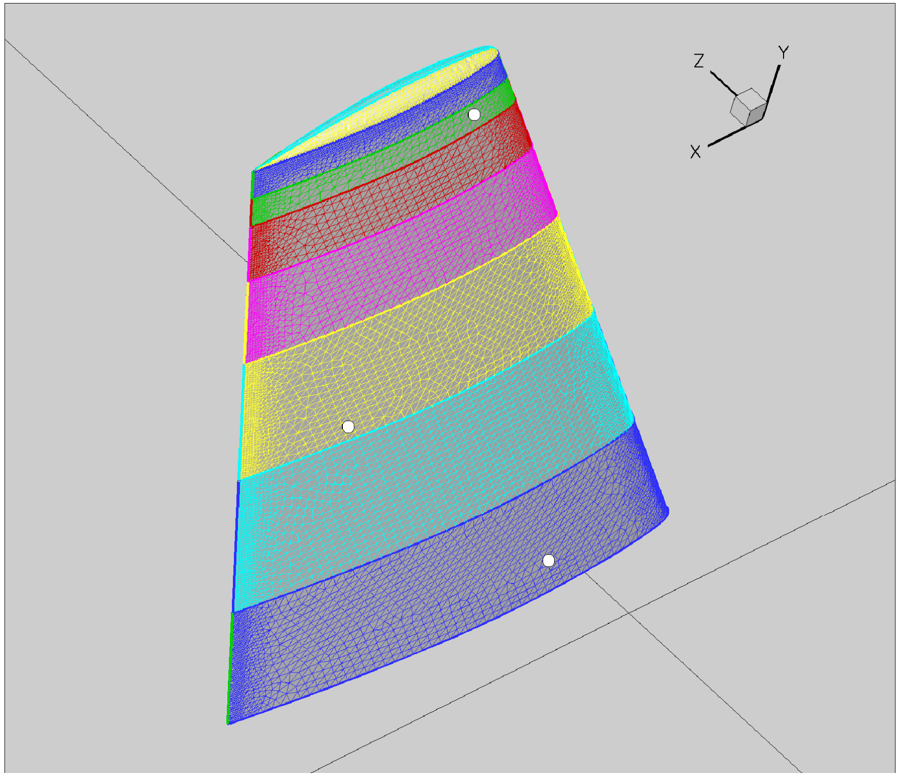

- 3-point polygonial line on upper side
- 3-point polygonial line on lower side

- transition line on ONERA M6 wing
3 points on upper and lower side in an unstructured grid

```
-----------------------------------------------------
 TRANSITION LINE INPUT
-----------------------------------------------------
   Boundary part namelist: wing_upper
Number of polyline points: 3
           Laminar height: 1.0

TransitionCoordinates
 5.00646 1.11995 0.463775
 7.09114 6.84792 0.388653
12.0258 13.1251  0.191133
transition end

   Boundary part namelist: wing_lower
Number of polyline points: 3
           Laminar height: 1.0

TransitionCoordinates
9.05048 13.7003   -0.251389
9.70724  6.8653   -0.249975
3.32732  0.774276 -0.467287
transition end
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- transition line on ONERA M6 wing
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transition end
```

- One data block for each transition line necessary
- coordinate order: x, y, z
- point order:
  - 1st point → beginning
  - last point → ending
- starting point:
  - either → at wing root
  - or → at wing tip

- transition line on ONERA M6 wing
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```

starts at tip

- One data block for each transition line necessary
- coordinate order: x, y, z
- point order:
  - 1st point → beginning
  - last point → ending
- starting point:
  - either → at wing root
  - or → at wing tip
- ordered sequence of a polygonial line MUST be kept
- NO loops or criss-crossing!!!

- transition line on ONERA M6 wing
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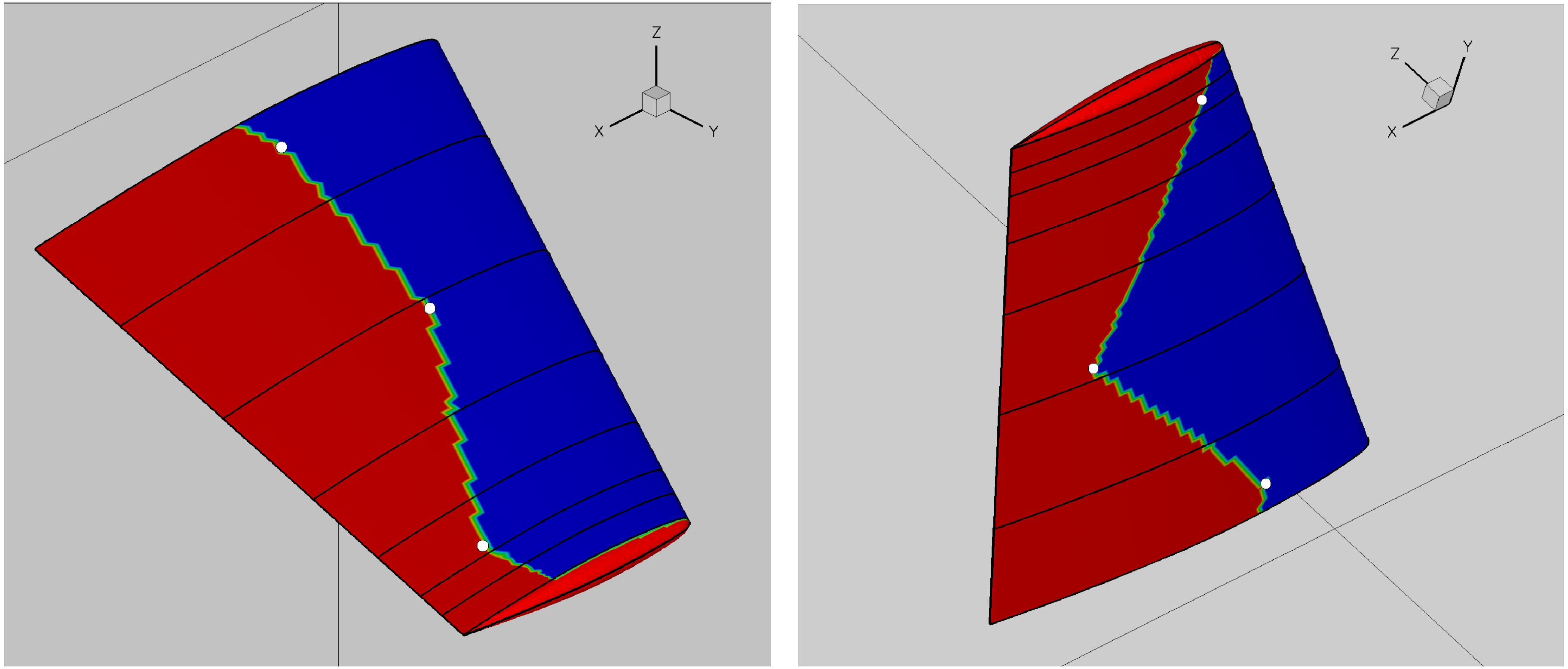

- at the ending points of the polygonial lines
  → extrapolation in y-direction with constant x-value of the ending point

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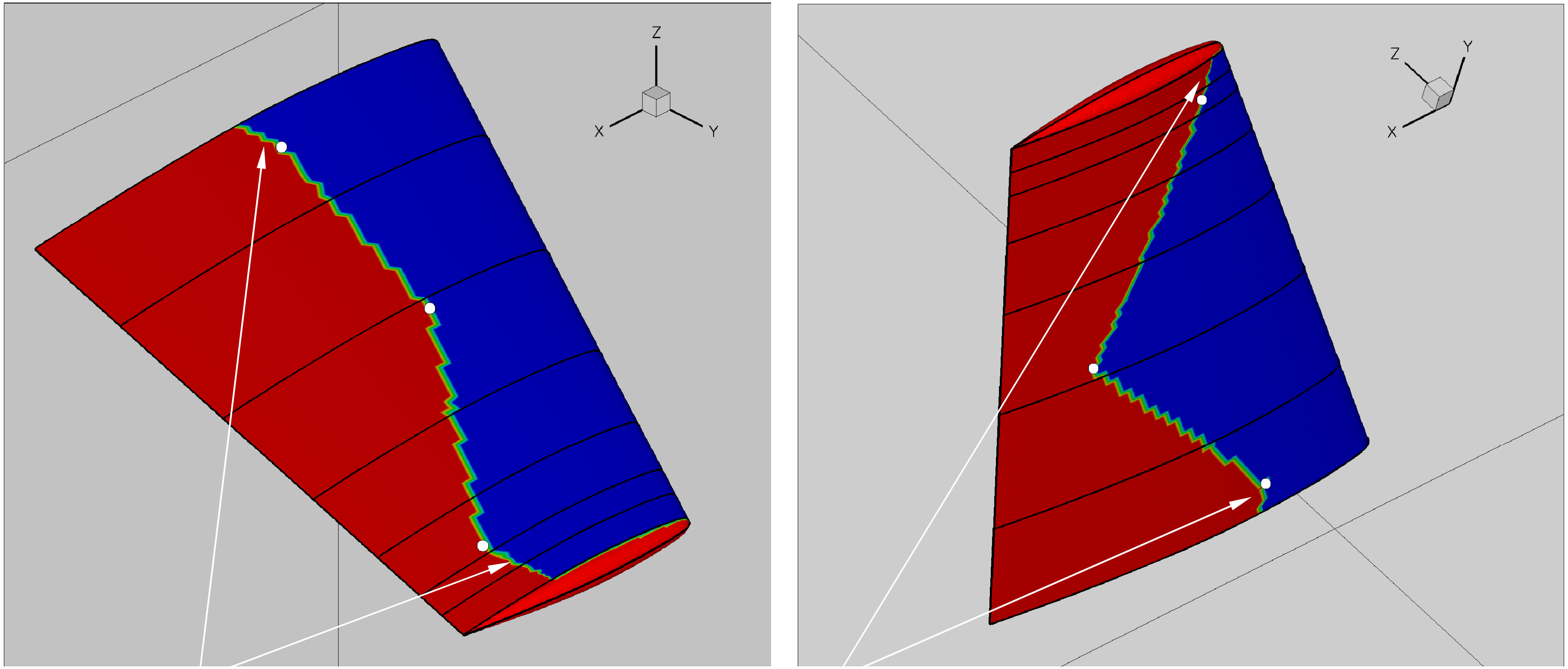

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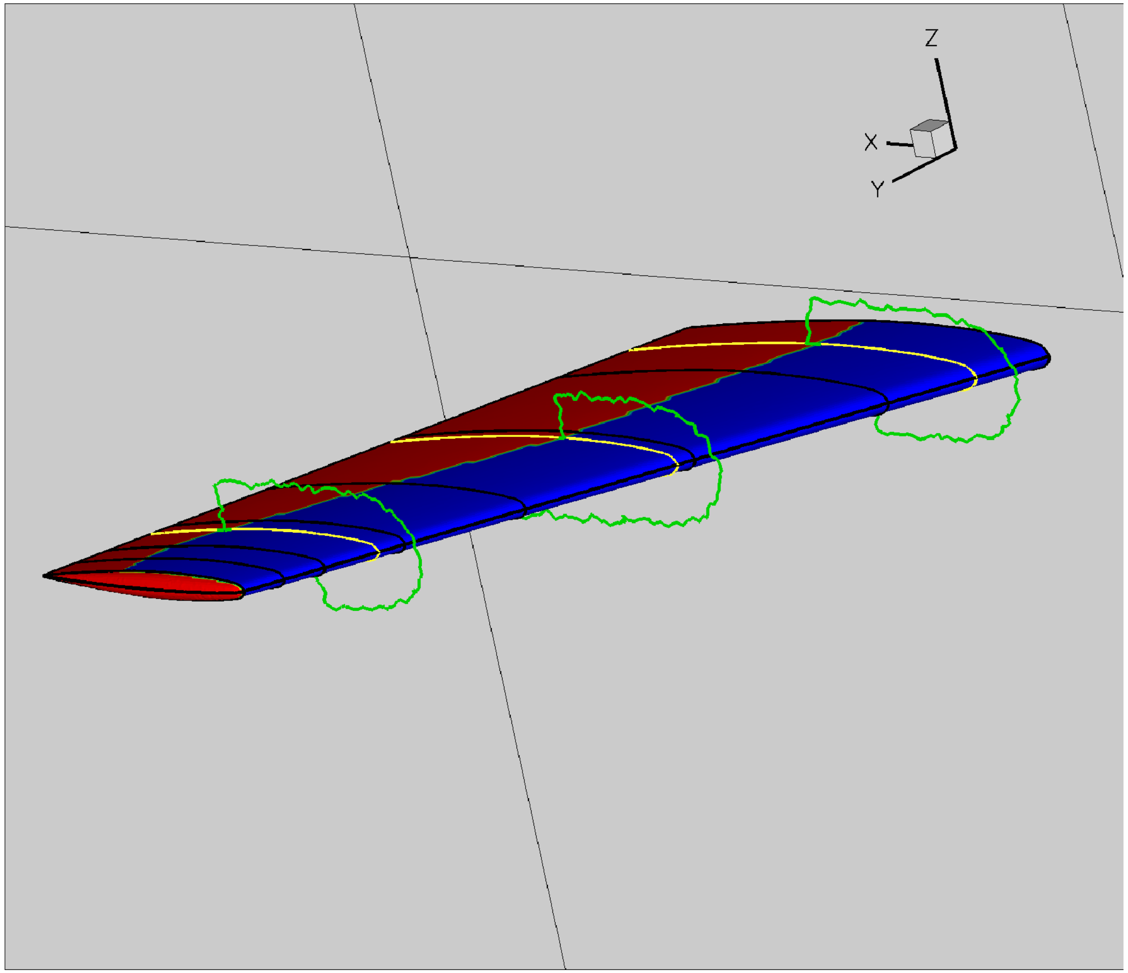

'laminar height' = d_{lam}:

- wall normal extension of the laminar zone
- approximates the shape of the real laminar boundary layer in the simulation
- must contain the maximum laminar boundary layer thickness
- no problem for single-element configurations → $d_{lam} \rightarrow \infty$
- take care in case of multi-element configurations → d_{lam} of downstream elements must NOT 'destroy' turbulent wakes of upstream elements

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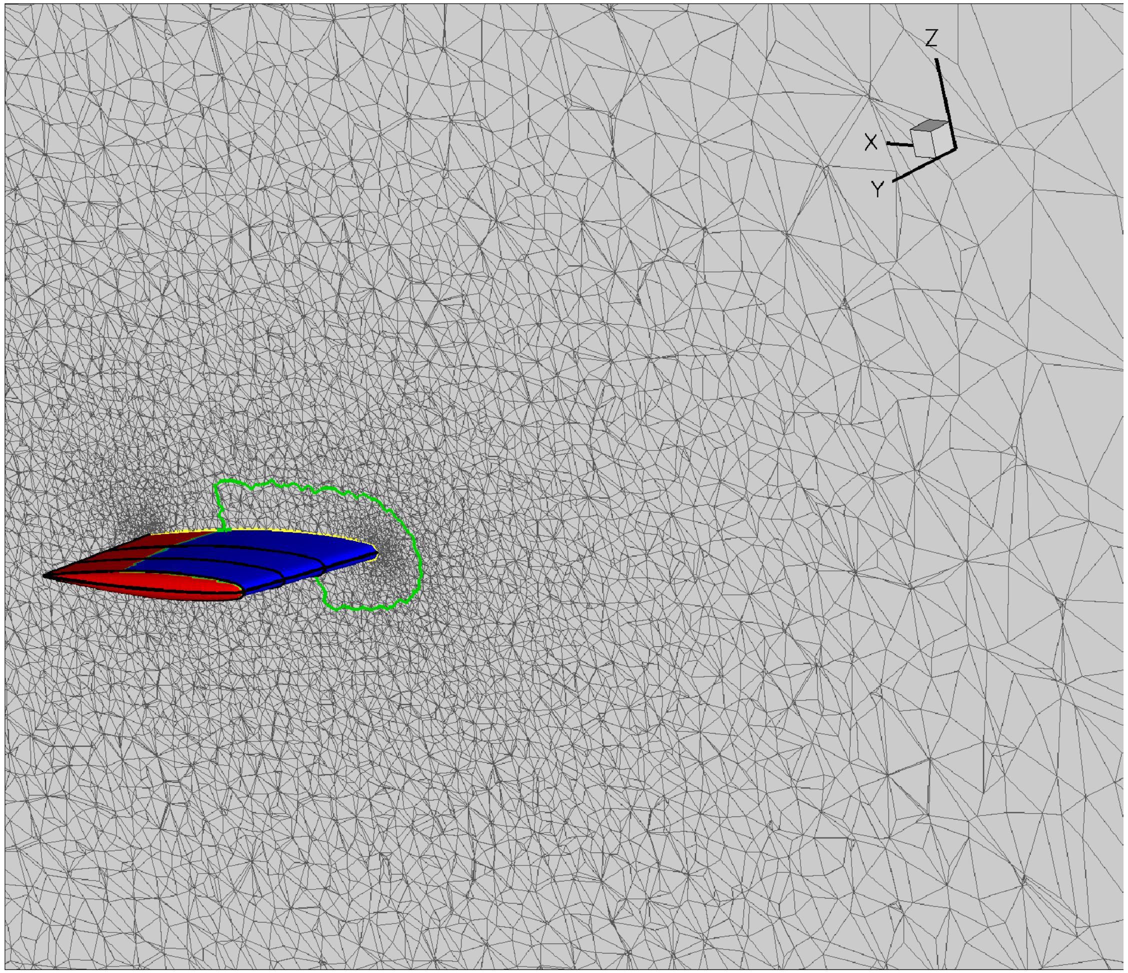

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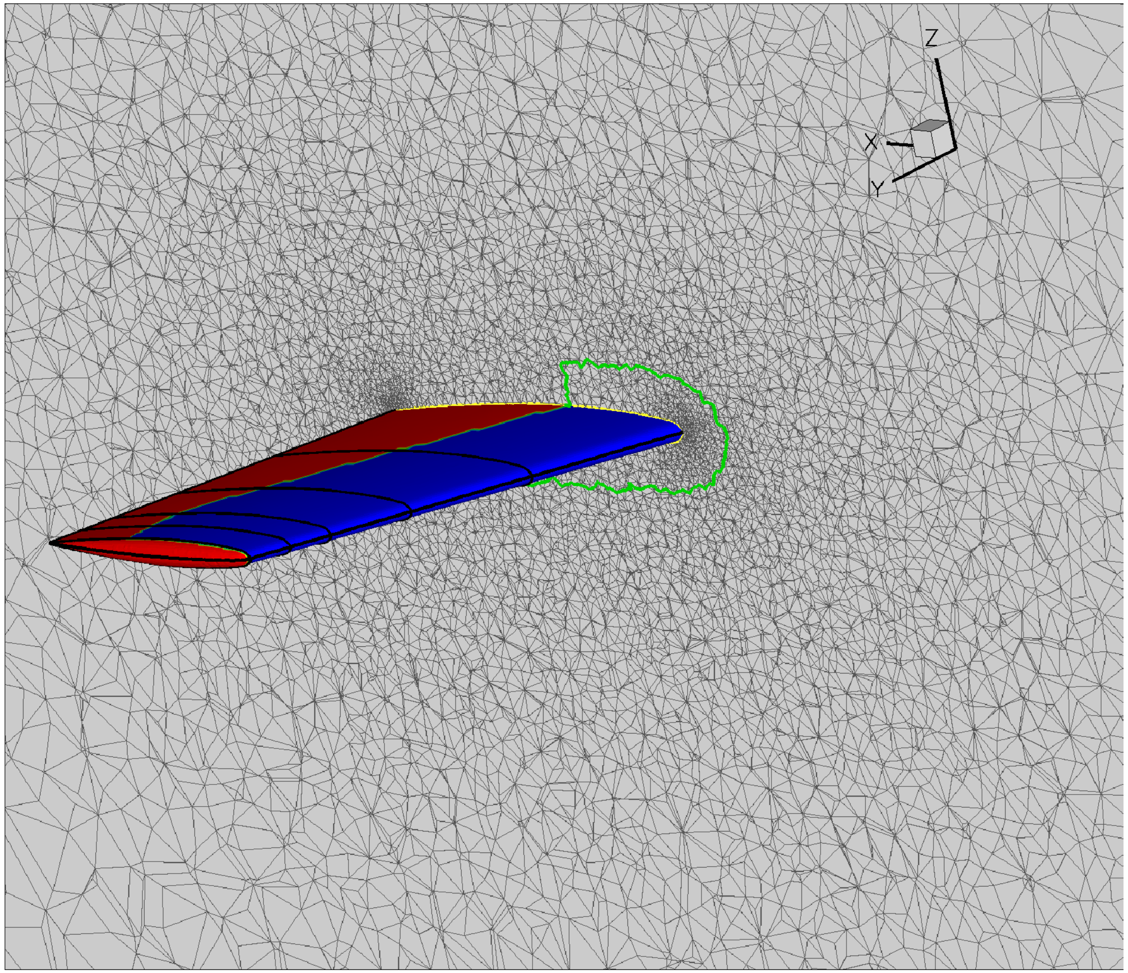

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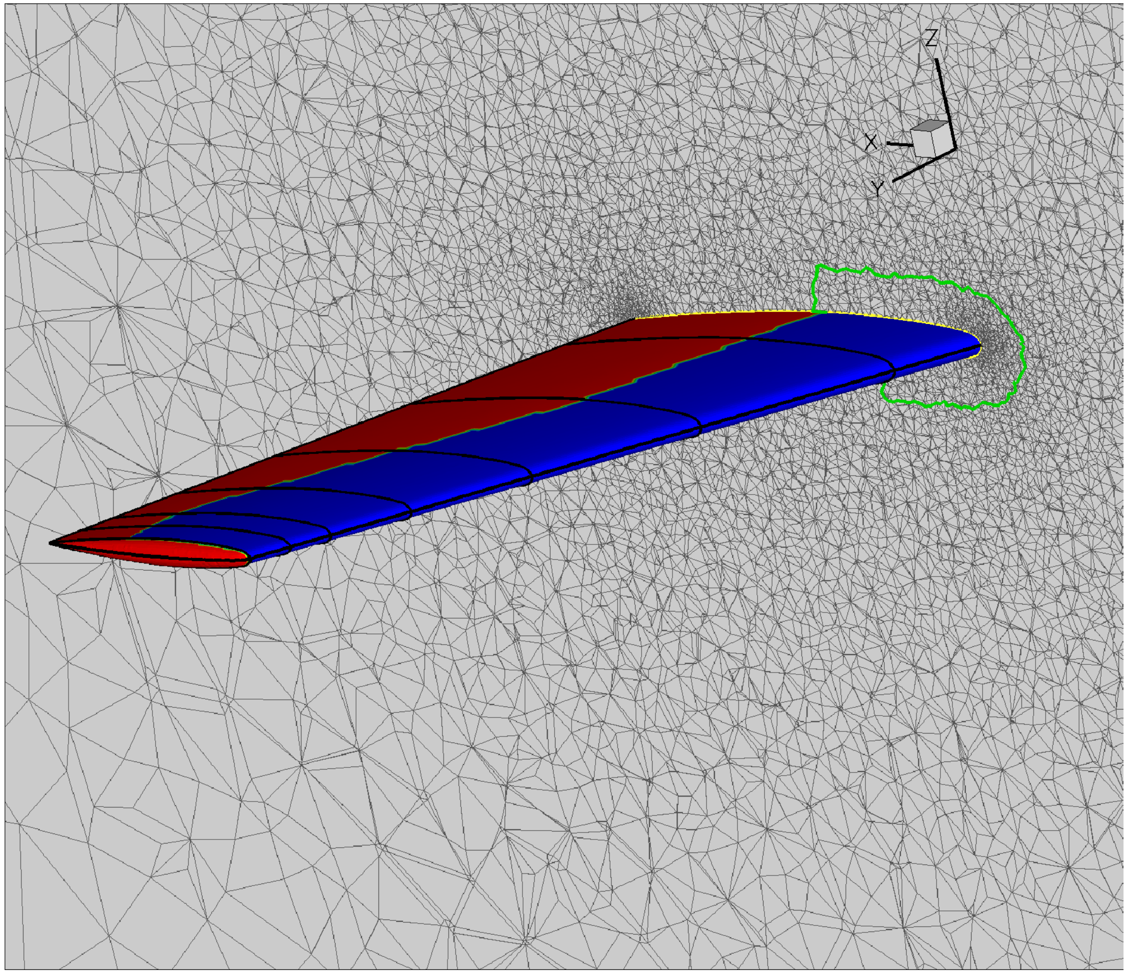

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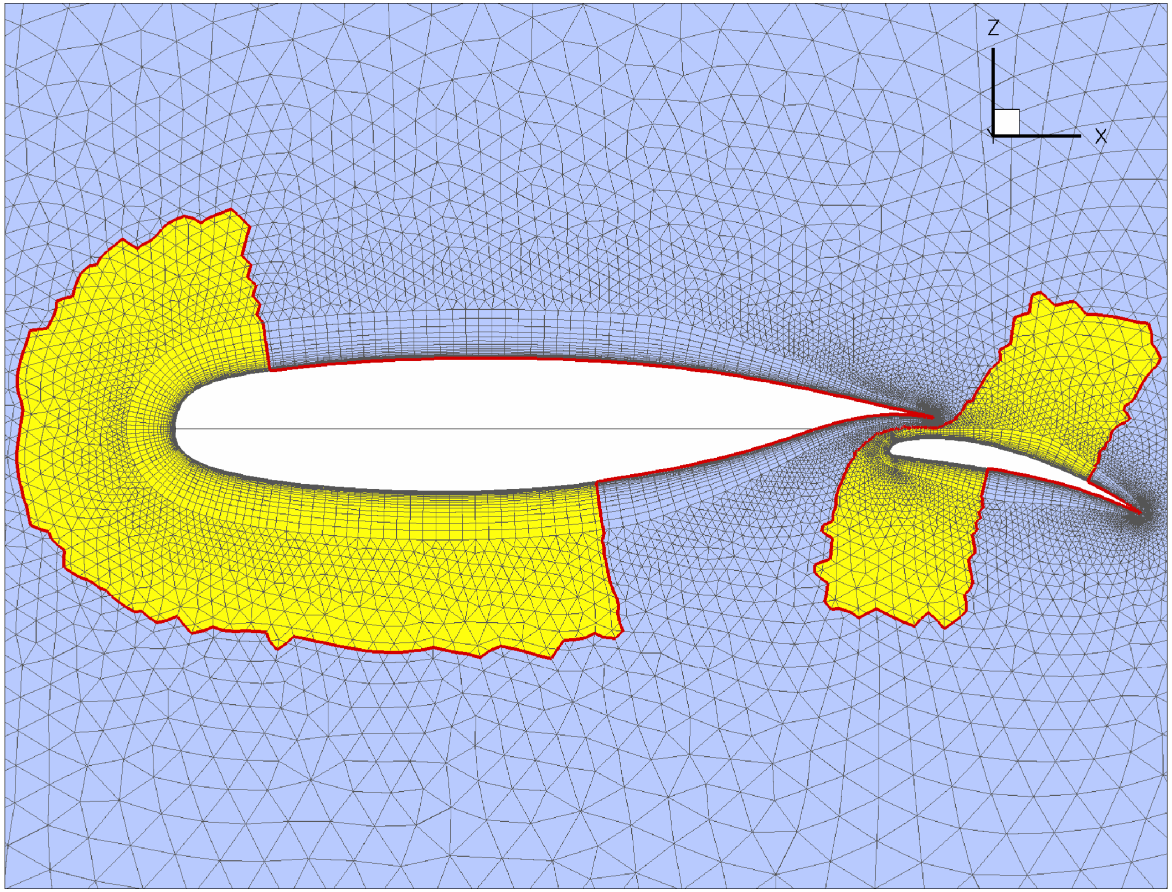
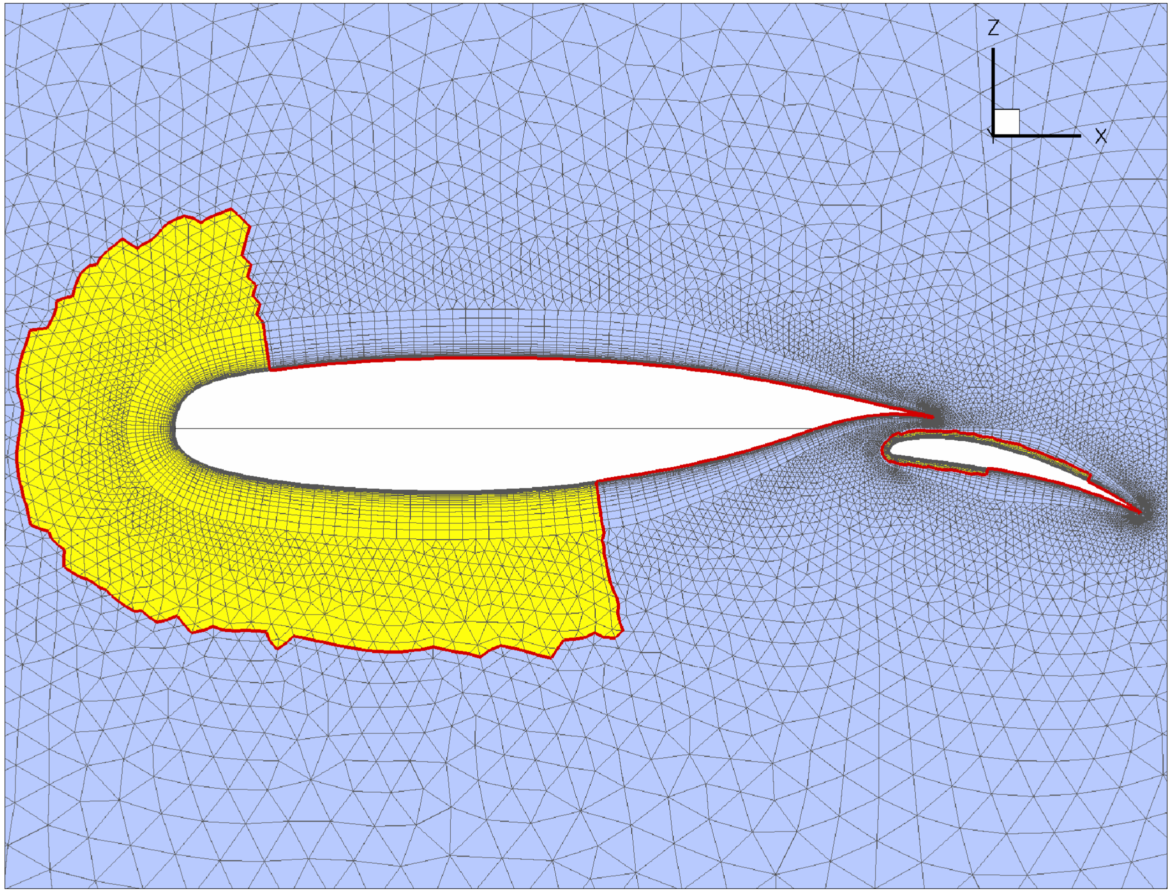
- laminar height at NLR7301 2-element airfoil



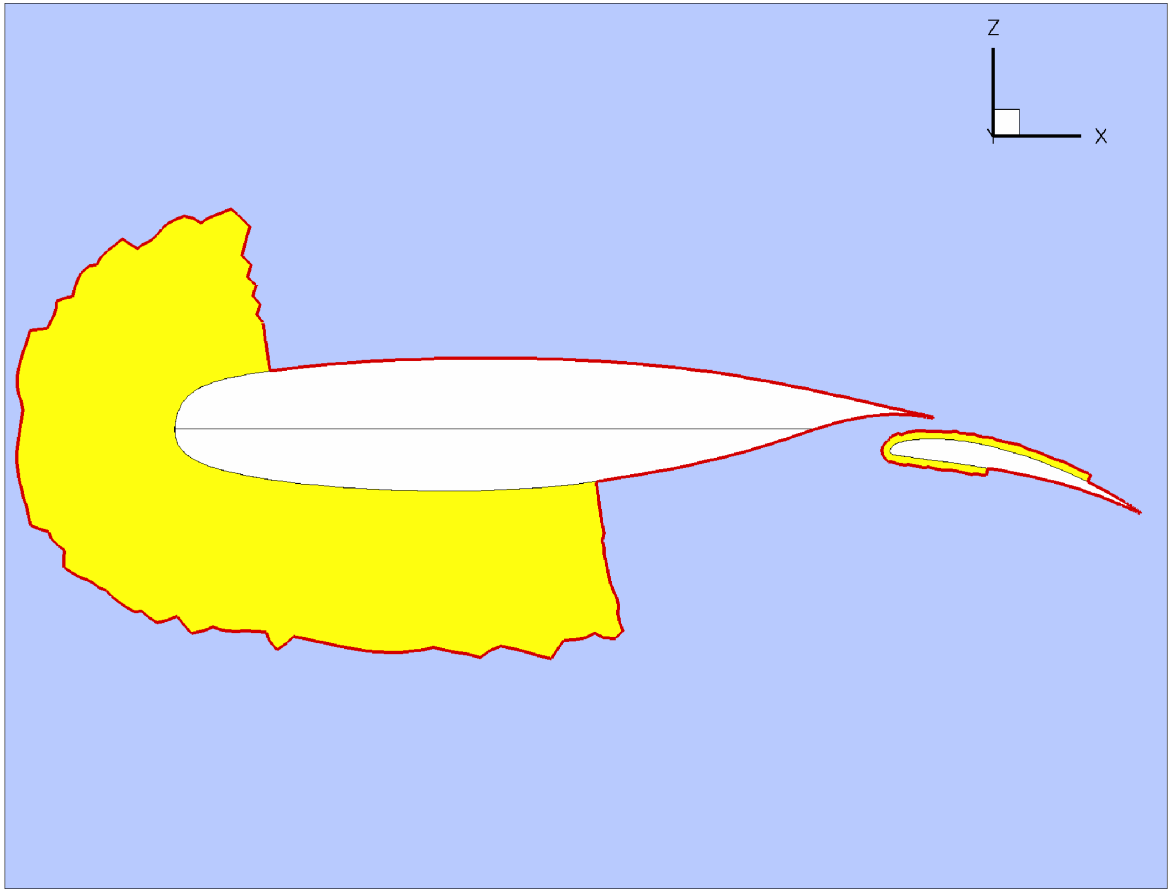
- d_{lam} = 20% chord length
- NOT adequate
  affects the turbulent wake of the main airfoil by artificial and unnatural laminarization over the flap

- laminar height at NLR7301 2-element airfoil



- $d_{lam, main}$ = 20% chord length
- $d_{lam, flap}$ = 1% chord length
- adequate

- laminar height at NLR7301 2-element airfoil



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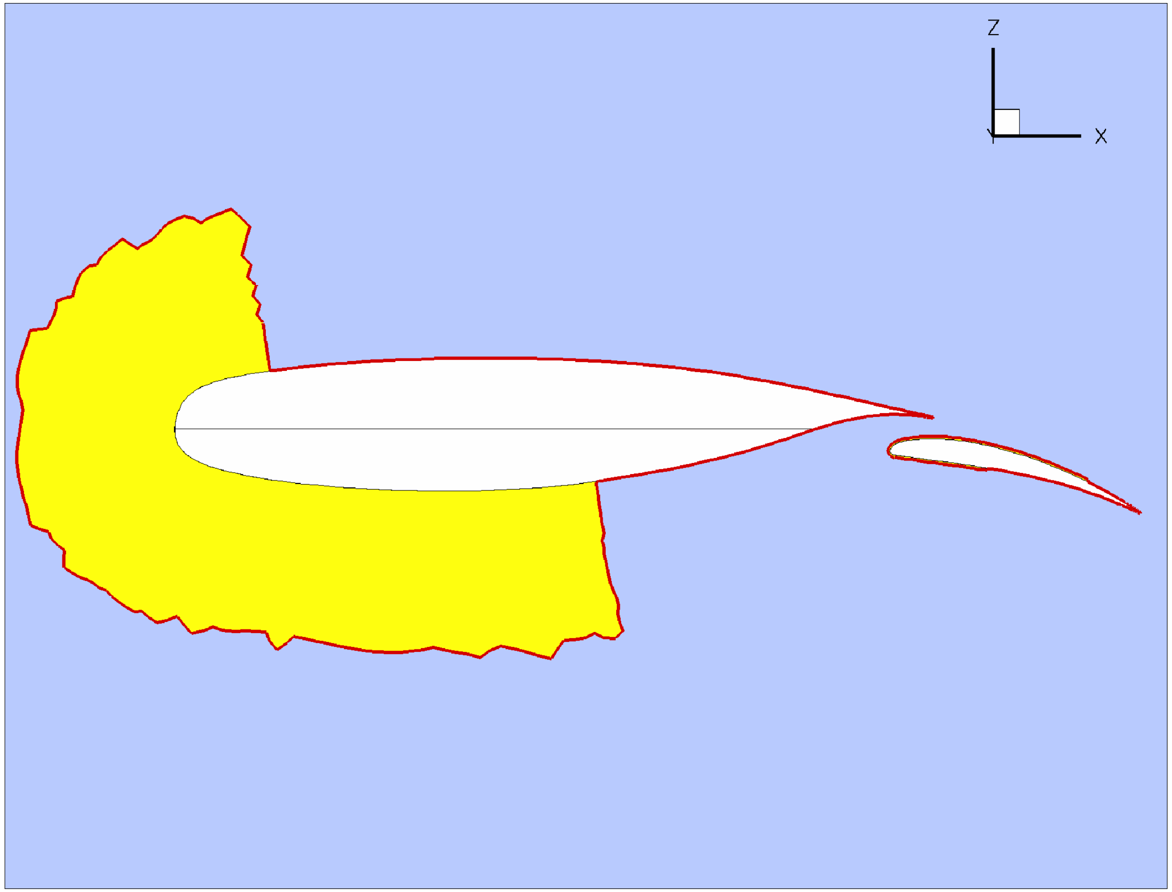
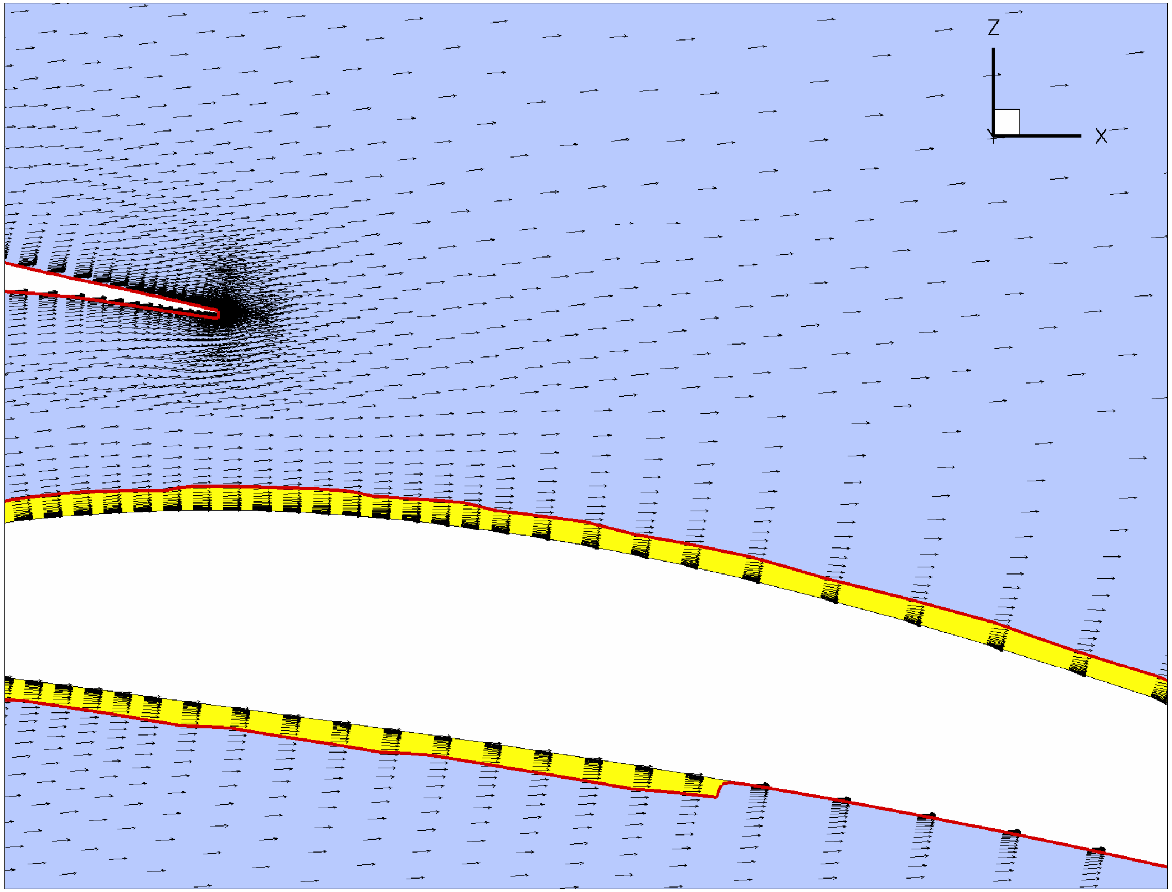


- $d_{lam, main}$ = 20% chord length
- $d_{lam, flap}$ = 0.3% chord length
- sufficient for:

  $Re = 2.51 \times 10^6$
  $Ma = 0.185$
  $\alpha = 6.0°$

- laminar height at NLR7301 2-element airfoil:

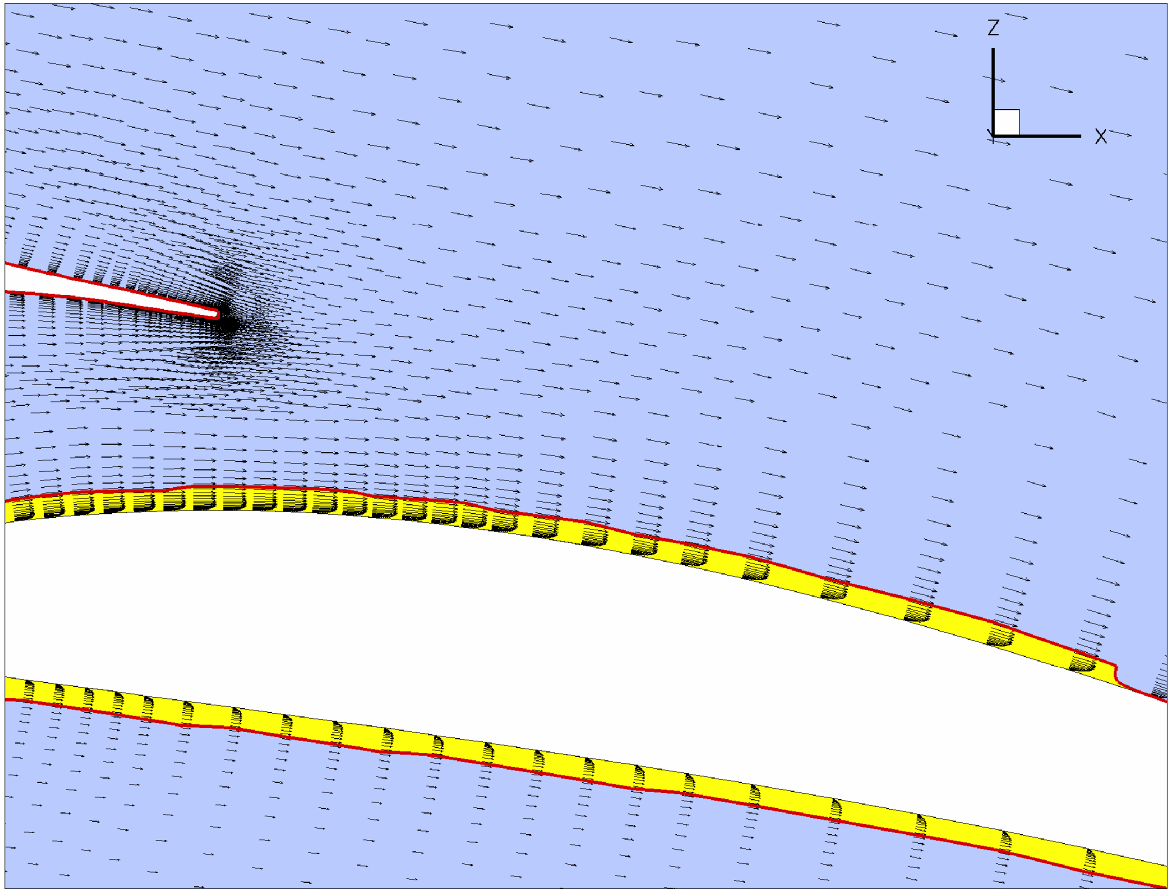


- $d_{lam, flap}$ = 0.3% chord length
- sufficient for:

  Re = 2.51×10^6
  Ma = 0.185
  α = 6.0°
- arbitrary transition points
- velocities after ONE single RANS cycle

Prescription

- laminar height at NLR7301 2-element airfoil:



- $d_{lam,\,flap}$ = 0.3% chord length
- results for:

  $Re = 2.51 \times 10^6$
  $Ma = 0.185$
  $\alpha = 6.0°$
- predicted transition points
- velocities after converged computation

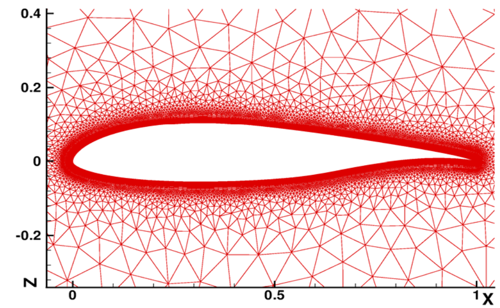
- numerical treatment of laminar points:

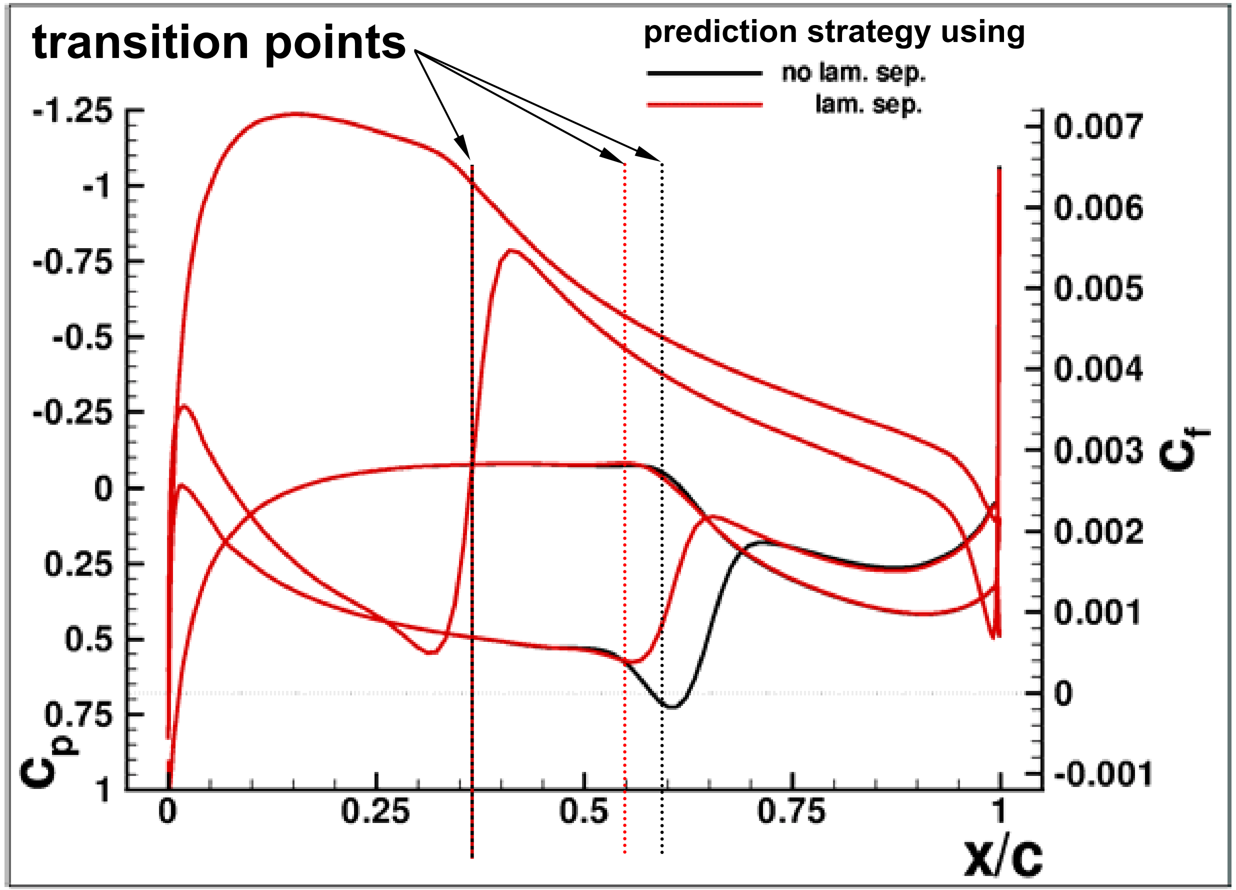
- SA turbulence models: $S_{lam} \leq 0$
- k-ω turbulence models: $S_{k,lam} \leq 0$
  $S_{\omega,lam} \leq 0$ (only if activated by the user via switch in input parameter file)
- RS turbulence models: $S_{RS,lam} \leq 0$

- intermittency:

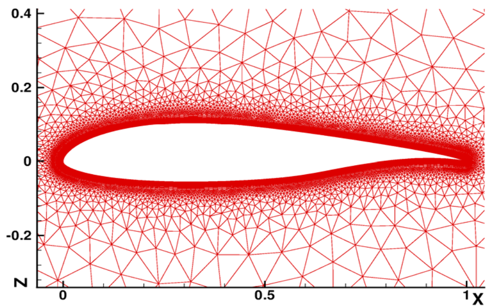
- 'point transition': intermittency function is approximated by a step function (from one point to the next one)

- numerical treatment of laminar points:
  - effect on c_f and c_p
  - Somers laminar airfoil
  - $Re = 4 \times 10^6$
  - $Ma = 0.3$
  - $\alpha = 2°$

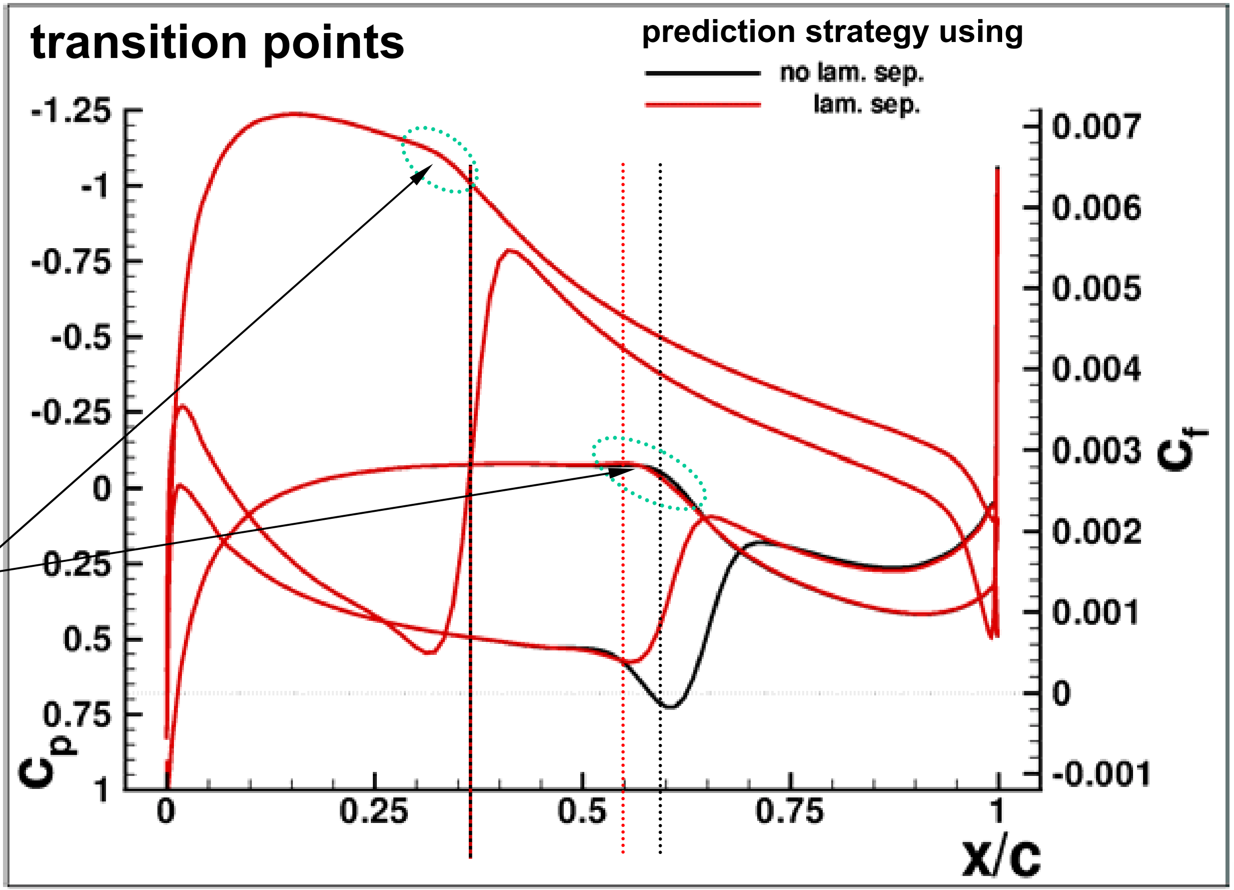




- numerical treatment of laminar points:

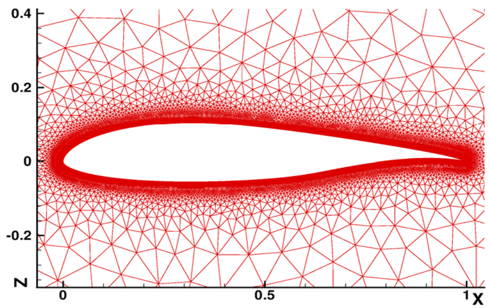


- effect on c_f and c_p
- Somers laminar airfoil with SAE tm
- Re = 4 × 10^6
- Ma = 0.3
- α = 2°
- transition points cause perturbation in c_p due to the change of the boundary layer parameter δ^* (displacement thickness) which affects the shape parameter H
- as if there were a slight separation (there is none)



Prescription

- numerical treatment of laminar points:

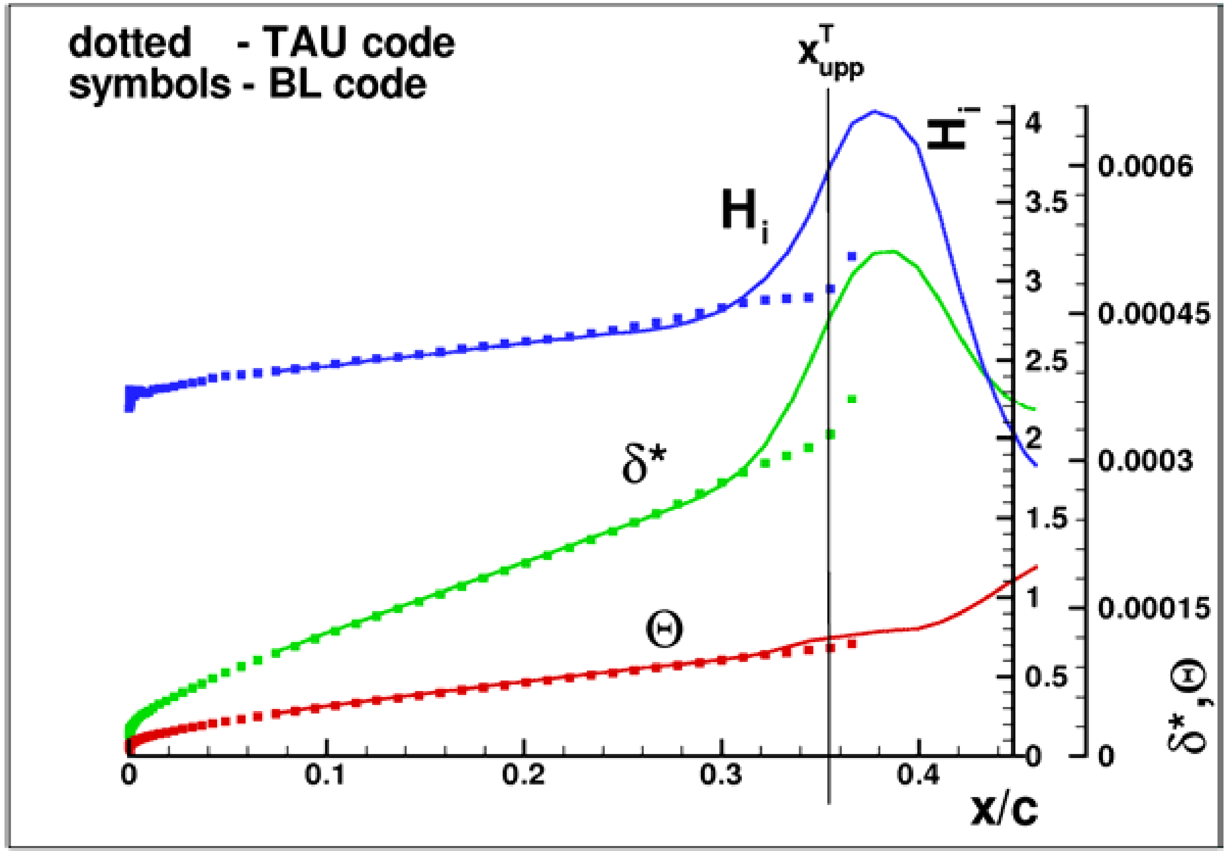


- effect on c_f and c_p
- Somers laminar airfoil
- $Re = 4 \times 10^6$
- $Ma = 0.3$
- $\alpha = 2°$

- shape parameter:
  $H_i = \delta^*/\Theta$

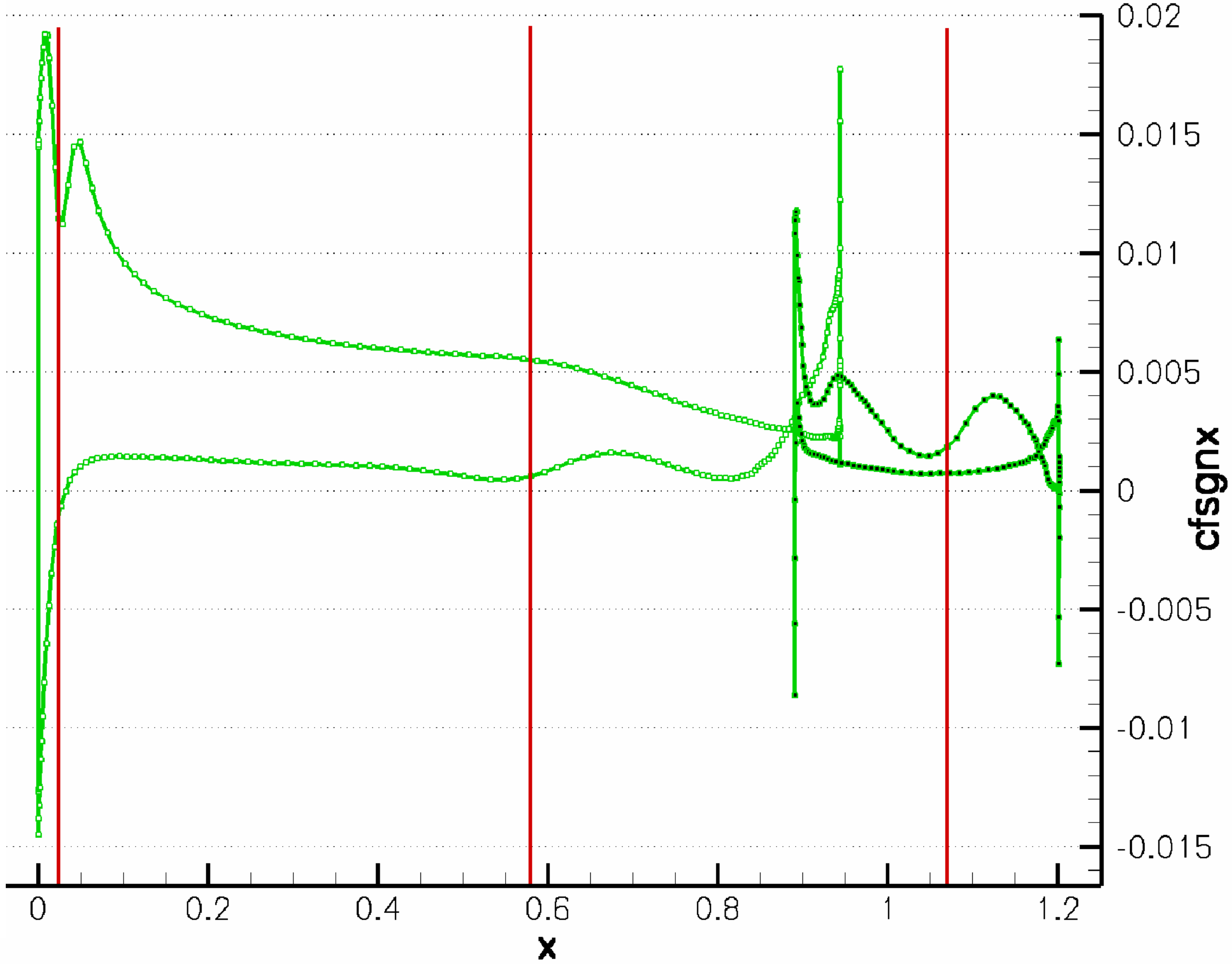
  δ^*: displacement thickness
  Θ: momentum loss thickness

- The higher the artificial dissipation is, the higher is the upstream effect in the results!



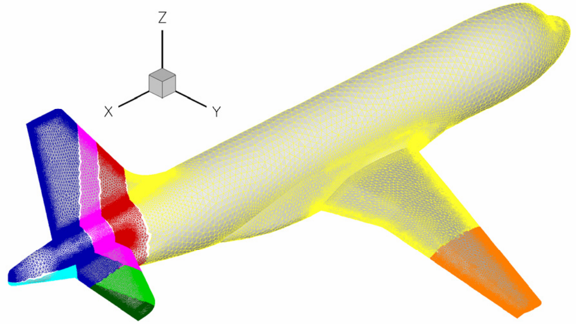
- numerical treatment of laminar points:

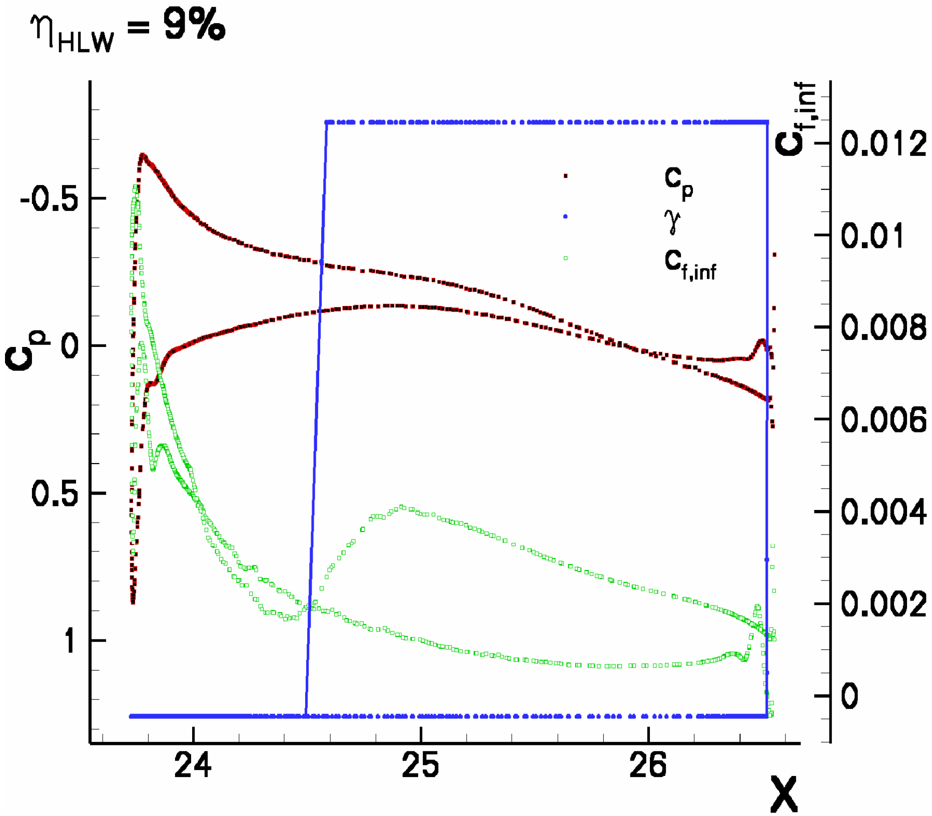
- **NLR7301 2-element airfoil with SAE**

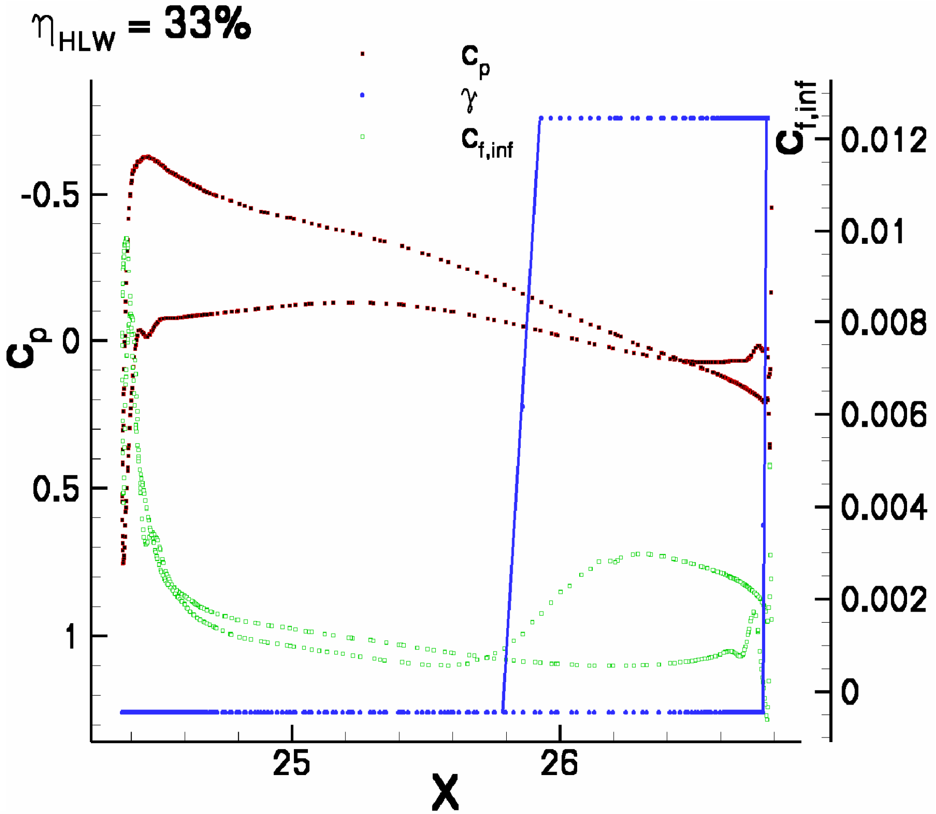


- numerical treatment of laminar points:

  - MPC75 with SAE
  - M = 0.2, Re = 2.3 × 10^6, α = -4°
  - two sections of HTP

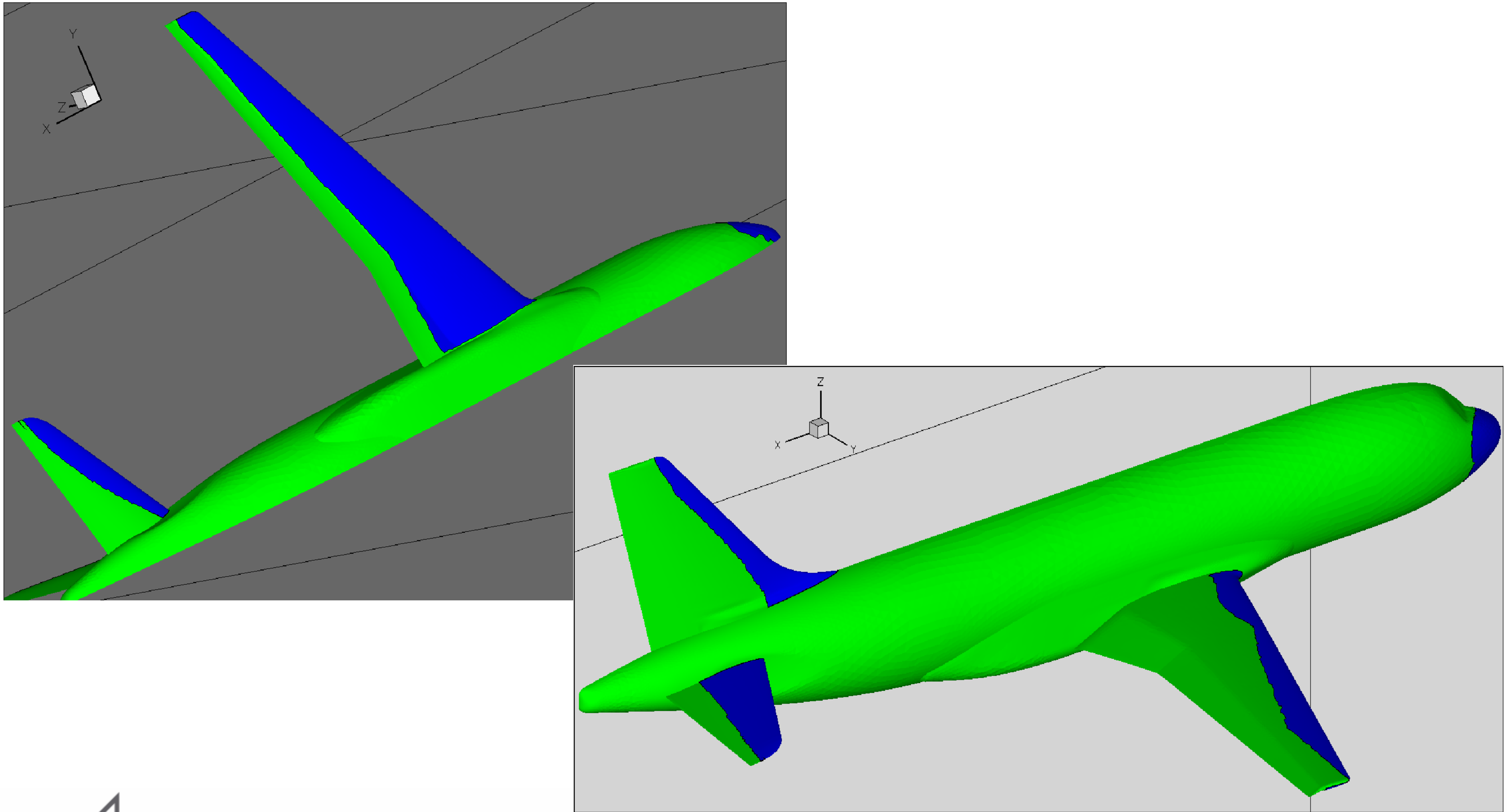






- numerical treatment of laminar points:

  • MPC75 with many, arbitrary transition lines



- **Final remarks:**

  - **Transition prescription is done using the TAU preprocessor**

  - **Laminar points are identified by having a minimum wall distance with a negative sign:**

    sign (wdist[P]) = -1 ⇒ P is laminar

    This information is contained in the dual grid.

  - **There are other (slightly different) possibilities to prescribe transition, but the one shown here, is the one needed for transition prediction**

    ⇒ different boundary markers for upper and lower sides necessary!

Transition Prediction

- **Different prediction approaches:**
  - **Empirical/semi-empirical transition criteria**
    for some mechanisms the only thing available, cheap, can be inaccurate
  - **Local, linear stability theory + e^N method**
    state-of-the-art method in engineering, relatively cheap, relatively accurate
  - **Parabolic stability equations (PSE)**
    non-local, linear&non-linear, rather expensive, very accurate, initial conditions: ?
  - **Large eddy simulation (LES)**
    unsteady, can be very accurate, not yet mature, very expensive
  - **Direct numerical simulation (DNS) of Navier-Stokes equations**
    unsteady, high end approach, nothing is more accurate, unaffordable

Transition Prediction

- Different prediction approaches:
  - Empirical/semi-empirical transition criteria ← 2
    for some mechanisms the only thing available, cheap, can be inaccurate
  - Local, linear stability theory + e^N method ← 1
    state-of-the-art method in engineering, relatively cheap, relatively accurate
  - Parabolic stability equations (PSE)
    non-local, linear&non-linear, rather expensive, very accurate, initial conditions: ?
  - Large eddy simulation (LES)
    unsteady, can be very accurate, not yet mature, very expensive
  - Direct numerical simulation (DNS) of Navier-Stokes equations
    unsteady, high end approach, nothing is more accurate, unaffordable

- **Different coupling approaches:**
  - RANS solver + stability code + e^N method
  - RANS solver + boundary layer code
    + stability code + e^N method
  - RANS solver + boundary layer code
    + e^N database method(s)
  - RANS solver + transition closure model or
    transition/turbulence model

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Different coupling approaches:

- RANS solver + stability code + e^N method
- RANS solver + boundary layer code
  + fully automated stability code
  + e^N method
- RANS solver + boundary layer code
  + e^N database method(s)
- RANS solver + transition closure model or
  transition/turbulence model

Different coupling approaches:

- RANS solver + fully automated stability code + e^N method ← 2
- RANS solver + boundary layer code + fully automated stability code + e^N method ← 1
- RANS solver + boundary layer code + e^N database method(s) ← 3
- RANS solver + transition closure model or transition/turbulence model ← future

Characteristics:

- for steady flows
- Local, linear stability theory + e^N method: TS, CF & LS
  → Tollmien-Schlichting (TS) instabilities: streamwise velocity profile
  → Cross flow (CF) instabilities: cross flow velocity profile
  → Transition in laminar separation bubble (LS): TS or Kelvin-Helm-holtz (free shear layer) instability
- Accurate results for many flow situations in aircraft aerodynamics, e.g. attached flow, laminar separation bubbles
- Empirical criteria
  - Attachent line transition (ALT): Pfenninger/Poll
  - Bypass transition (BPT): Mayle
  - LS (with BL code): Schmidt/Müller (to come)
  - TS: Arnal-Habiballah-Delcourt (AHD), Michel/Cebeci/Thwaites (only 2d)
  - CF: C1
  - Relaminarization: Beasley (to come)

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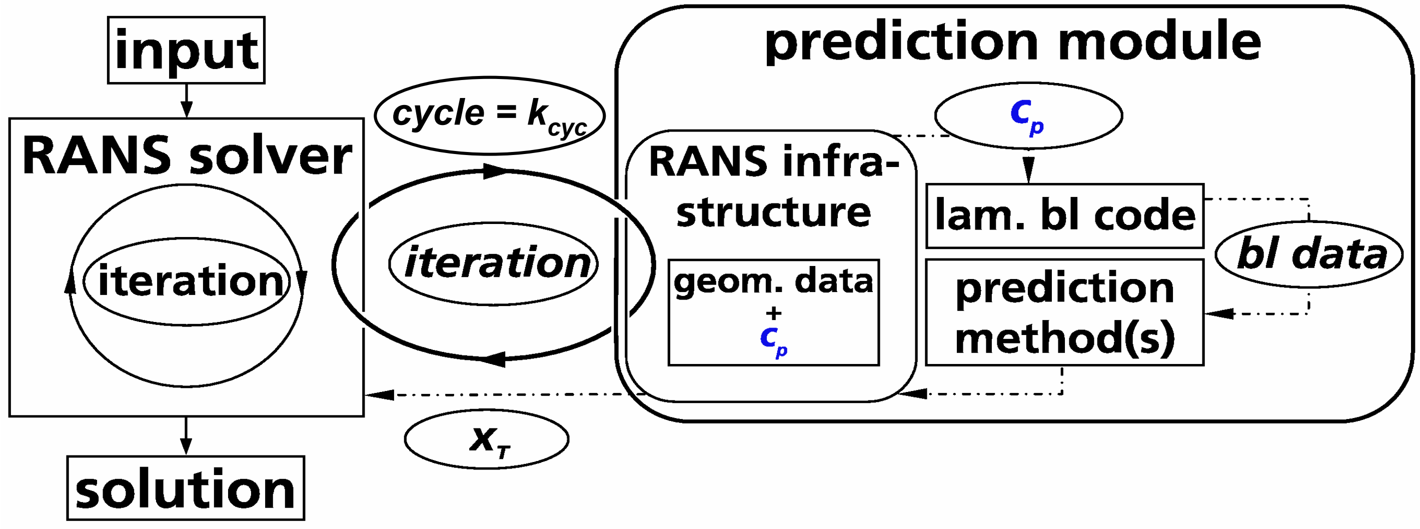
  - CF: C1
  - Relaminarization: Beasley (to come)

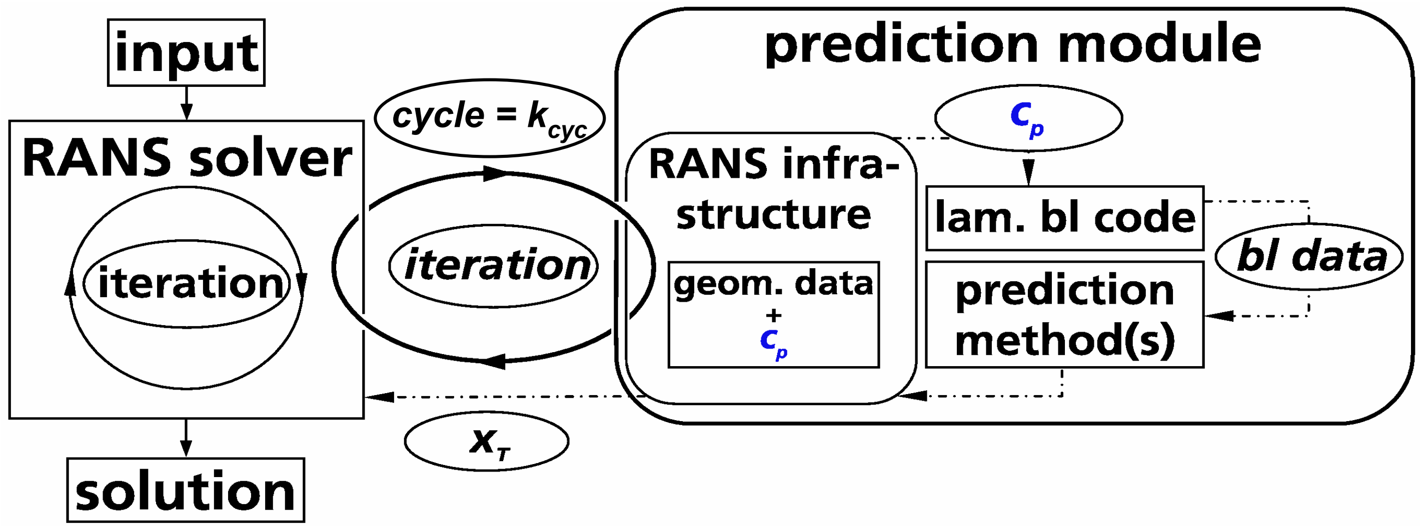
Criteria not yet tested!

Transition Prediction Coupling Structure

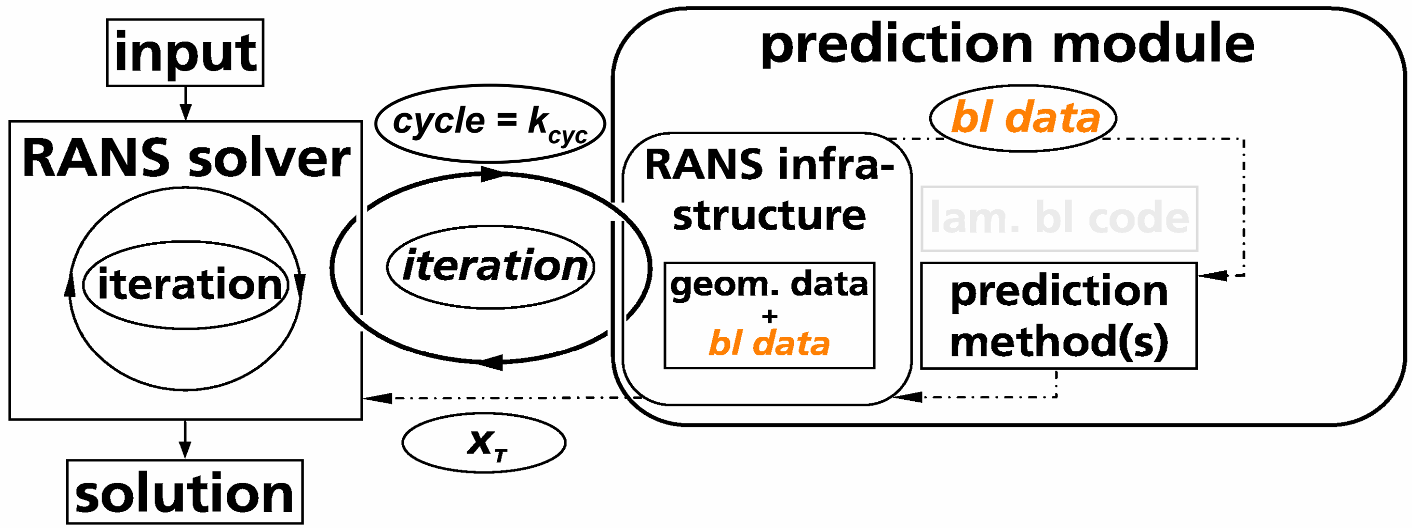
external BL approach



external BL approach



internal BL approach



Transition module

transition module

- **line-in-flight cuts**

  or
- **inviscid stream lines**

- ***c_p-extraction***

  or
- **lam. BL data from RANS grid**

- ***lam. BL code COCO*** (Schrauf)
  - **swept, tapered → conical flow, 2.5d**
  - **external code**

- **local lin. stability code LILO** (Schrauf)
  - **e^N method for TS & CF**
  - **external code**

  or
- **e^N database methods**
  - **for TS** (Stock) **& CF** (Casalis/Arnal)
  - **external codes**

Transition module

transition module

RANS infrastructure

- **line-in-flight cuts**

  or
- **inviscid stream lines**
- ***c_p-extraction***

  or
- **lam. BL data from RANS grid**
- ***lam. BL code COCO*** (Schrauf)
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  or
- **e^N database methods**
  - **for TS** (Stock) **& CF** (Casalis/Arnal)
  - **external codes**

Application areas

- 2d airfoil configurations
- 2.5d wing configurations: inf. swept
- 3d wing configurations
- 3d fuselages
- 3d nacelles

- Single-element configurations
- Mulit-element configurations

- Flow topologies
  - attached
  - with lam. separation:
    - LS point as transition point
    - bubble with criterion OR
      real stability analysis with LILO code inside bubble
      + many points in prismatic layer

Application areas

- 2d airfoil configurations
- 2.5d wing configurations: inf. swept
- 3d wing configurations
- 3d fuselages
- 3d nacelles

→ streamlines necessary!

- Single-element configurations
- Mulit-element configurations

- Flow topologies
  - attached
  - with lam. separation:
    - LS point as transition point
    - bubble with criterion OR
      real stability analysis with LILO code inside bubble
      + many points in prismatic layer

lam. BL data from RANS grid needed!
for 3d case: for CF
→ 128 points in wall normal direction necessary!!!

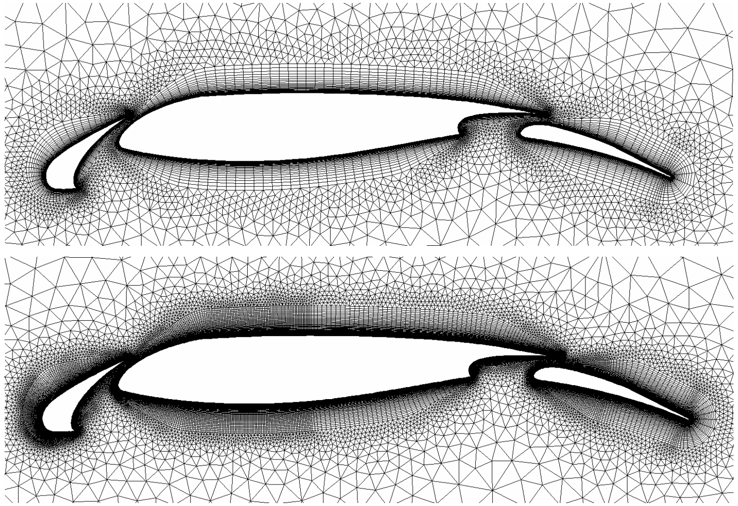
Algorithm

- **set** s_{tr}^{u} **and** s_{tr}^{l} **far downstream** (→ start mit quasi fully-laminar conditions)
- **compute flow field**
- **check for lam. separation in RANS grid**
  - → **set laminar separation points as new** $s_{tr}^{u,l}$
  - ⇒ stabilization of the computation in the transient phase
- $c_l \approx const.$ in cycles
  - → **call transition module**
  - → **use** **a.) new transition point directly**
    or
    b.) lam. separation point of BL code as approximation
- **see new** $s_{tr}^{u,l}$ **underrelaxed** → $s_{tr}^{u,l} = s_{tr}^{u,l}\,\delta, \quad 1.0 < \delta < 1.5$
  - ⇒ damping of oscillations in transition point iteration
- **check convergence** → $\Delta s_{tr}^{u,l} < \varepsilon$

no (→ back to compute flow field) | **yes** → ***STOP***

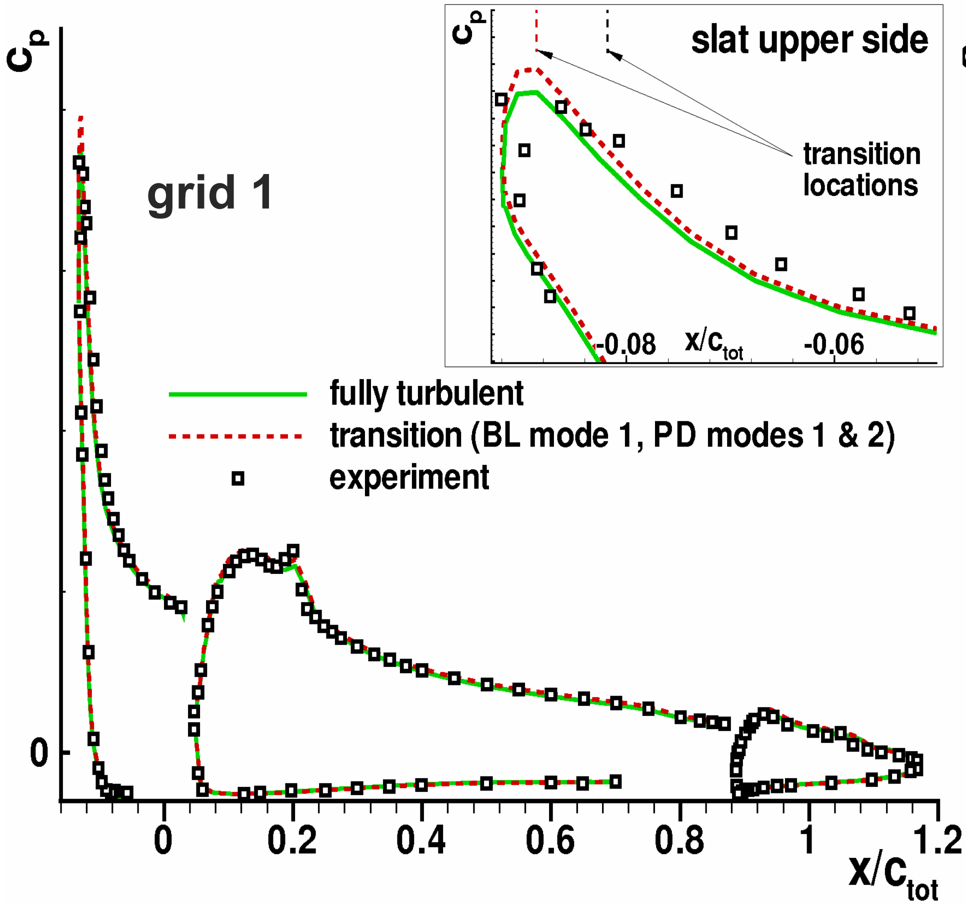
Computational Results

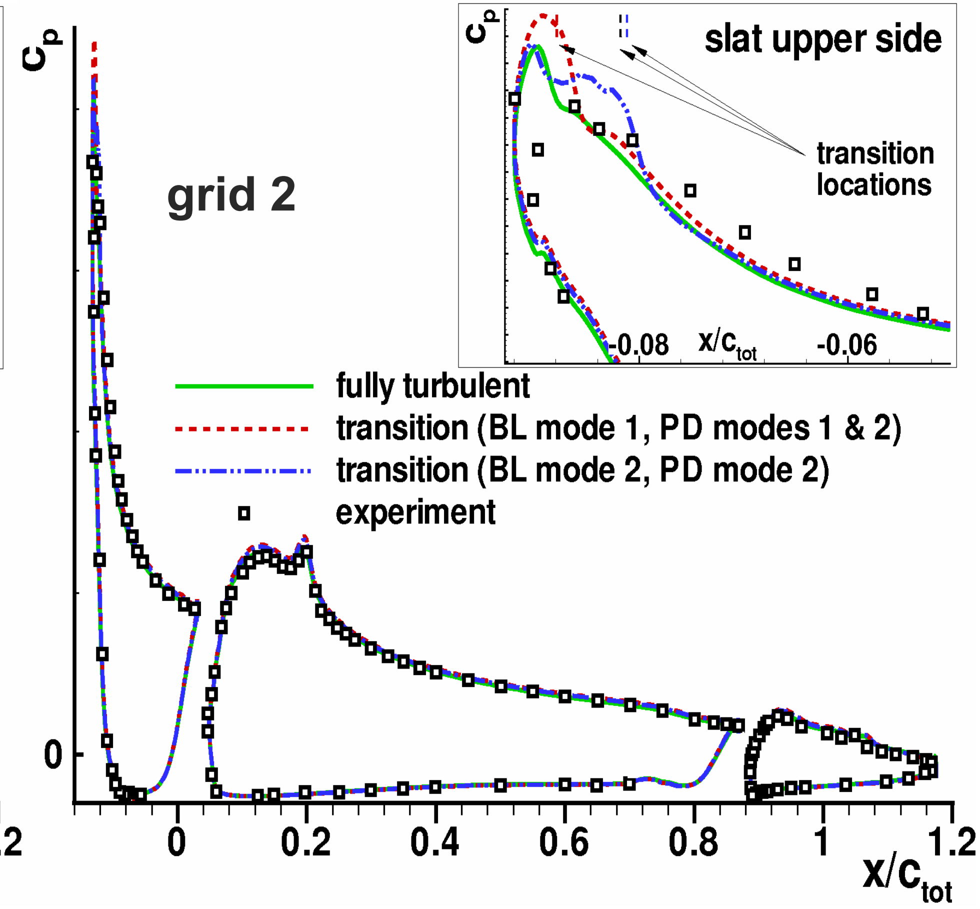
- **2d A310 take-off:**
  - **$M = 0.221$, $Re = 6.11 \times 10^6$, $\alpha = 21.4°$**
  - **grid 1: 22.000 points**
    grid 2: 122.000 points, noses highly resolved
  - **SAE**
  - **$N_{TS} \approx 8.85$ (F1)**
  - **Prediction on upper sides only, lower sides fully-laminar**
  - **exp. transition locations → slat: 15% & flap: 34.5%**
    'kink' on main upper side → 19%
  - **different mode combinations:**
    a) BL code & TS database method → BL mode 1 & PD mode 1
    b) BL code & stability code LILO → BL mode 1 & PD mode 2
    c) BL in TAU & stability code LILO → BL mode 2 & PD mode 2



grids: J. Wild, DLR

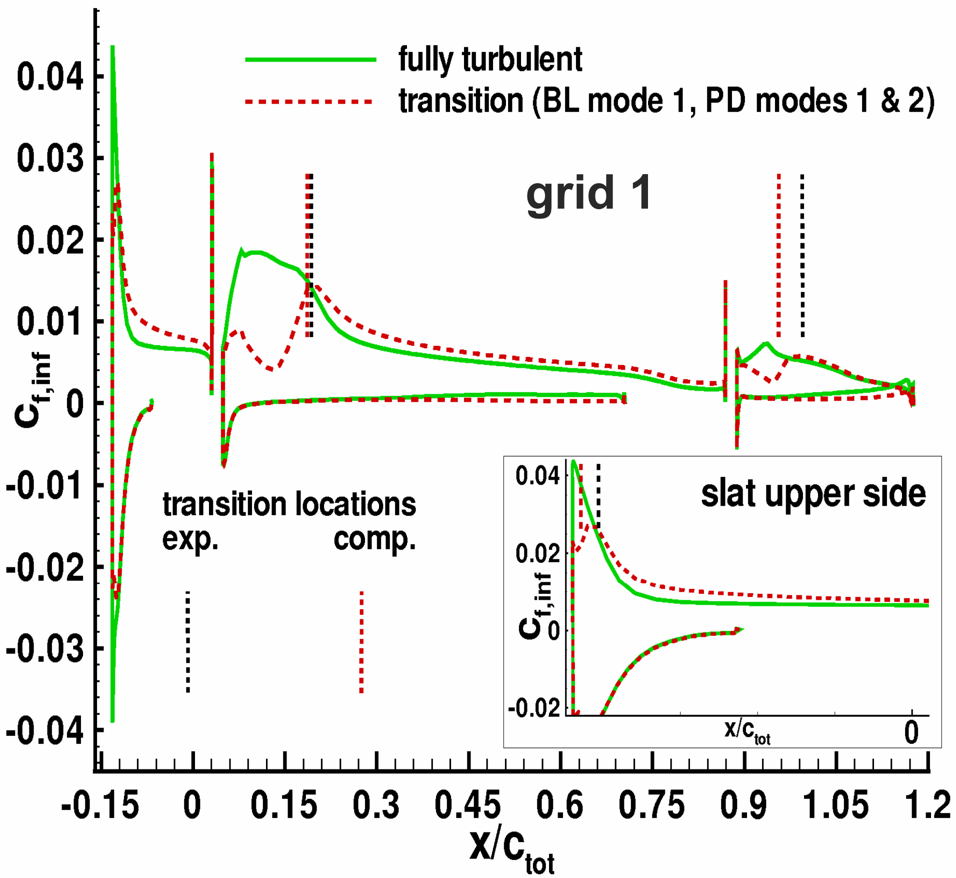
Surface pressure distributions

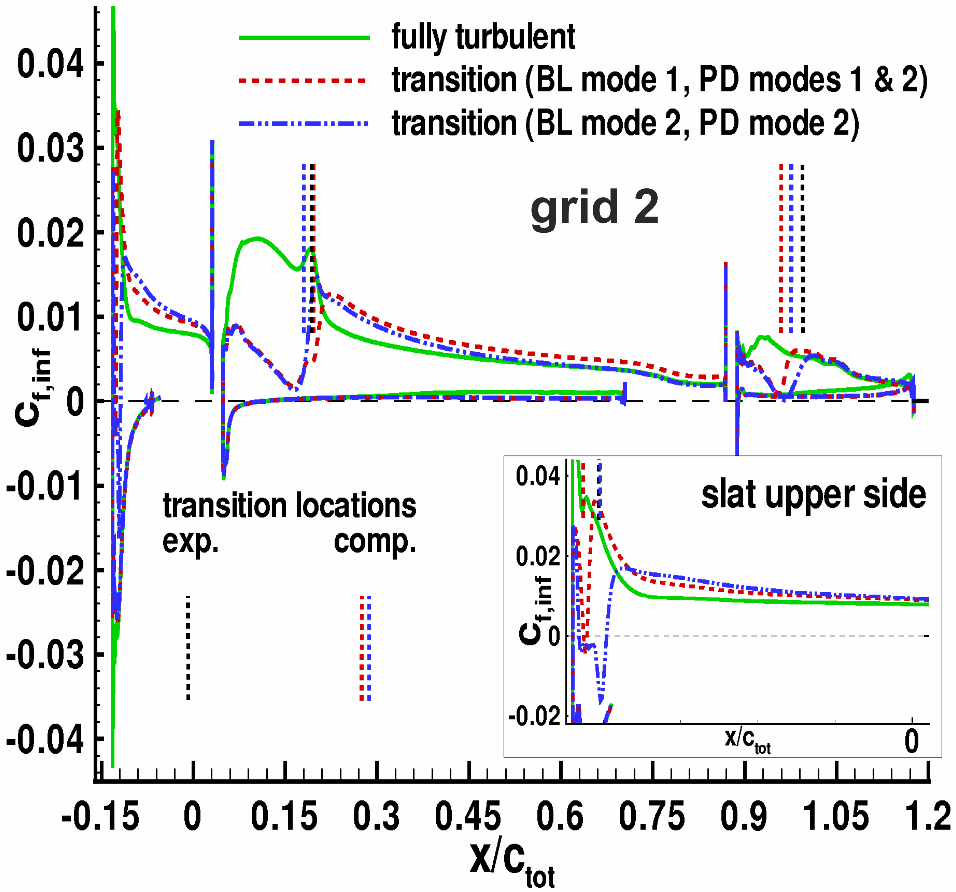




a.) & b.) results identical → all LS	a.) & b.) results identical → all LS
c.) no convergence → grid too coarse	c.) all from stability code LILO

Skin friction distributions





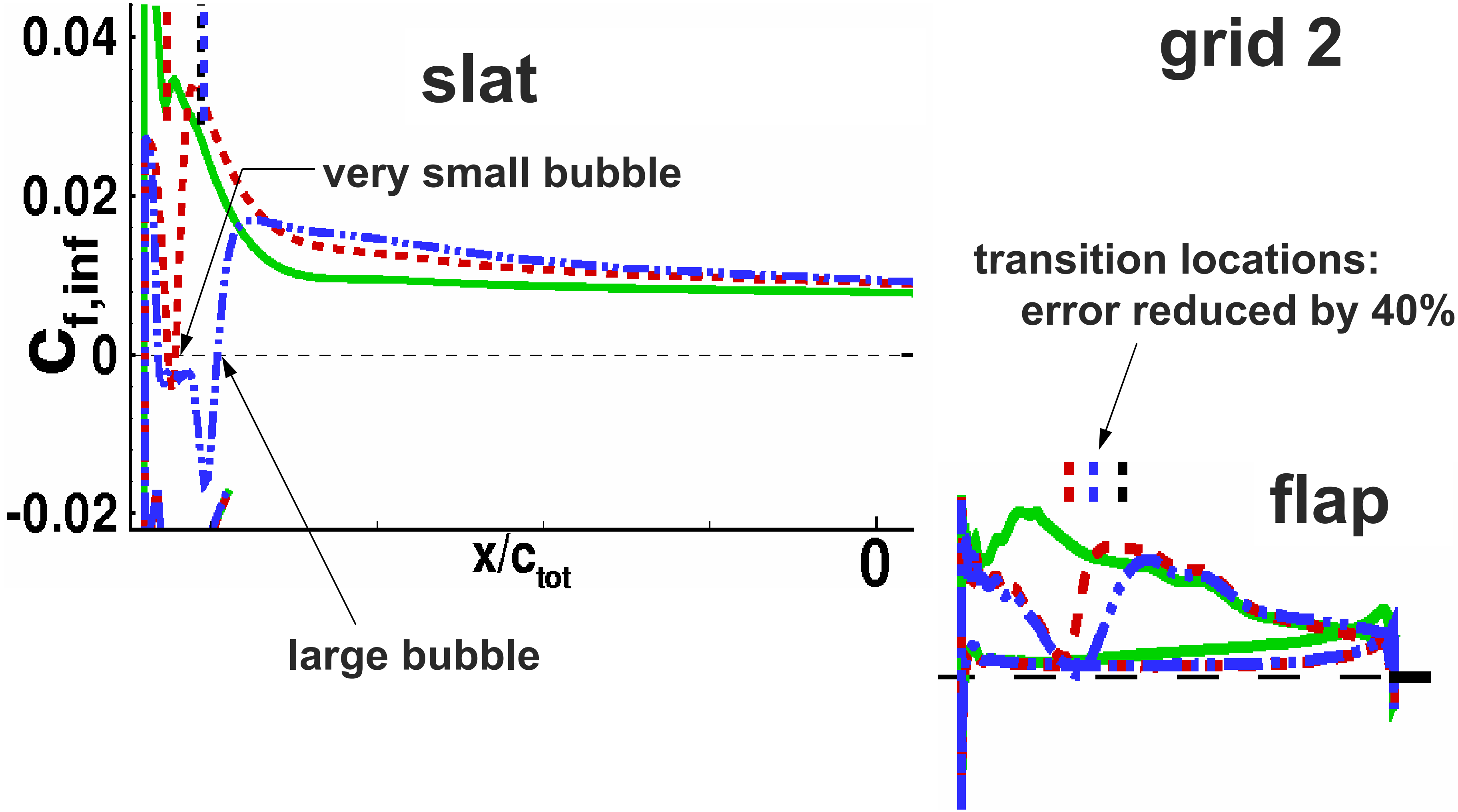
a.) & b.) no separation bubbles

c.) no convergence

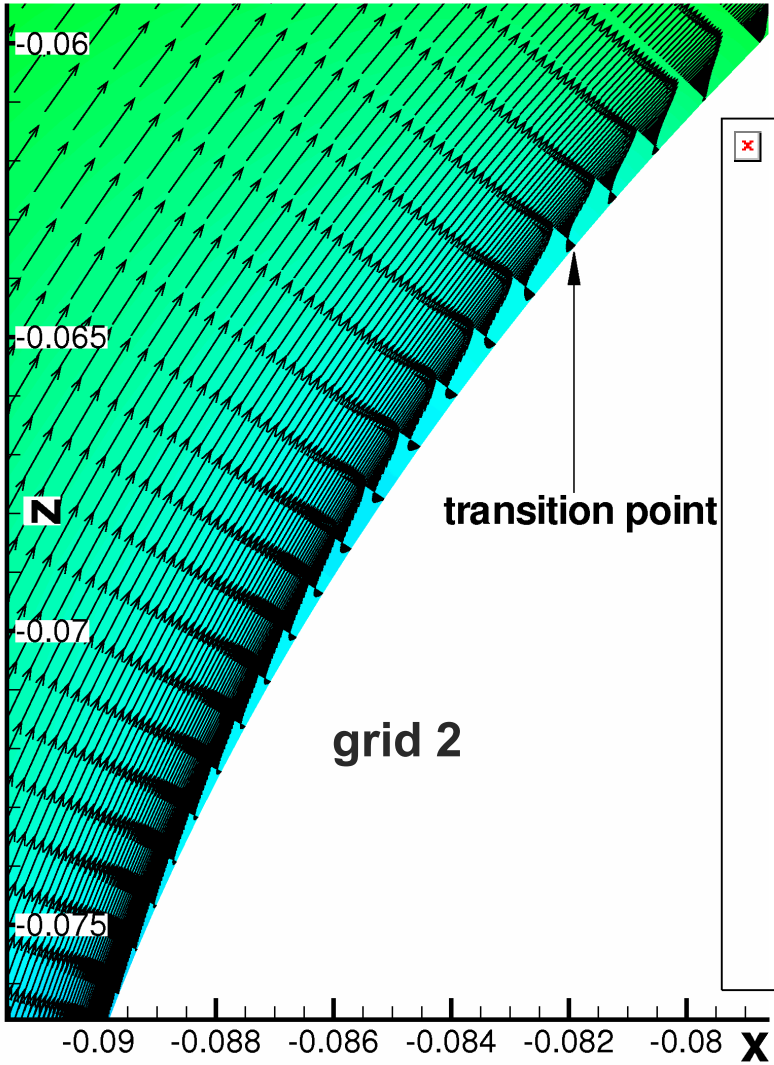
a.) & b.) very small bubble on slat

c.) much bigger slat bubble & improvement on flap

Skin friction distributions

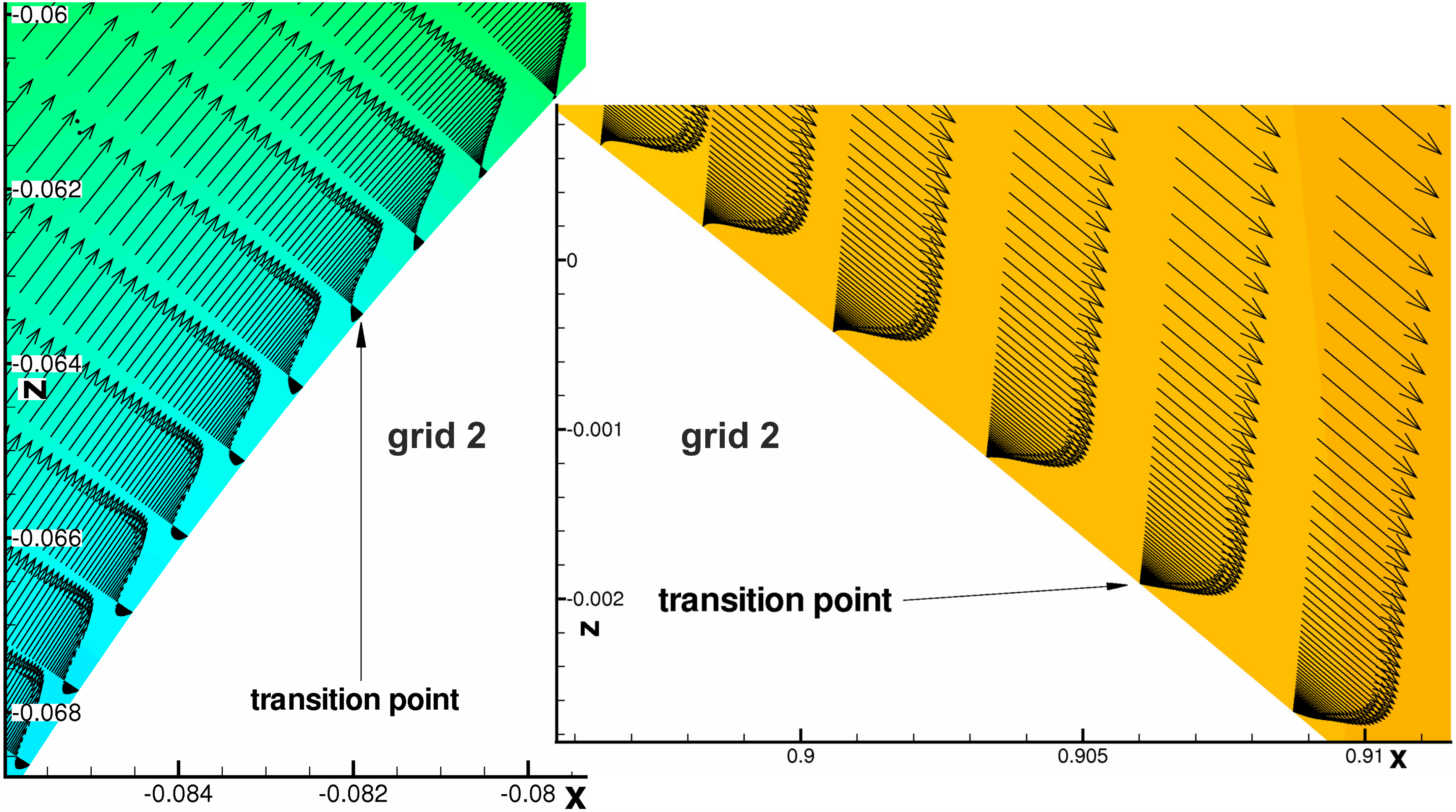


Transition points and separation regions



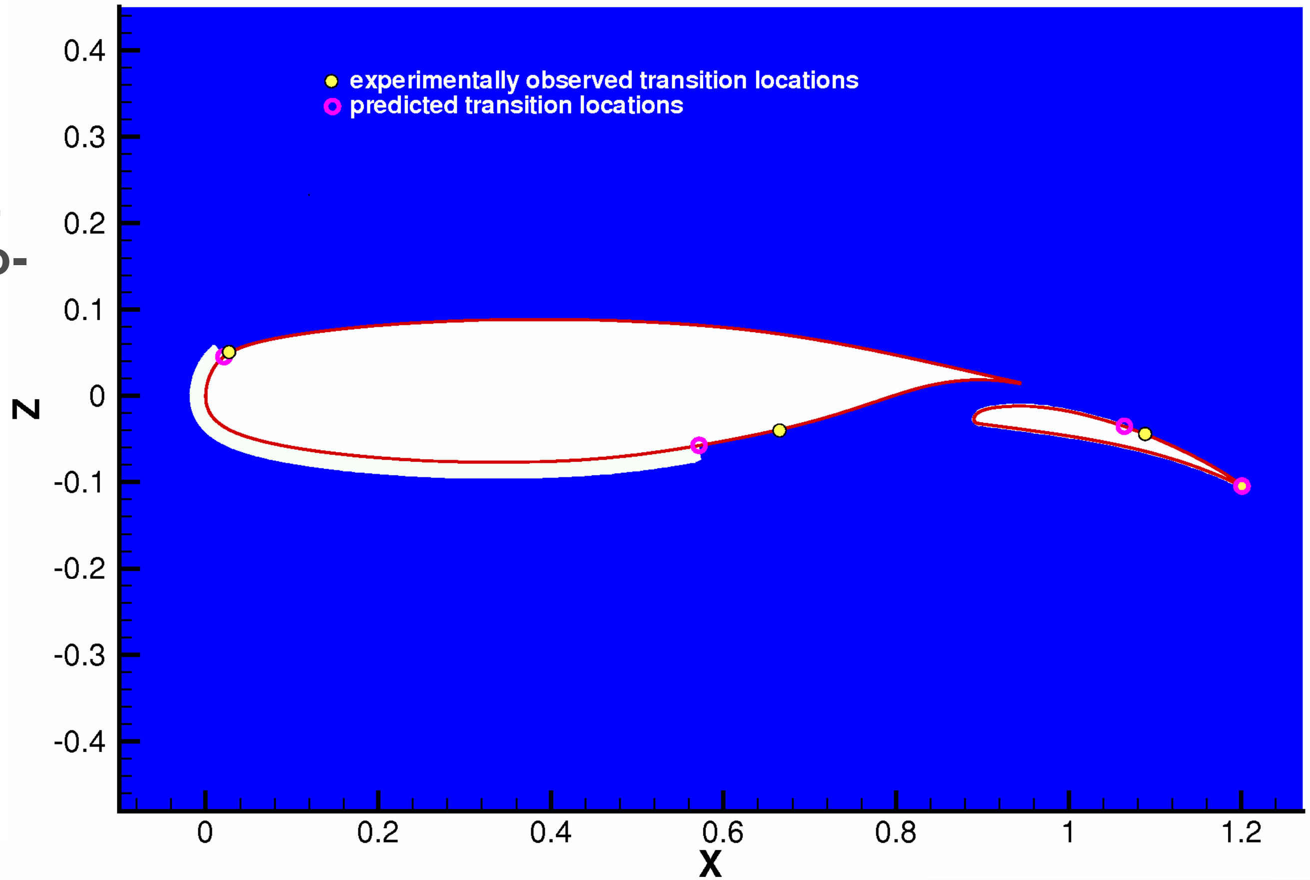
grid 2

Transition points and separation regions

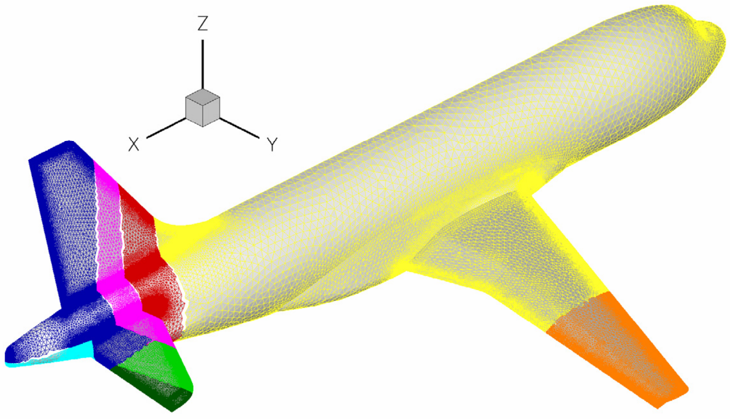


2d NLR7301 2-element airfoil:

- M = 0.185, Re = 2.51×10^6, $\alpha = 6°$
- Airbus grid: ???
- SAE
- N_{TS} = 9, however not relevant here, because all appro-ximated by LS
- next test: internal BL data

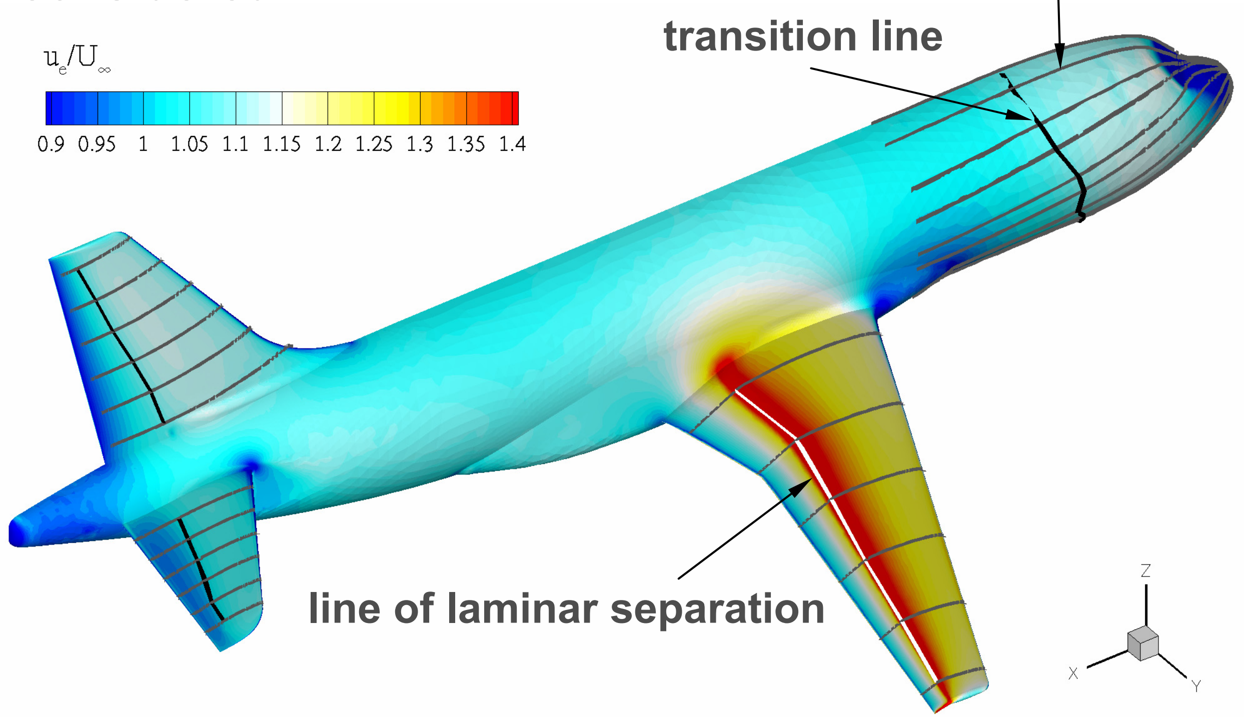


- **MPC75** (N. Krimmelbein, ISM, TU-BS):
  - **parallel computation: 8 processes**
  - **Parallelization of TAU transition module**
    - **Determination of wall normals**
    - **BL velocity profiles**
    - **Calculation of inviscid streamlines**
    - **Execution of external codes**



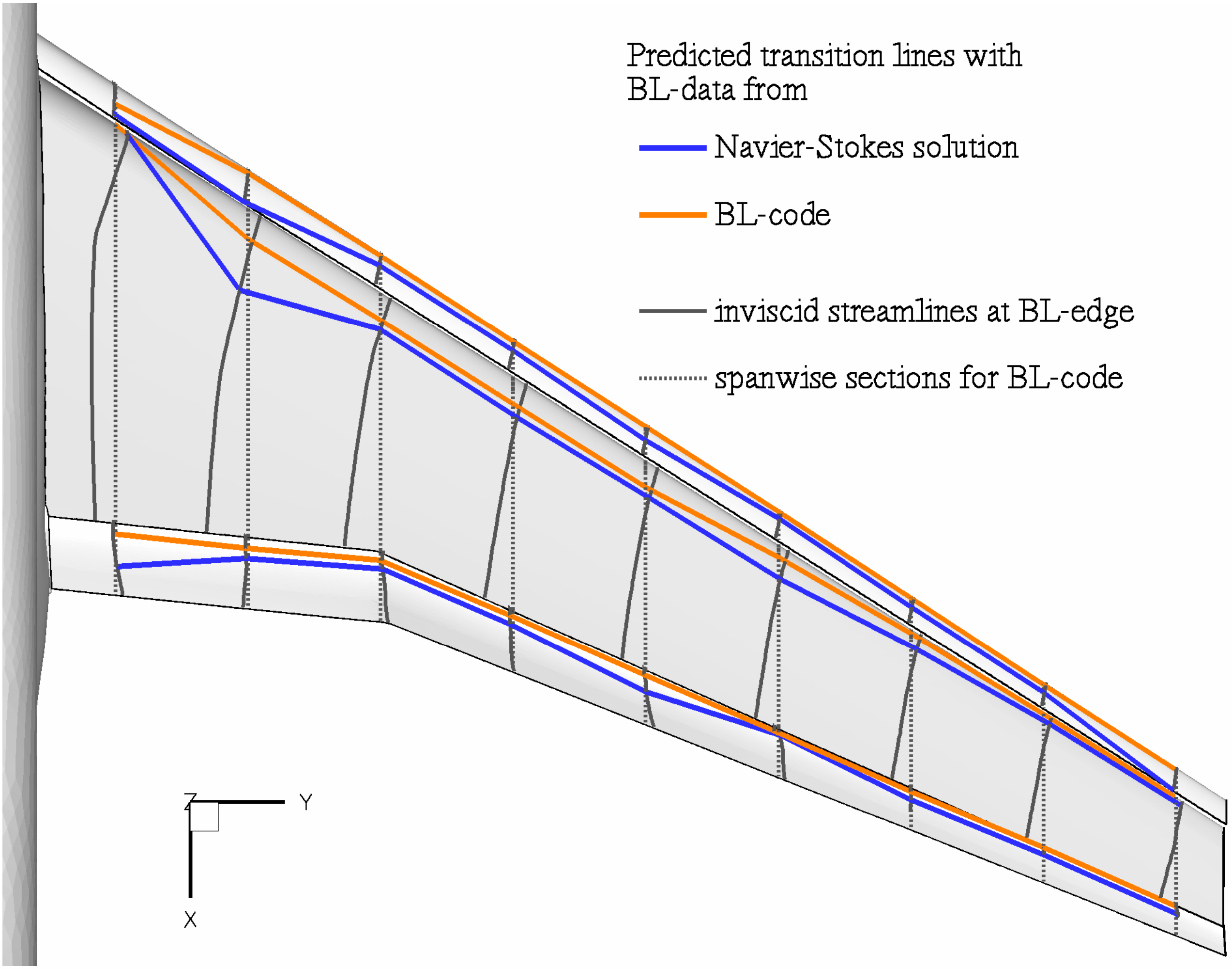
  - **Parallel computation: capability of using ‘decomposed TAU solutions’**
  - **Proof of technical feasibility**

- **MPC75** (N. Krimmelbein, ISM, TU-BS):
  - **grid: • 12 mio. points**
    • 32 (at HTP 48) cells in prismatic layer
  - **$M = 0.2$, $Re = 2.3x10^6$, $\alpha = -4°$, $i_h = 4°$**
  - **$N_{TS} = 7.5 \Leftrightarrow Tu_\infty = 0.13\%$**
  - **on all wings: only TS considered**
  - **at fuselage: $c_{p,min}$**
  - **SAE**

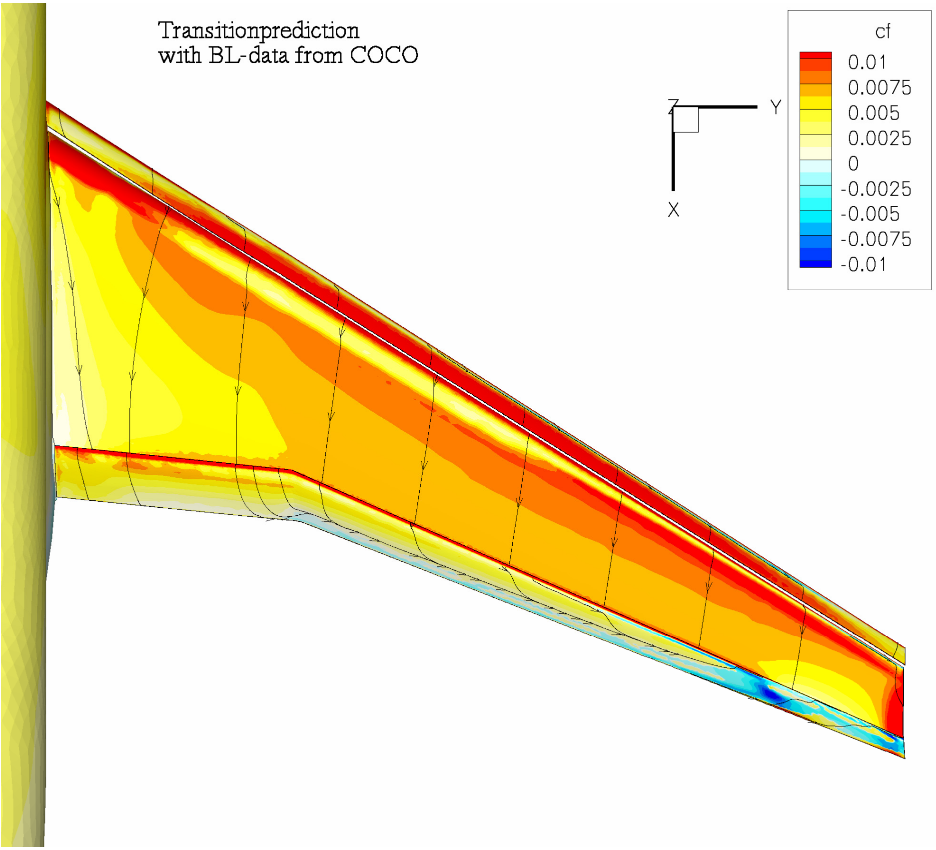


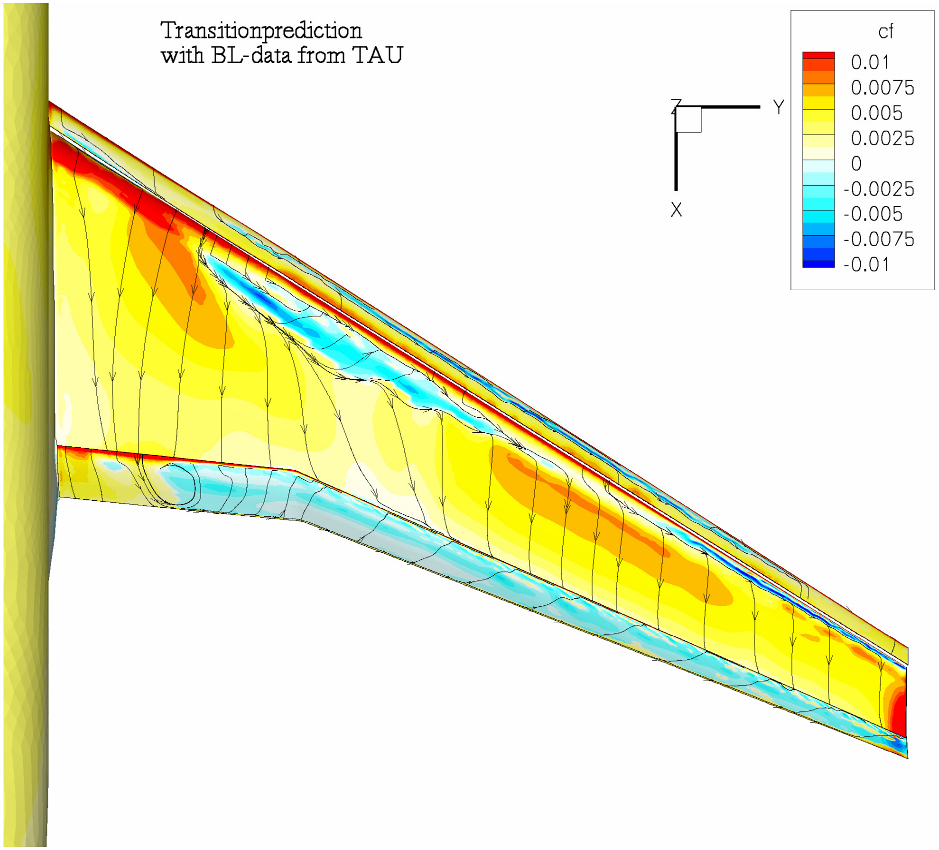
KH3Y Wing-Body (DLR F11): (N. Krimmelbein, ISM, TU-BS):

EL II TC214: Re_∞ = 1.35 mio., M_∞ = 0.174, α = 12.0°



KH3Y Wing-Body (DLR F11): (N. Krimmelbein, ISM, TU-BS):

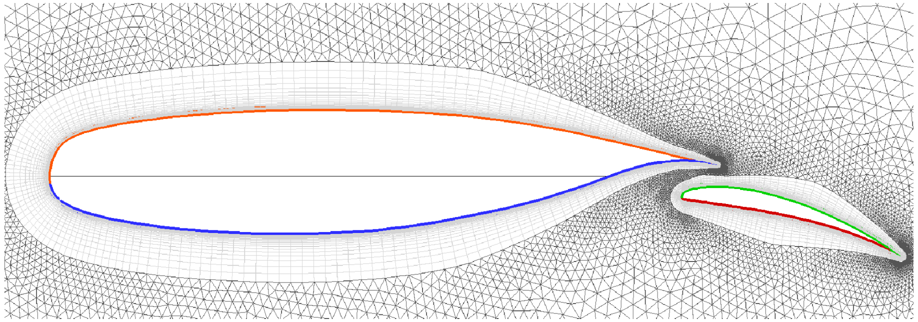




- **Proof of technical feasibility**
- **no validation**

Example input file

- **2d NLR7301 2-element airfoil:**



```
                   Markers: 1
                      Type: farfield
                      Name: farfield
      Angle alpha (degree): 6.0
               Mach number: 0.185
block end
```

Boundary markers

```
---------------------------
                   Markers: 2
                      Type: viscous wall
                   Subtype: transition
                      Name: wing_lower
block end
---------------------------
                   Markers: 3
                      Type: viscous wall
                   Subtype: transition
                      Name: wing_upper
block end
---------------------------
                   Markers: 4
                      Type: viscous wall
                   Subtype: transition
                      Name: flap_upper
block end
---------------------------
                   Markers: 5
                      Type: viscous wall
                   Subtype: transition
                      Name: flap_lower
block end
---------------------------
                   Markers: 6
                      Type: viscous wall
                   Subtype: turbulent
                      Name: wing_te
block end
---------------------------
                   Markers: 7
                      Type: viscous wall
                   Subtype: turbulent
                      Name: flap_te
block end
---------------------------
                   Markers: 8
                      Type: symmetry plane
                      Name: Side1
block end
---------------------------
                   Markers: 9
                      Type: symmetry plane
                      Name: Side2
block end
```

Transition line input:

- initial transition locations
- near trailing edges
- set by TAU prepro-cessor

```
Boundary part namelist: wing_upper
         Number of polyline points: 1
                    Laminar height: 0.02

TransitionCoordinates
0.871328  0.0  0.0313486
transition end
---------------------------
Boundary part namelist: wing_lower
         Number of polyline points: 1
                    Laminar height: 0.02

TransitionCoordinates
0.943506  0.0  0.0141137
transition end
---------------------------
Boundary part namelist: flap_upper
         Number of polyline points: 1
                    Laminar height: 0.003

TransitionCoordinates
 1.20166 0.0 -0.10363
transition end
---------------------------
Boundary part namelist: flap_lower
         Number of polyline points: 1
                    Laminar height: 0.003

TransitionCoordinates
1.20138  0.0 -0.104784
transition end
```

Transition module input:

- **General parameters**

```
                 Transition prediction (0/1): 1
      Transition prediction description file: (thisfile)
                     Info output level (0-5): 5
                     File output level (0/1): 1 (default)
         Write streamline data to file (0/1): 1 (default)
 Write boundary layer profiles to file (0/1): 1
----------------------------------------------
```

Transition module input:

- **Defaults block**

```
Defaults TransitionBlock

                    Pre-prediction mode: 2
                                   #Mode 1: transition at cp,min + offset
                                   #Mode 2: laminar separation from TAU

  Pre-prediction start iteration nr: 20
    Pre-prediction end iteration nr: 1000
               Pre-prediction period: 20

      Prediction start iteration nr: 1000
        Prediction end iteration nr: 7500
                   Prediction period: 500
--------------------------------------
      TS transition prediction mode: 10 (default)
      CF transition prediction mode: 0
                                   #Mode  9: Database Methods
                                   #Mode 10: Linear Stability Code LILO

           Boundary layer data mode: 1
                                   #Mode  0: use TAU  BL-data
                                   #Mode  1: use COCO BL-data

               Critical N-factor TS: 9.0
               Critical N-factor CF: 4.0

                  Relaxation factor: 0.8
       Maximum delta for transition: 0.4

TransitionBlock end
```

Transition module input:

- **Individual blocks**

```
TransitionBlock
      Boundary part list: wing_upper
   Transition block name: wing_upper
         Streamline type: 2
                     #Type 1: inviscid streamline
                     #Type 2: line-in-flight cut
                     #Type 3: attachment line
TransitionBlock end
--------------------------------------
TransitionBlock
      Boundary part list: wing_lower
   Transition block name: wing_lower
         Streamline type: 2
TransitionBlock end
--------------------------------------
TransitionBlock
      Boundary part list: flap_upper
   Transition block name: flap_upper
         Streamline type: 2
TransitionBlock end
--------------------------------------
 TransitionBlock
      Boundary part list: flap_lower
   Transition block name: flap_lower
         Streamline type: 2
TransitionBlock end
--------------------------------------
```

Transition module input:

- **External tools**

```
                     Coco input parameter:
                     --------------------
          Coco executable: ./tm_BLcode_coco
Keep Coco log files (0/1): 1 (default)
Keep Coco run files (0/1): 1

                     Lilo input parameter:
                     --------------------
          Lilo executable: ./tm_STABcode_lilo
Keep Lilo log files (0/1): 1 (default)
Keep Lilo run files (0/1): 1


                      Database methods input parameter:
                      --------------------------------
           Dbm executable: ./tm_eN_DatabaseModule
 Keep Dbm run files (0/1): 1
```

- Some remarks:

  - All parameters from the ‘defaults block’ can be individually set in the ‘individual blocks’.

  - Parameters not set in the ‘individual blocks’ get their values from the ‘defaults block’.

  - The ‘general parameters’ are applied to all transition blocks.

  - There are more parameters than those presented here, especially for 3D applications.

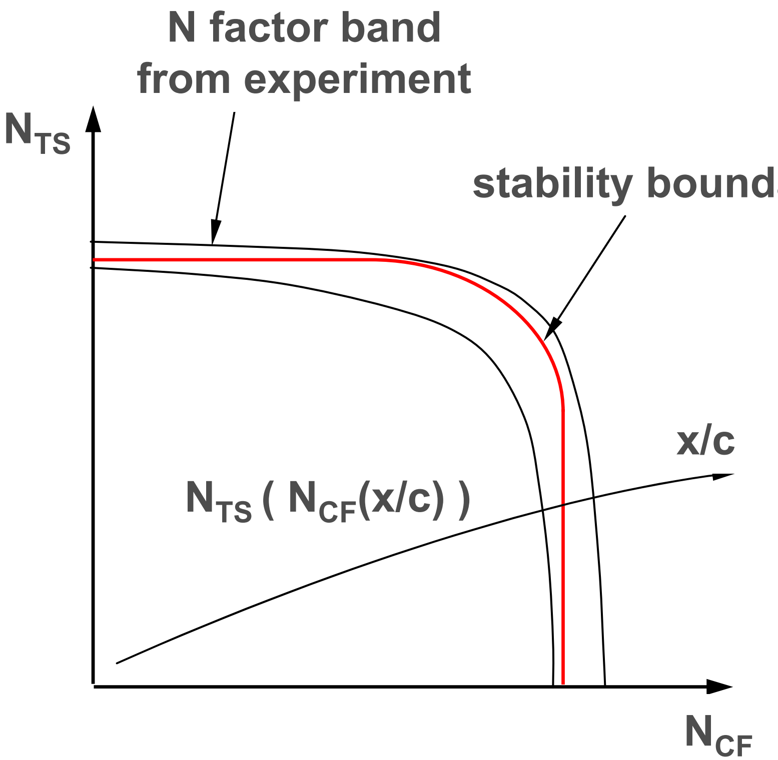
  - 3D example available on request

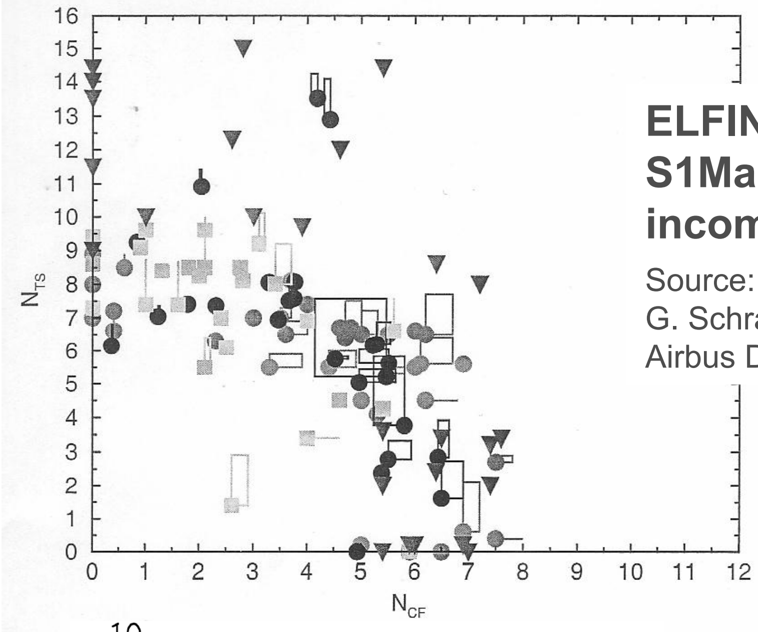
  - Transition prediction is carried out in the TAU solver, not in the TAU preprocessor.

Stability boundary

- **The critical N factors: a problem ?**
  - For free flight applications the critical N factors for the tools available are at hand (from extensive flight experiments): $N_{TS}^{cr} \approx 12$, $N_{CF}^{cr} \approx 9$
  - For wind tunnels: $N_{TS}^{cr} \approx -8.43 - 2.4\,\ell n\left(Tu_{\infty}\right)$ Mack's formula; $N_{CF}^{cr} \approx$?????
    (Tu_{∞}: of the wind tunnel)
  - Problem for WT experimental data:
    - Transition location information often very limited.
    - Rarely c_f-distributions → information on transition and separation
    - Often no detailed information on transition measurement technique in the measurement reports.
    - Critical N factors are often unknown.
    - Mack's formula only for TS and incompressible + official values for Tu_{∞}(WT) often not compatible with measurements (e.g. LSWT, Bremen)
    - Two critical N factors often not sufficient, we have to know the stability boundary in the N_{TS}-N_{CF} diagram → minimum 4 points!
    - Critical N factors for wings and fuselages can be different.
    - The stability method used for the exp. determination of the critical N factor must be identical to the one applied in the stability tool used later in the simulation.

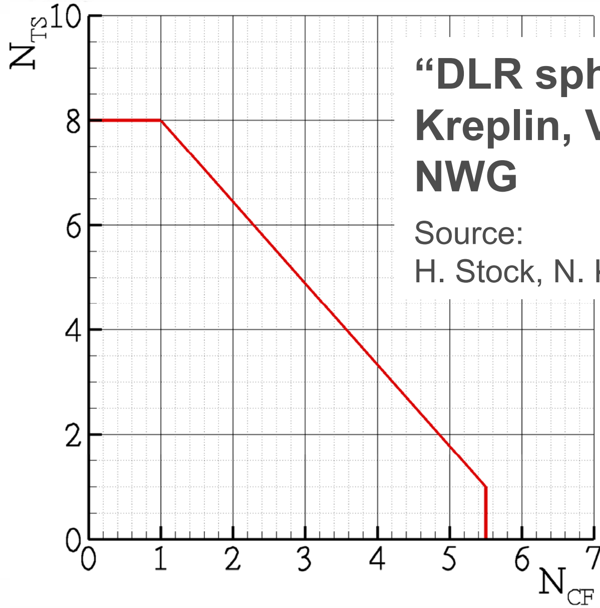
Experimental experience





ELFIN II
S1Ma tests
incompressible

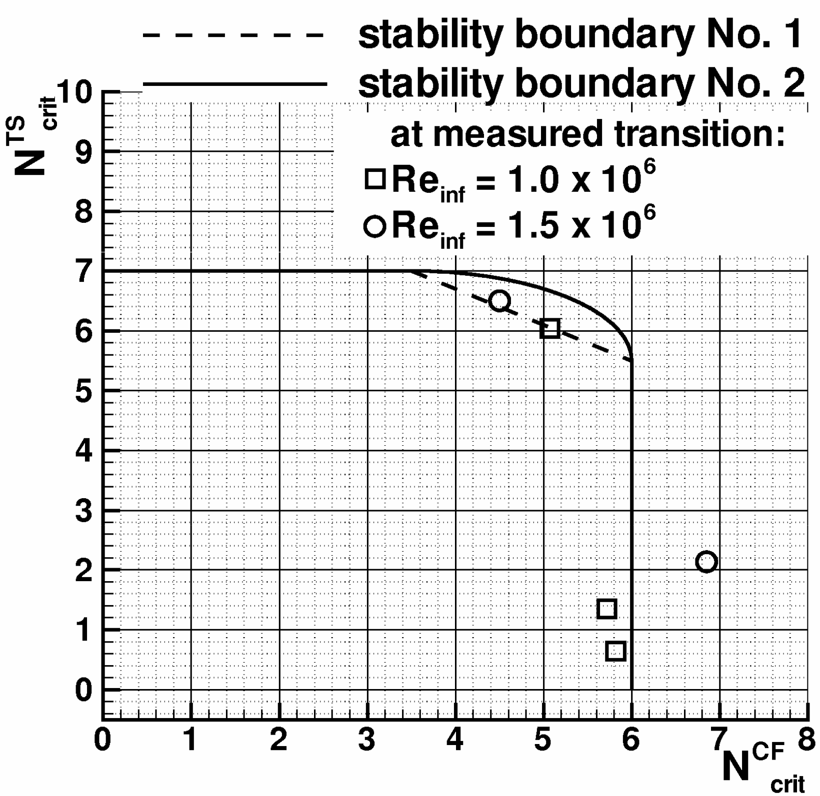
Source:
G. Schrauf
Airbus Deutschland



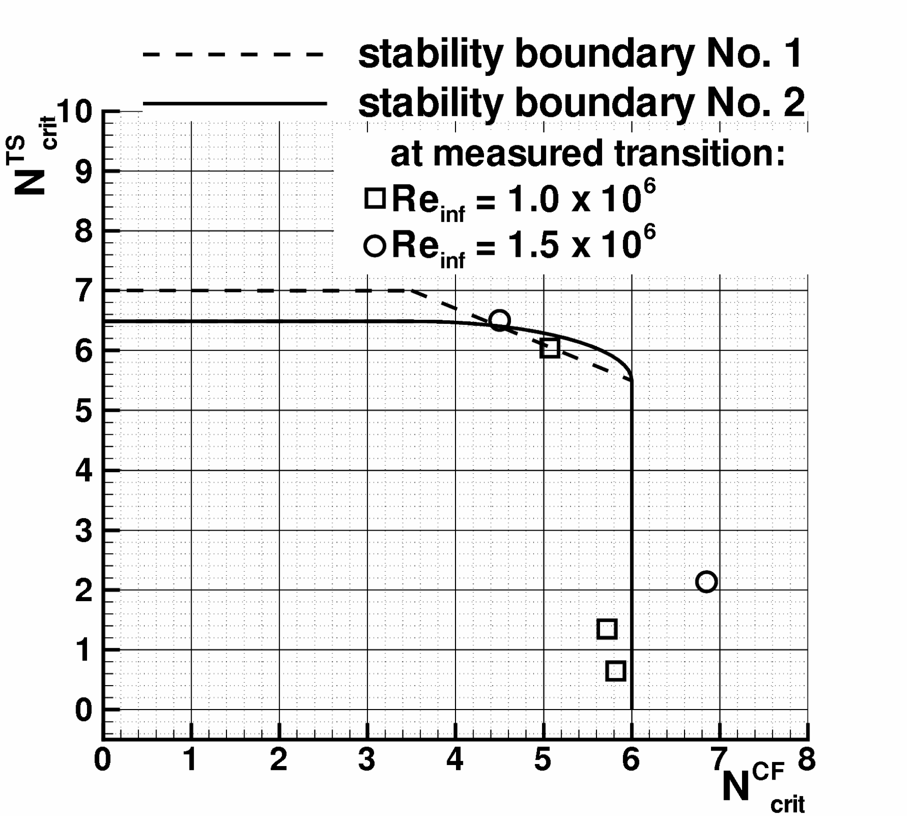
“DLR spheroid”
Kreplin, Vollmers, Meier
NWG

Source:
H. Stock, N. Krimmelbein

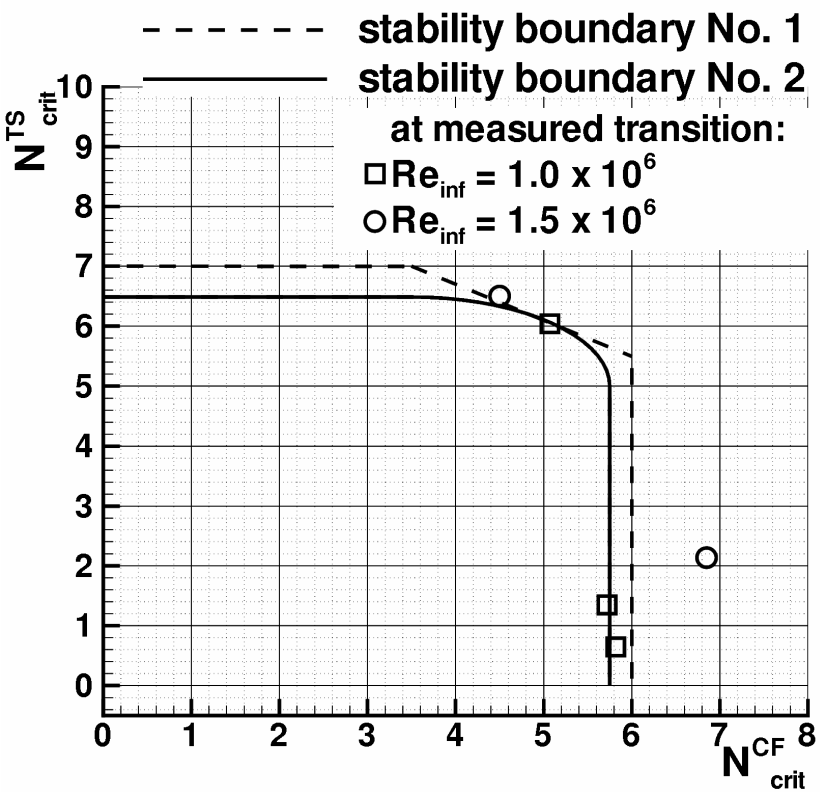
Stability boundary



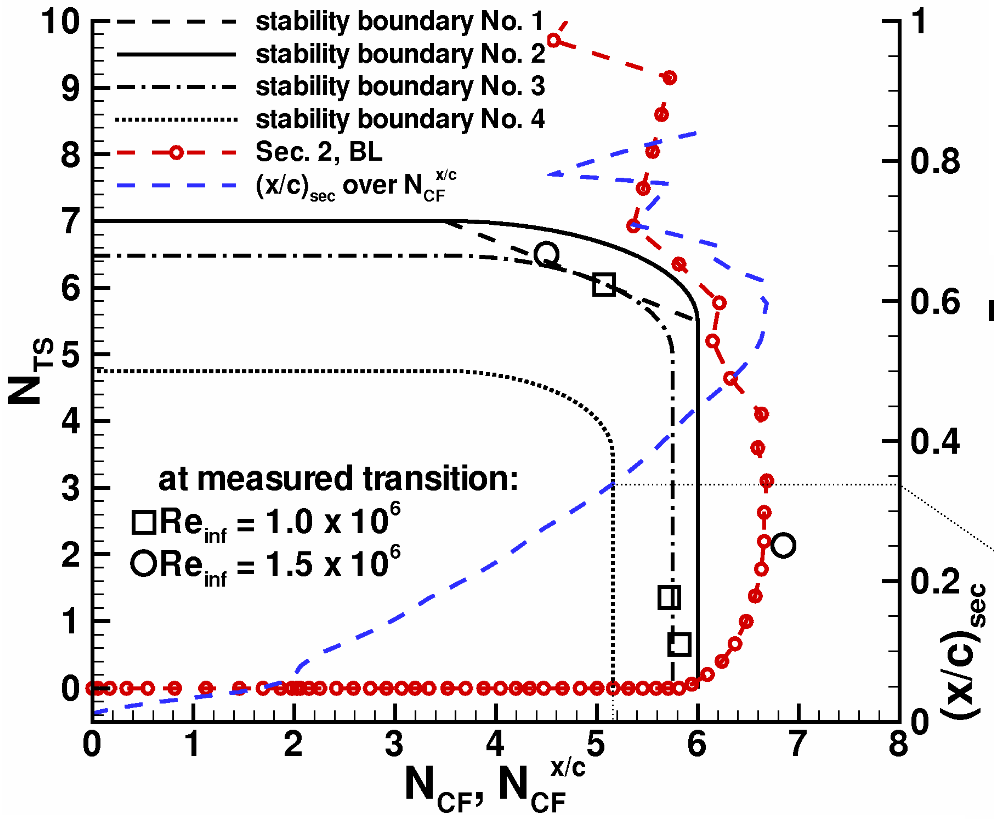
Stability boundary



Stability boundary

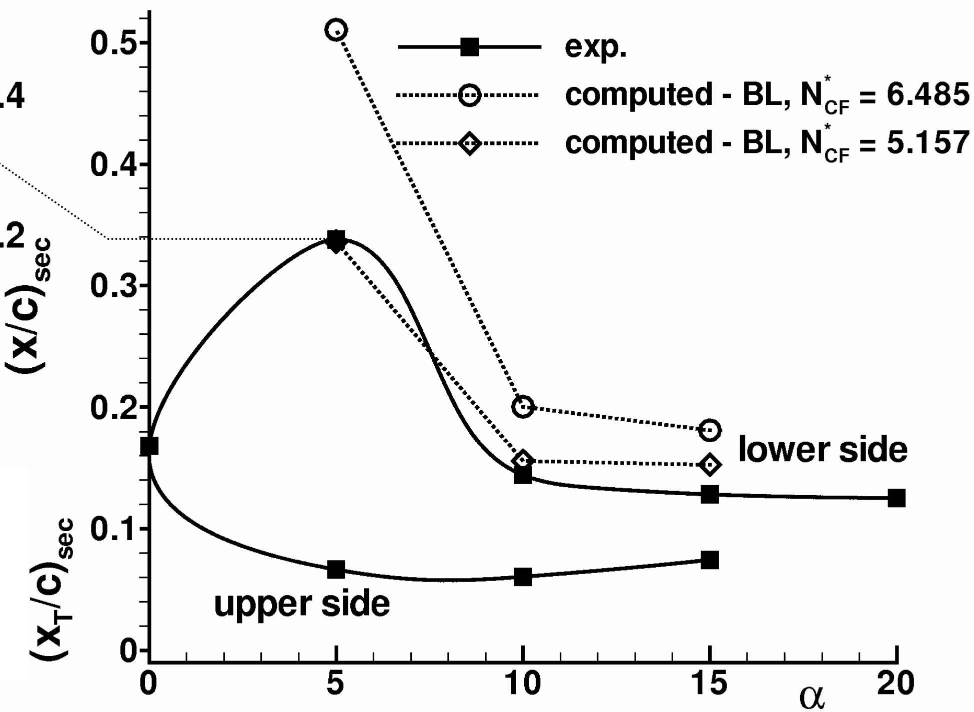


Stability boundary

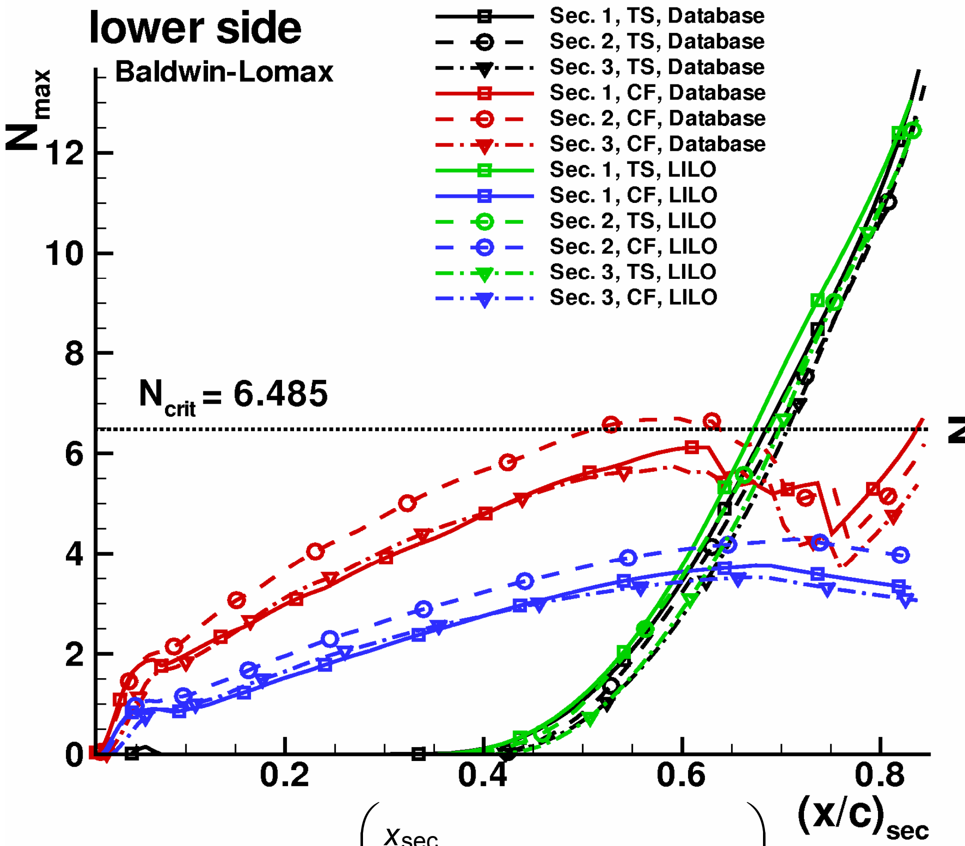


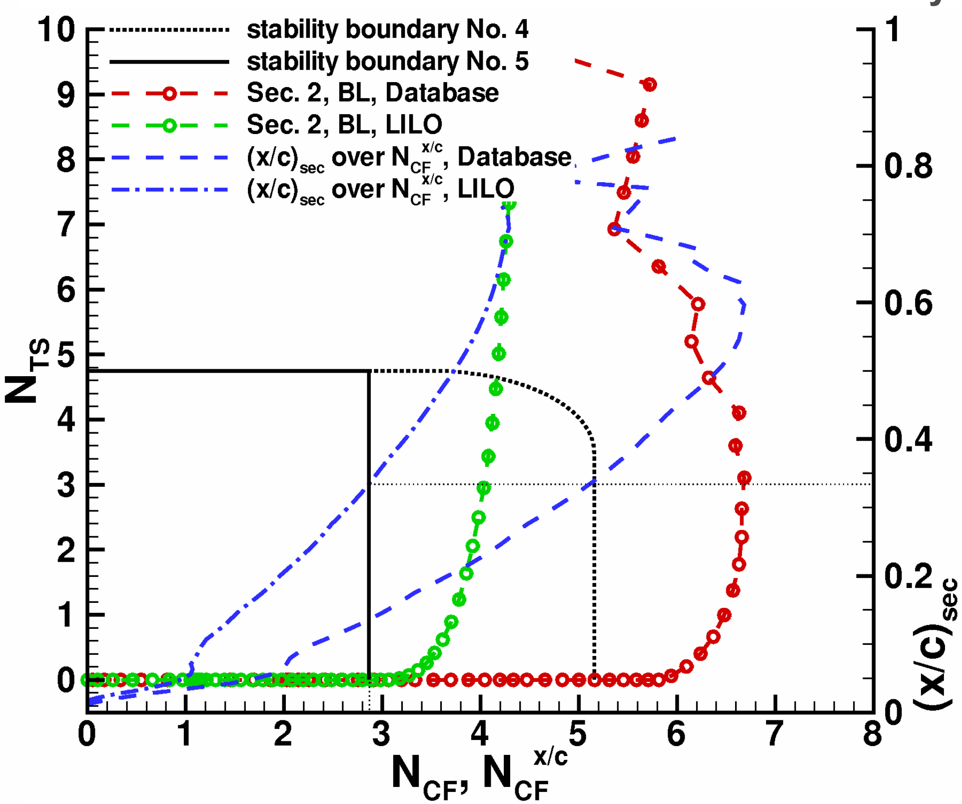
calibration of critical N factor for CF for M6 lower side and α = 5.0° at η = 0.42 → N_{CF}^{cr} = 5.157

mid wing section



Very probably the naphtalene accelerated transition!





$$N_{TS}(x_{sec}) = \max_{f}\left(\int_{x_{sec}^{0}}^{x_{sec}} -\alpha_i(f; x_{sec})\, dx_{sec}\right)$$ **TS in database and LILO**

$$N_{CF}(x_{sec}) = \max_{\Psi}\left(\max_{f}\left(\int_{x_{sec}^{0}}^{x_{sec}} -\alpha_i(f, \Psi; x_{sec})\, dx_{sec}\right)\right)$$

CF in database: travelling

$$N_{CF}(x_{sec}) = \max_{\lambda}\left(\int_{x_{sec}^{0}}^{x_{sec}} -\alpha_i(f=0,\ \lambda; x_{sec})\, dx_{sec}\right)$$

CF in LILO: stationary

Calibration of the N factors

- For every wind tunnel
- For every stability method
- Desirable: setup of a N factor database of wind tunnels
- Minimum requirements:
  - Pressure distributions for each wing element in 3 wind sections (inboard, midboard, outboard; if kink, one more: left and right of the kink), resolution fine enough
  - Directly aside: transition location detection on upper and lower sides (incl. detailed information w.r.t. measurement technique, its application in the test and special occurrences)
  - Several angles of attack and Re numbers
- Analysis of c_p-distributions with BL code and transition tool
  - Determination of the N factors, which belong to the measured transition locations

Conclusion and Outlook

- The transition tools work well, fast and reliable.
- Complex cases (e.g. transport aircraft) can be handled; fighter configurations too, but:

  Are the stability methods compatible with the transition mechanisms occurring on fighter aircraft?
- In the next future:
  - Much, much more validation
    - transonic cases
    - 3d wings, e.g. F4, F6 a.s.o.
    - complex high lift configurations, e.g. from EL I & II
  - Setup of Best Practice guidelines

- **Current limitations:**
  - **"physically reliable" only for steady flows**
  - **extremely many points needed for CF, when BL parameter from RANS grid (indispensable for lam. separation and for fuselages because of conical BL code)**
    - **streamline oriented BL code with transverse pressure gradient COCO-3d shall replace COCO (end 2007)**
    - **Application of criteria for transition in laminar separation bubbles (Are they accurate enough?)**
    - **Solves the TAU adaption this problem ? $\Rightarrow$ δ-adaption !!!**
      δ is available anyway, 70 wall normal points in prismatic layer "arbitrarily" distributed, adapt the outer edge of the prismatic layer using the values of δ $\Rightarrow$ 46% less points in prismatic layer

Outlook

- Validation, validation, validation
- Flight at the borders of the flight envelope
  - Unsteady phenomena
  - Interaction transition – separation
  - Exploit full potential of highly advanced turbulence models

→ Provison of a transition prediction approach for unsteady flows
  - Widely automated
  - a.) based on d e^N method
  - b.) based on differential equations (CFX & Warren/Hassan)

- Best Practice Guidelines