Application of the Automatic Transition Prediction Functionality of the DLR TAU Code to 3D Aircraft Configurations

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Outline

- Introduction
- Transition Prediction Coupling Structure
- Technical Feasibility
- First Validation Results
- Conclusion & Outlook

Introduction

Requirements from Aircraft Industry and Research:

- RANS based CFD tool with transition prediction
- Automatic: no intervention of the user
- Autonomous: as little additional information as possible
- Reduction of modeling based uncertainties
  - Accuracy of results from fully turbulent flow or flow with prescribed transition often not satisfactory
  - Exploitation of the full potential of advanced turbulence models
- Improved simulation of the interaction between transition locations and separation

- **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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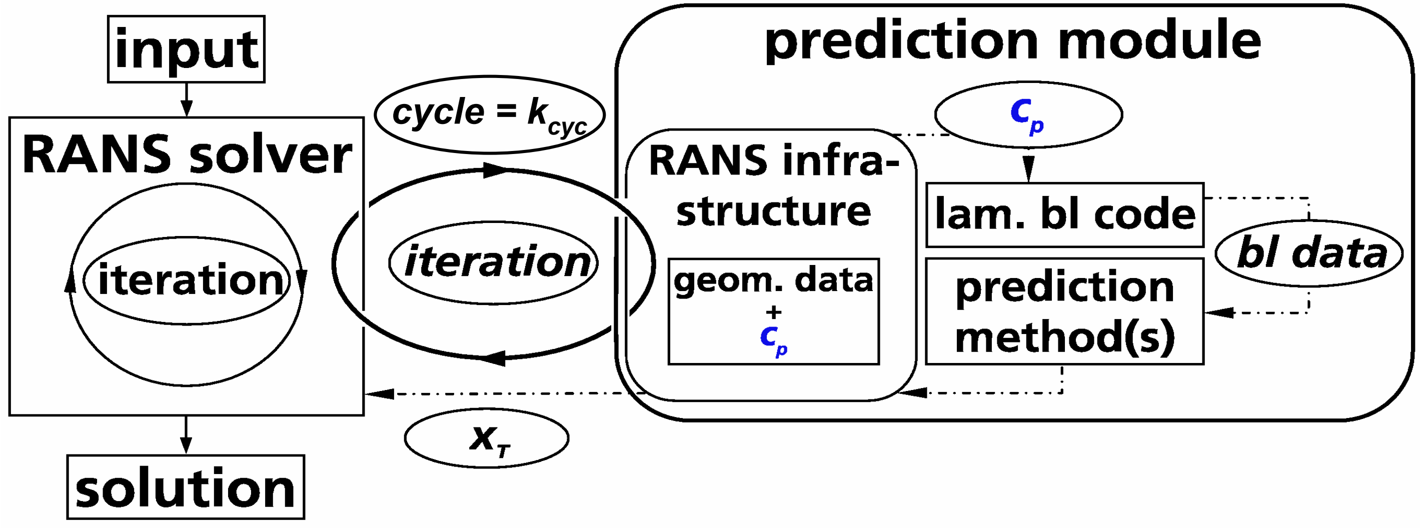
Different coupling approaches:

- 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

Transition Prediction Coupling Structure

external BL approach



Transition Prediction Coupling Structure

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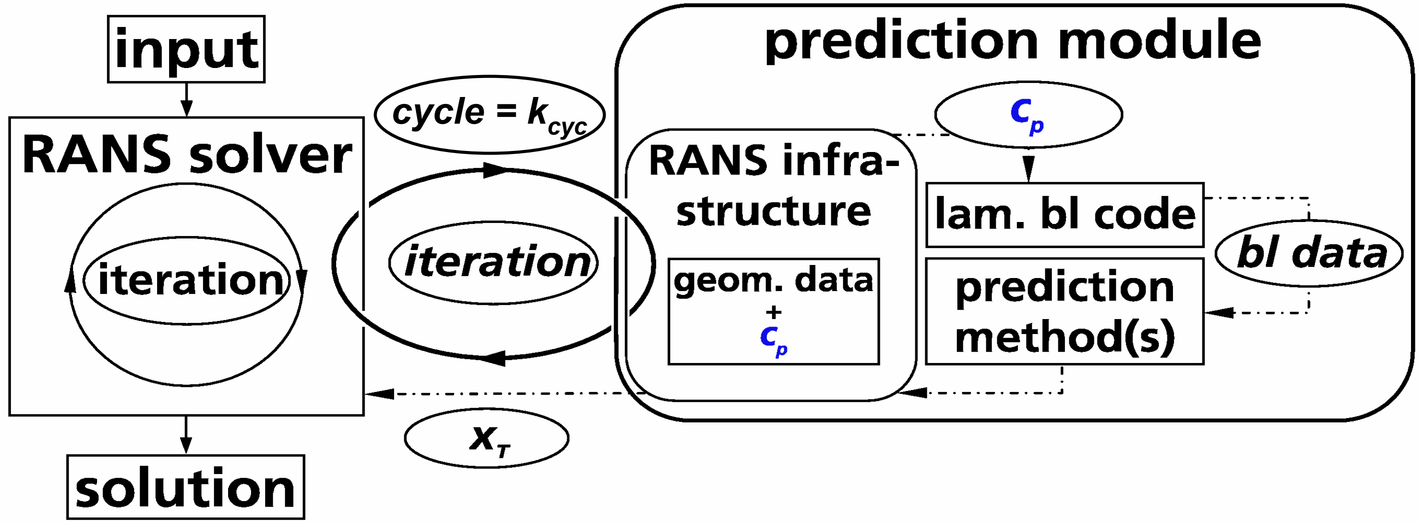
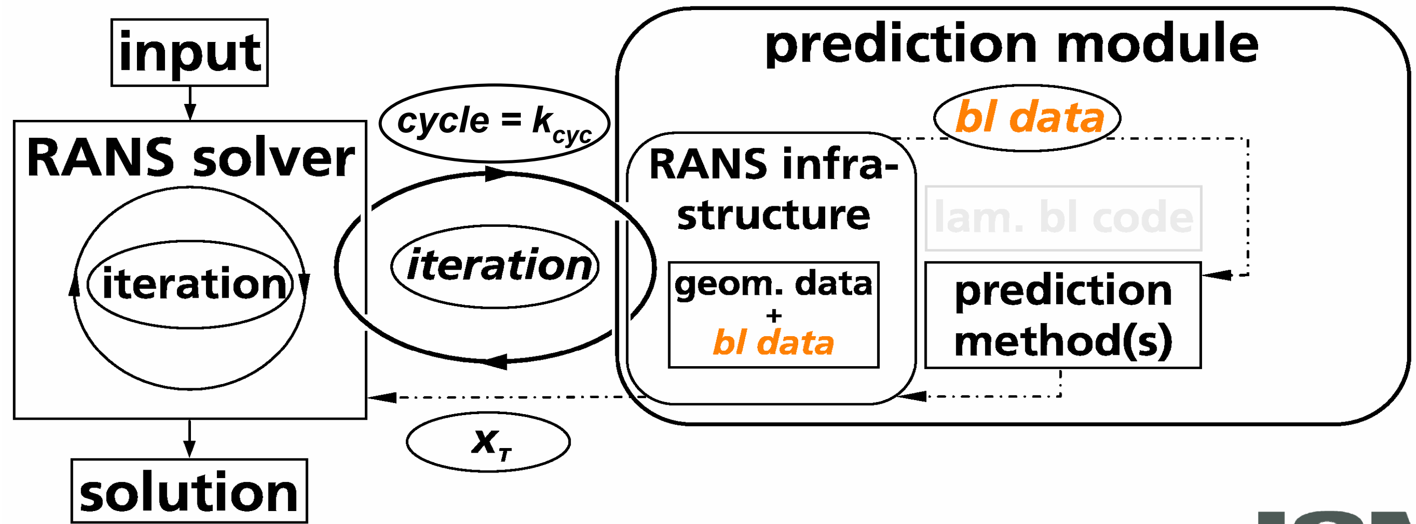


internal BL approach



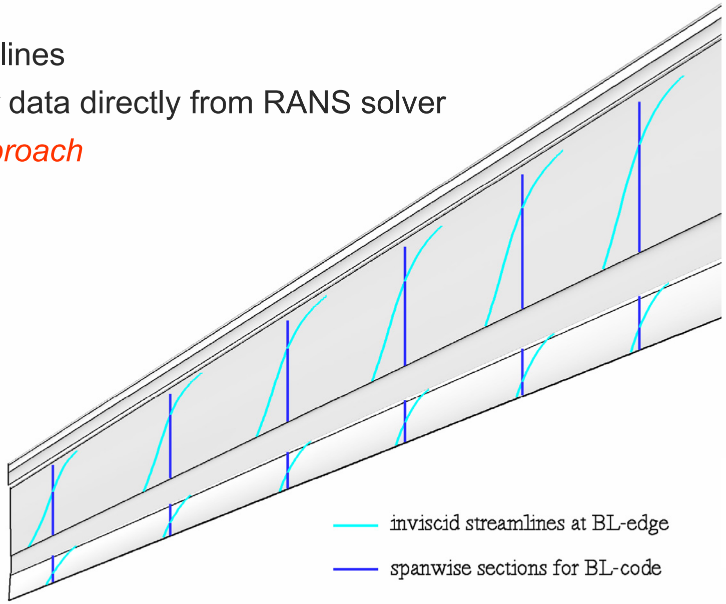
Integration paths:

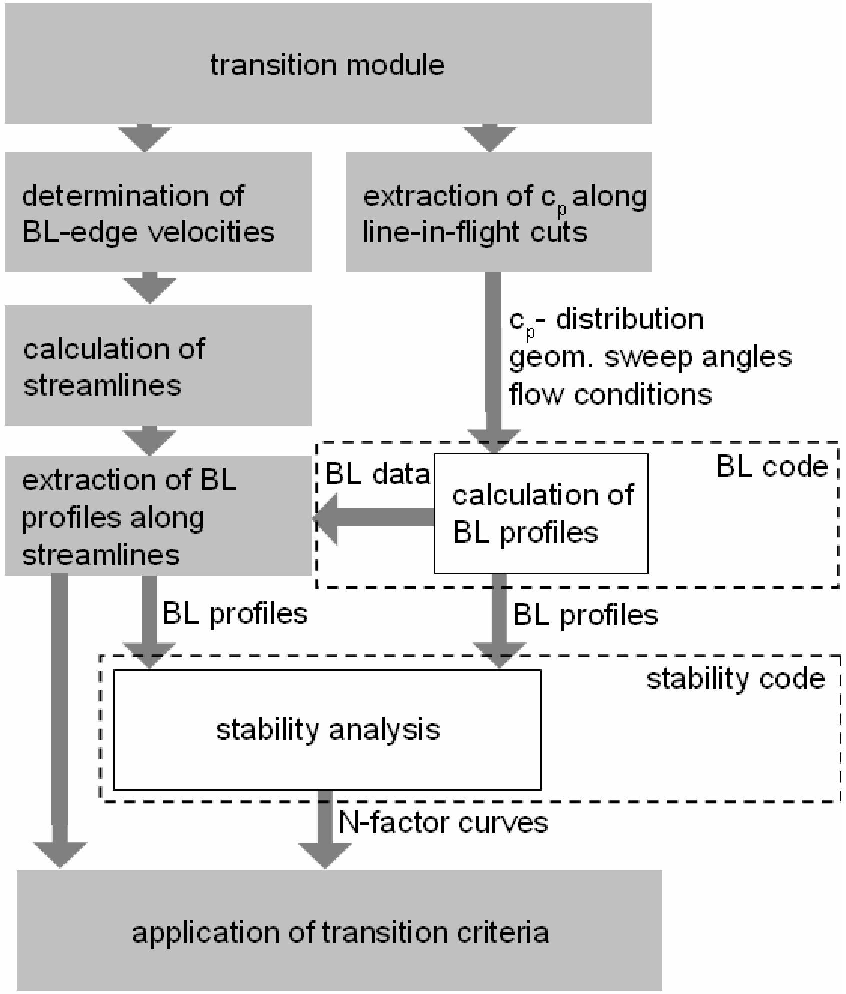
integration path in 3D:

- energy transport of a wave represented by the group velocity
- group velocity direction can be taken as amplification direction
- group velocity trajectory can be approximated by edge streamline

- “line-in-flight” cuts
- pressure distribution along cuts
- boundary layer data from BL code
- group velocity trajectory approximated with stability code
- *external BL approach*

- inviscid streamlines
- boundary layer data directly from RANS solver
- *internal BL approach*





Transition prediction module:

2D

external BL approach

internal BL approach

transition module

- line-in-flight cuts

  or
- inviscid stream lines
- c_p-extraction

  or
- lam. BL data from RANS grid
- lam. BL code *COCO* (G. Schrauf)
  - swept, tapered → conical flow, 2.5d
  - streamline-oriented
  - external code
- local lin. stability code *LILO* (G. Schrauf)
  - e^N method for TS & CF
  - external code

  or
- e^N database methods
  - one for TS & one for CF
  - external codes

  or
- empirical transition criteria

Transition prediction module:

3D

external BL approach

internal BL approach

N factor integration

N factor integration

transition module

- line-in-flight cuts

  or
- inviscid stream lines
- c_p-extraction

  or
- lam. BL data from RANS grid
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  or
- e^N database methods
  - one for TS & one for CF
  - external codes

  or
- empirical transition criteria

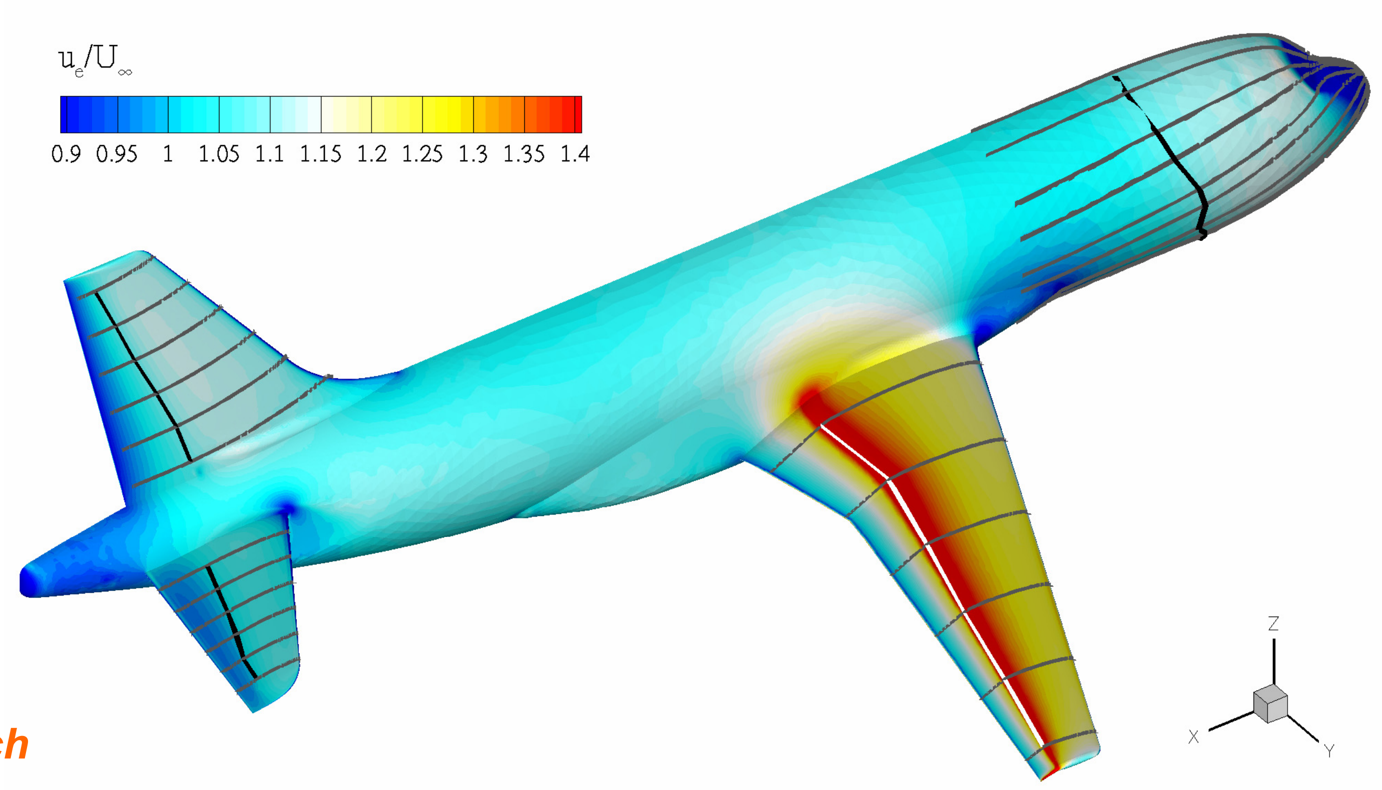
Transition prediction module:

- 2d, 2.5d (infinite swept) + 3d wings, fuselages and nacelles
- Single + multi-element configurations
- Flow topologies
  - attached
  - with laminar separation:
    - laminar separation approximates transition if transition is located downstream of the laminar separation point (*external BL approach*)
    - real stability analysis with stability code inside bubble + many points in prismatic layer (*internal BL approach*)

- Criteria for attachment line transition, by-pass transition & transition inside laminar separation bubbles (*external BL approach*) are available, but until now only ALT criterion was tested for only one test case.

Transition lines on a generic transport aircraft:

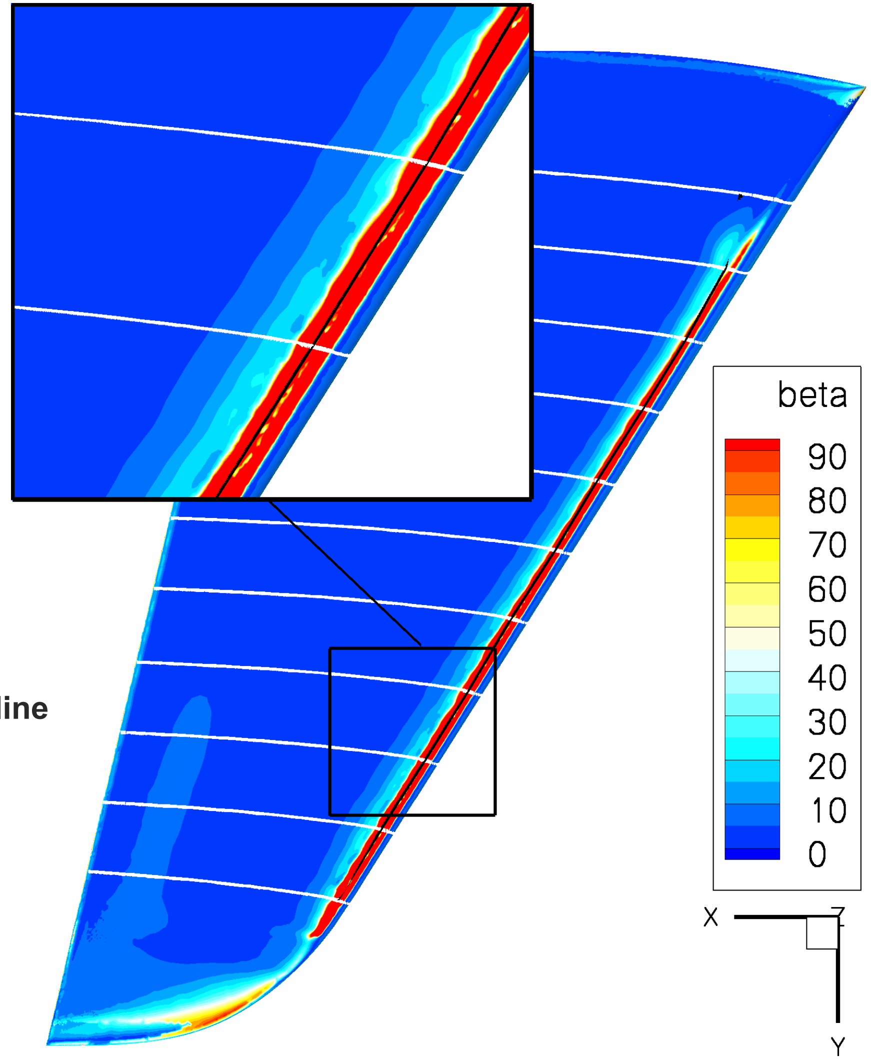
- Ma = 0.2, Re = $2.3x10^6$, α = -4.0°, i_h = 4.0°
- 32 cells normal to wall in structured grid part (HTP: 48), 12 million grid points
- only TS-instabilities considered (N_{crit} = 7.5, Tu = 0.13%)
- except: body → $c_{p, min, local}$, wing upper surface → laminar separation



internal BL approach

3D laminar separation bubble:

- HTP, generic transport aircraft
- 48 cells normal to wall in structured grid part for HTP
- *Ma = 0.2, Re = 2.3x10⁶,*
- $\alpha = 4.0°$, $i_h = 4.0°$
- transition over 3D laminar separation bubble



beta:
angle between skin friction line and inviscid streamline

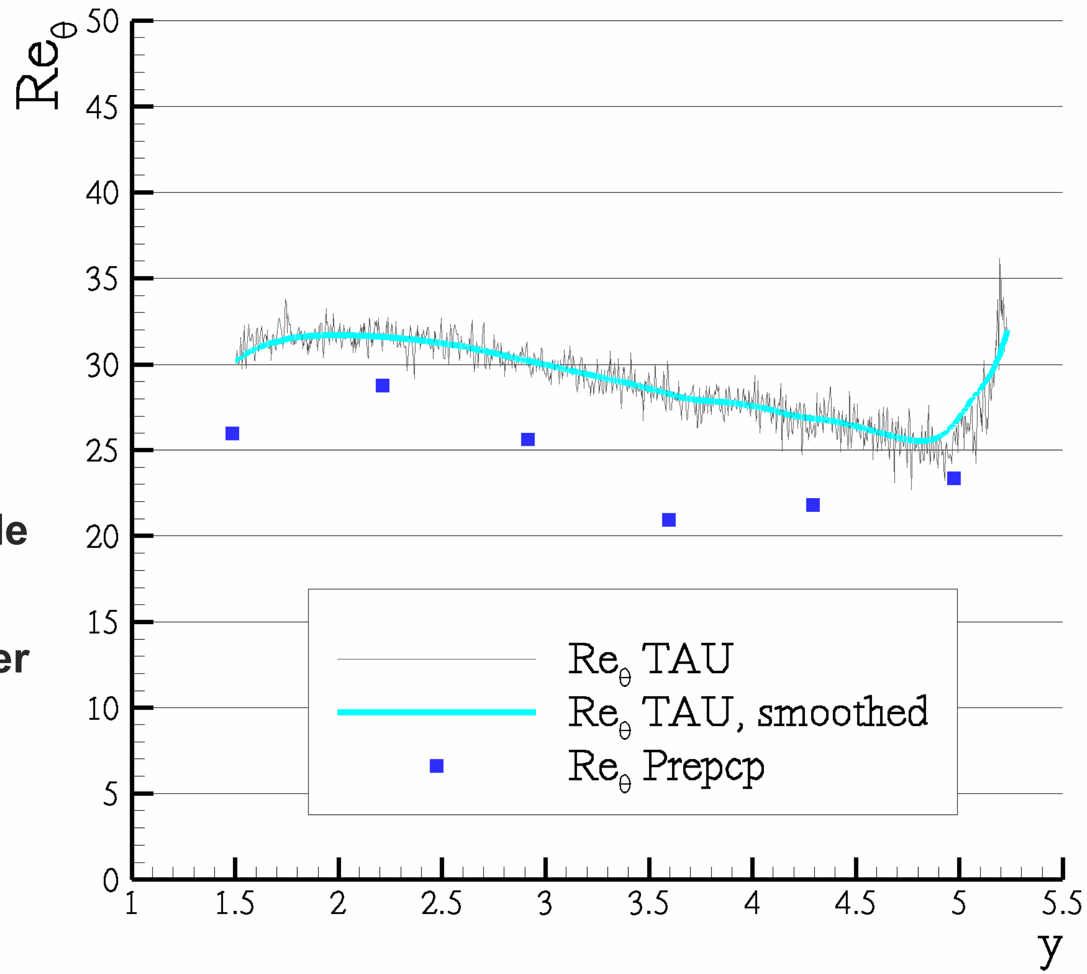
internal BL approach

Attachment line transition:

- HTP, generic transport aircraft
- 15-20 points in attachment line boundary layer
- *M = 0.2, Re = 2.3x10⁶,* → $M = 0.2$, $Re = 2.3 \times 10^6$,
- $\alpha = -4.0°$, $i_h = 4.0°$
- LE sweep angle 32°
- TE sweep angle 13°

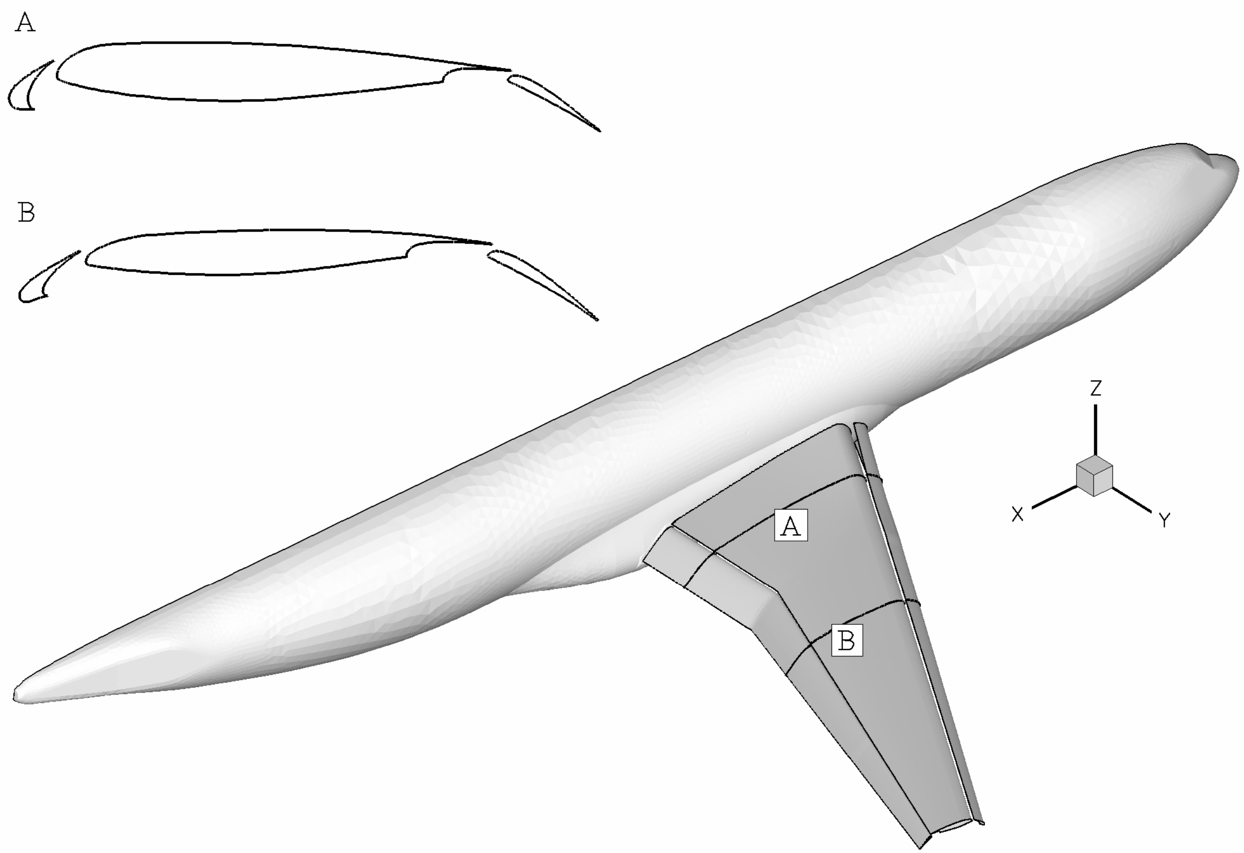
- $Re_\theta > 100$ (Pfenninger/Poll)
- here: θ from TAU velocity profile

- planned: detailed swept cylinder attachment line investigation



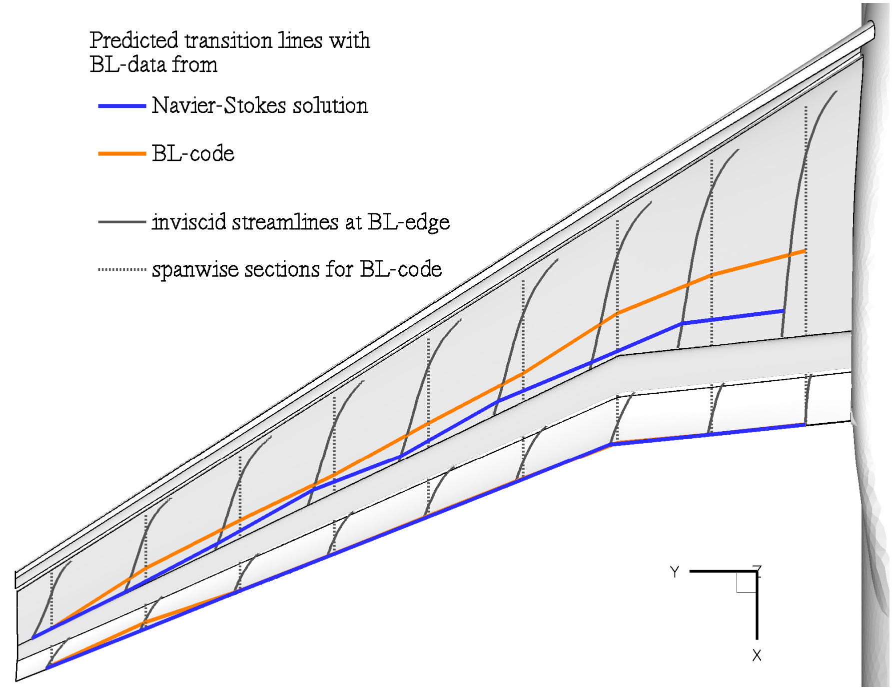
High lift configuration:

- transition prediction for slat, wing & flap
- *Ma = 0.174, Re = 1.34 x 10*^{6}*,* α *= 12°*
- BL resolution:
  20 points normal to wall
- total point number:
  8 million

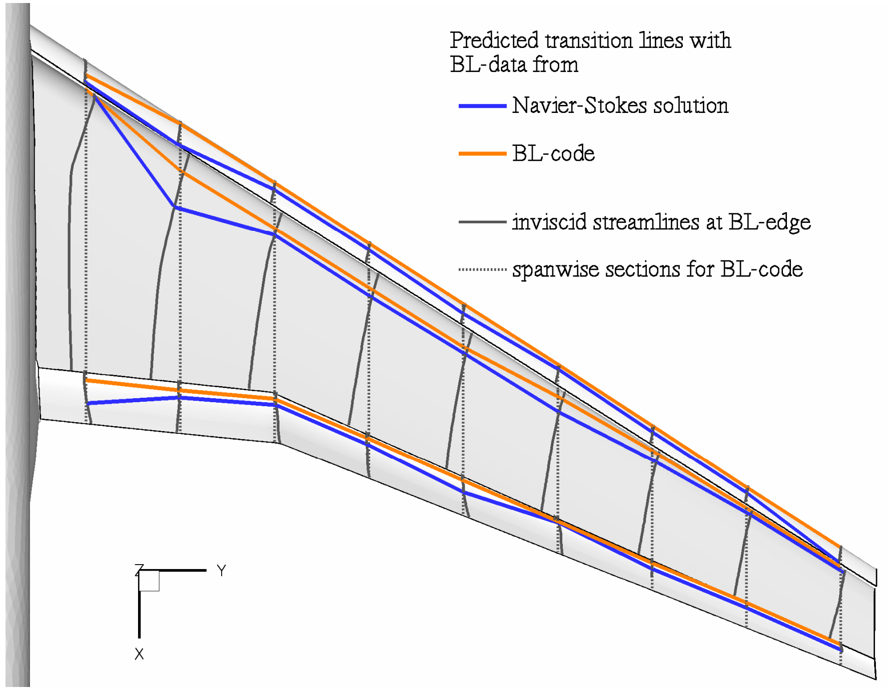


High lift configuration, transition lines:

- only TS waves considered for TAU BL data
- transition at laminar separation for COCO BL data



lower surfaces



upper surfaces

Validation for high lift configuration:

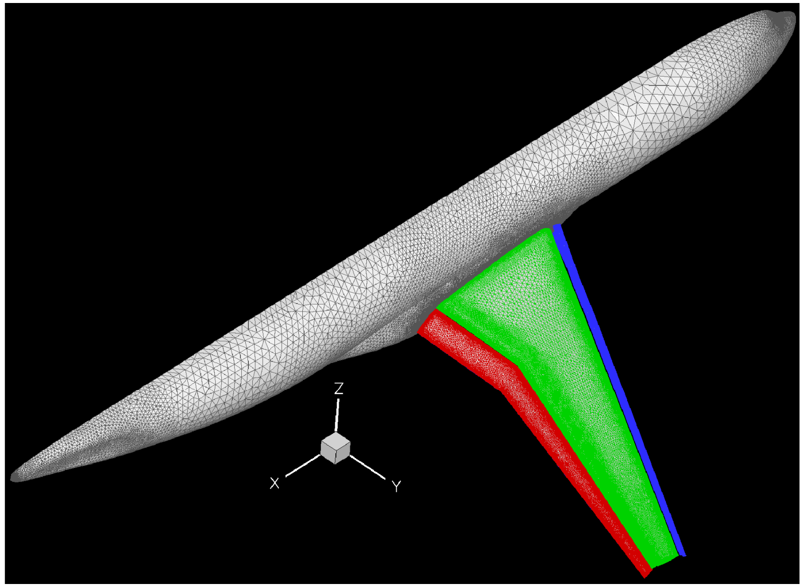
- KH3Y geometry (DLR F11 model)
  - Half-model with fuselage
  - Wing with full span slat and flap high-lift system
  - Landing configuration: $\delta_S = 26.5°$, $\delta_F = 32.0°$

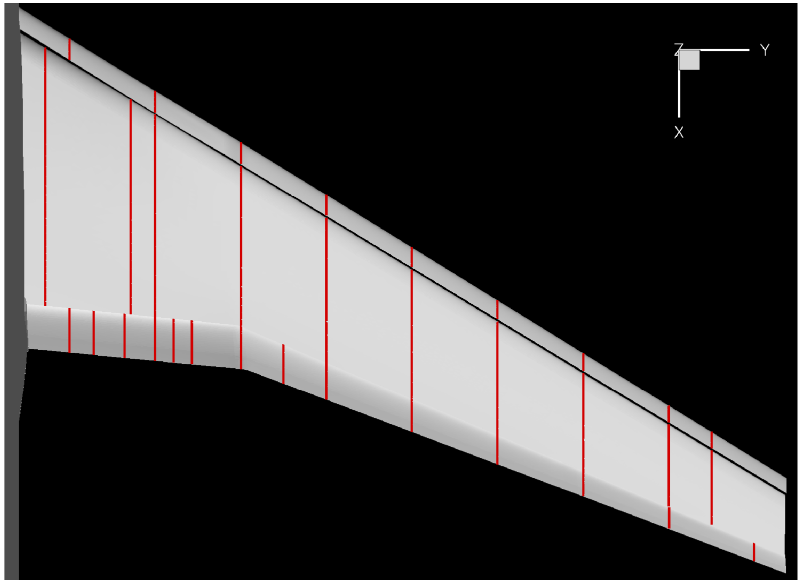
- Measurements
  - European High Lift Programme (EUROLIFT), partly funded by EU
  - Airbus LSWT (Bremen, Germany)
  - $Re_\infty = 1.35$ million, $M_\infty = 0.174$

Computations

- α = 10.0° and 14.0°
- Fully turbulent & predicted transition
- Spalart-Allmaras one-equation TM with Edwards & Chandra mod.
- 8 million points, 2.24 million cells, 660.000 surface cells
- Transition prediction in sections:
  9 on slat
  10 on main wing
  14 on flap
- Wall normal resolution too coarse (only 20 to 30 points in BL)

$\Rightarrow$ ***external BL approach:***
  - line-in-flight cuts
  - c_p-extraction
  - laminar BL code
- 'Point transition'





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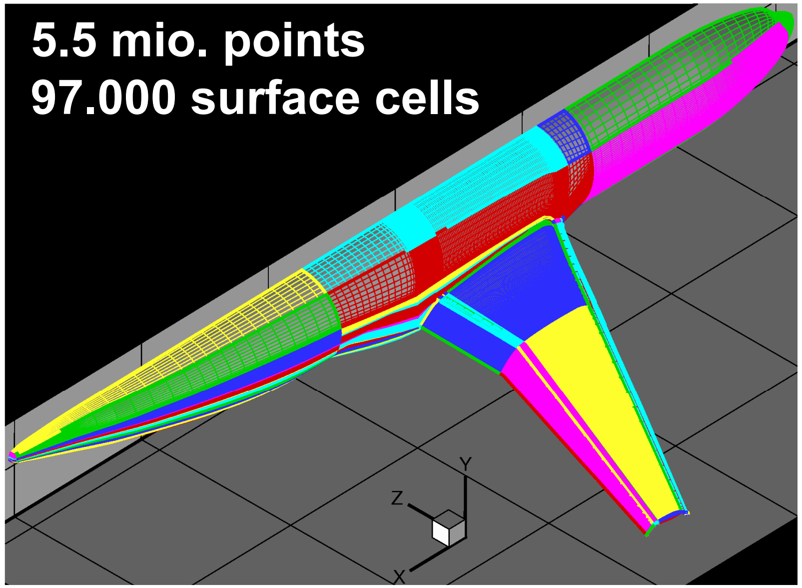
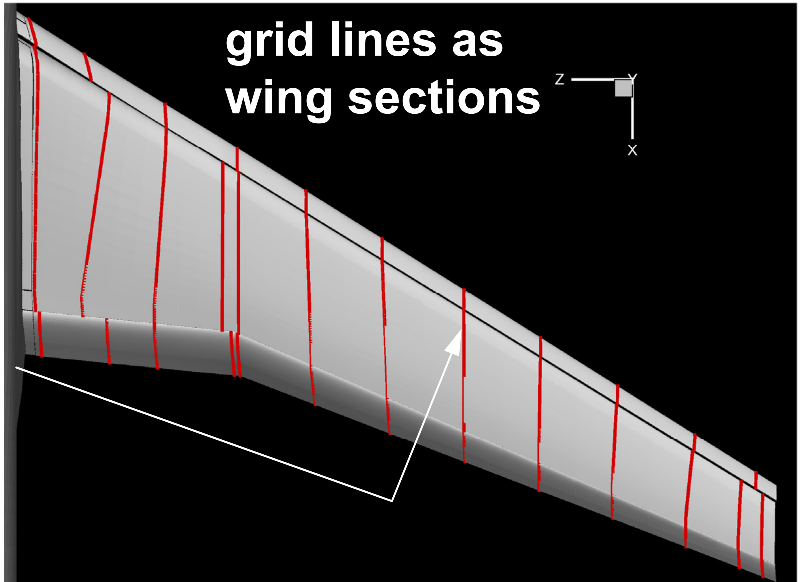
- **Computations**
  - **1.5 years ago: the same test case was computed**
  - **block-structured RANS solver with different BL code and e^N database methods**
  - **much coarser resolution of the surface**
  - **grid lines approximate the wing sections**
  - **Calibration of critical N factors: α = 10°, hot film on main wing upper side at 68% span → $(x^T/c)^{main} = 0.08$**

    $\Rightarrow N_{TS} = 4.9$

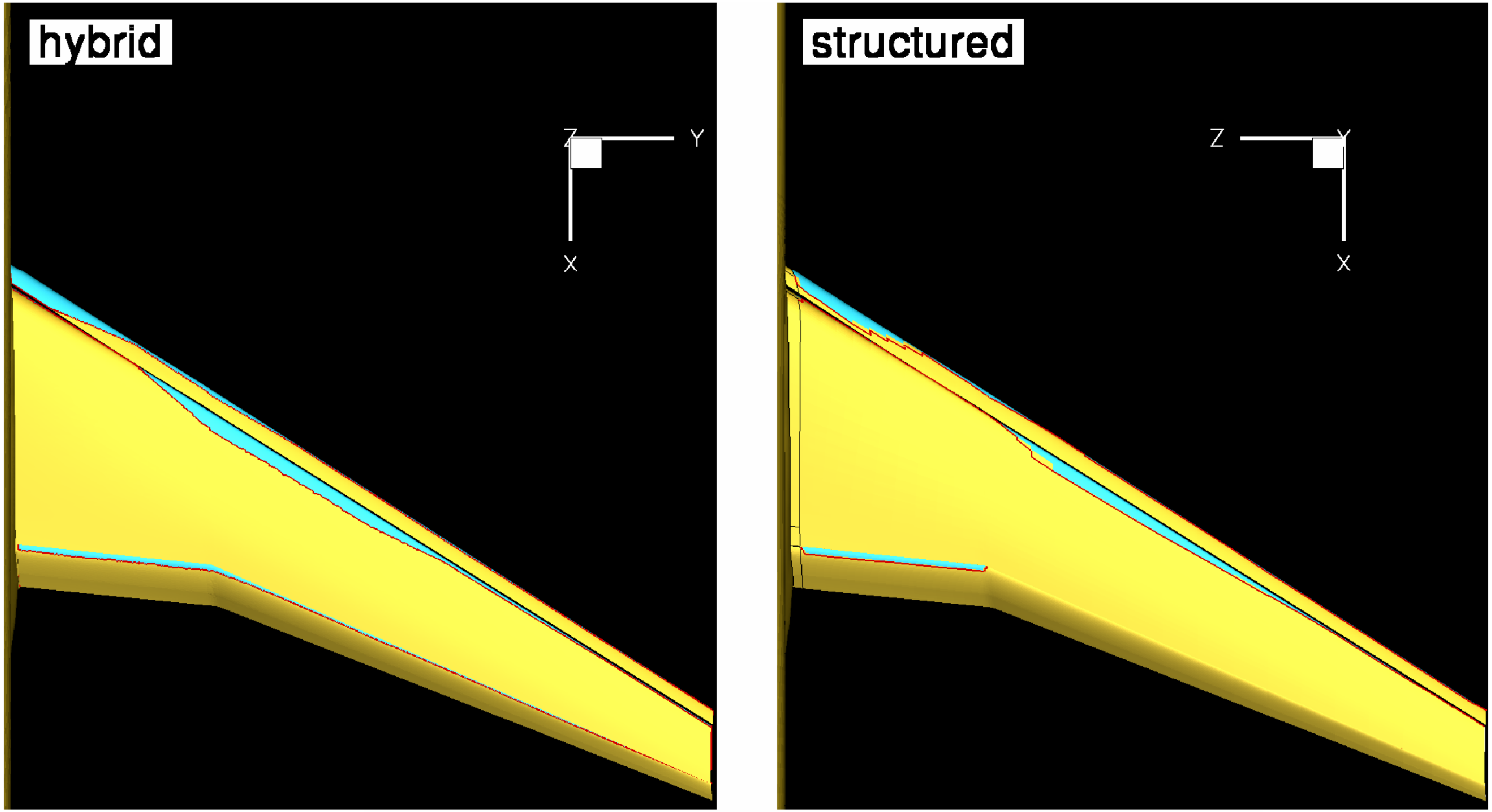
    No indications for CF $\Rightarrow N_{CF} = N_{TS}$





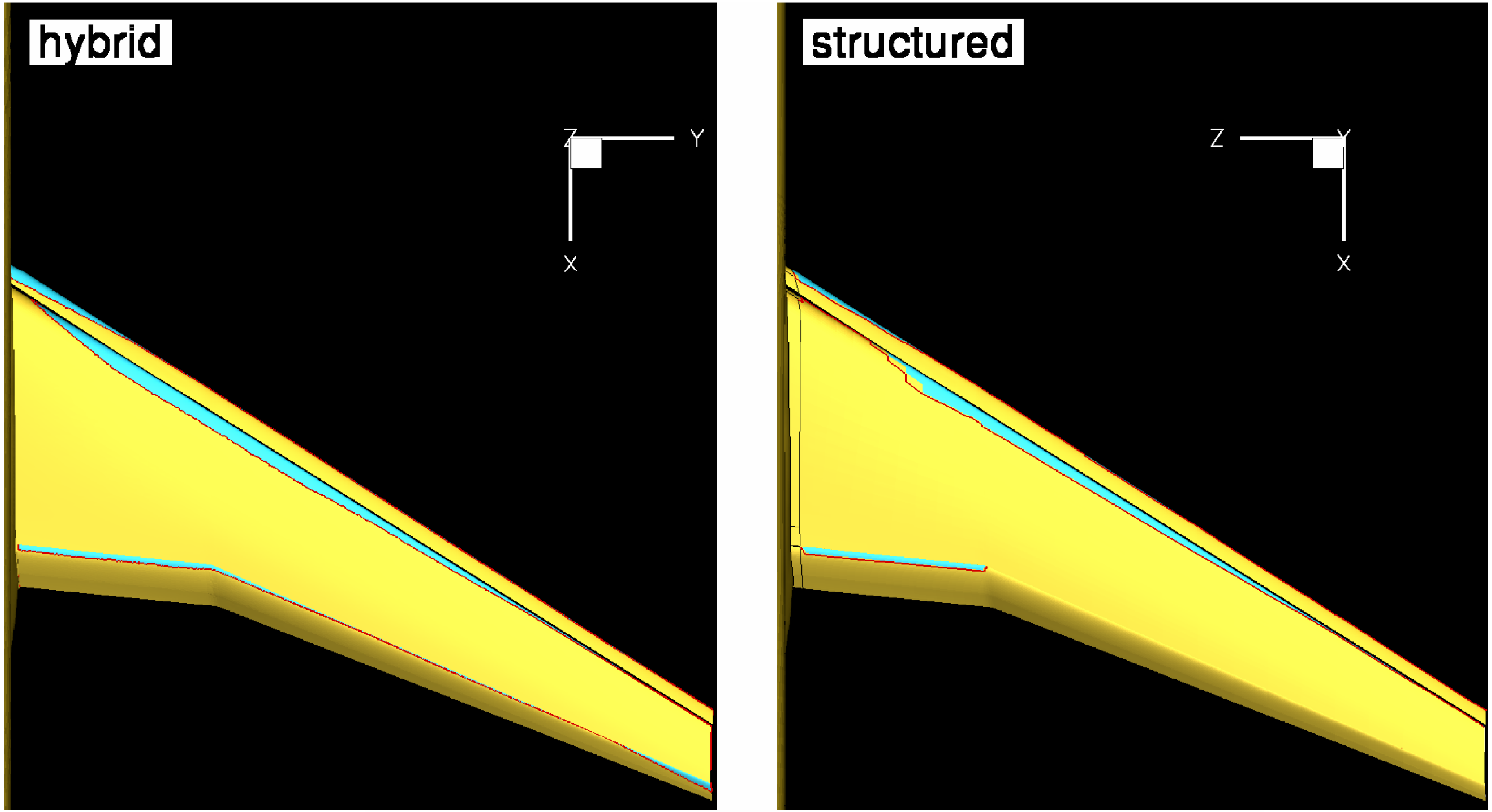
Results

- α = 10.0°, upper side: laminar surface regions



Results

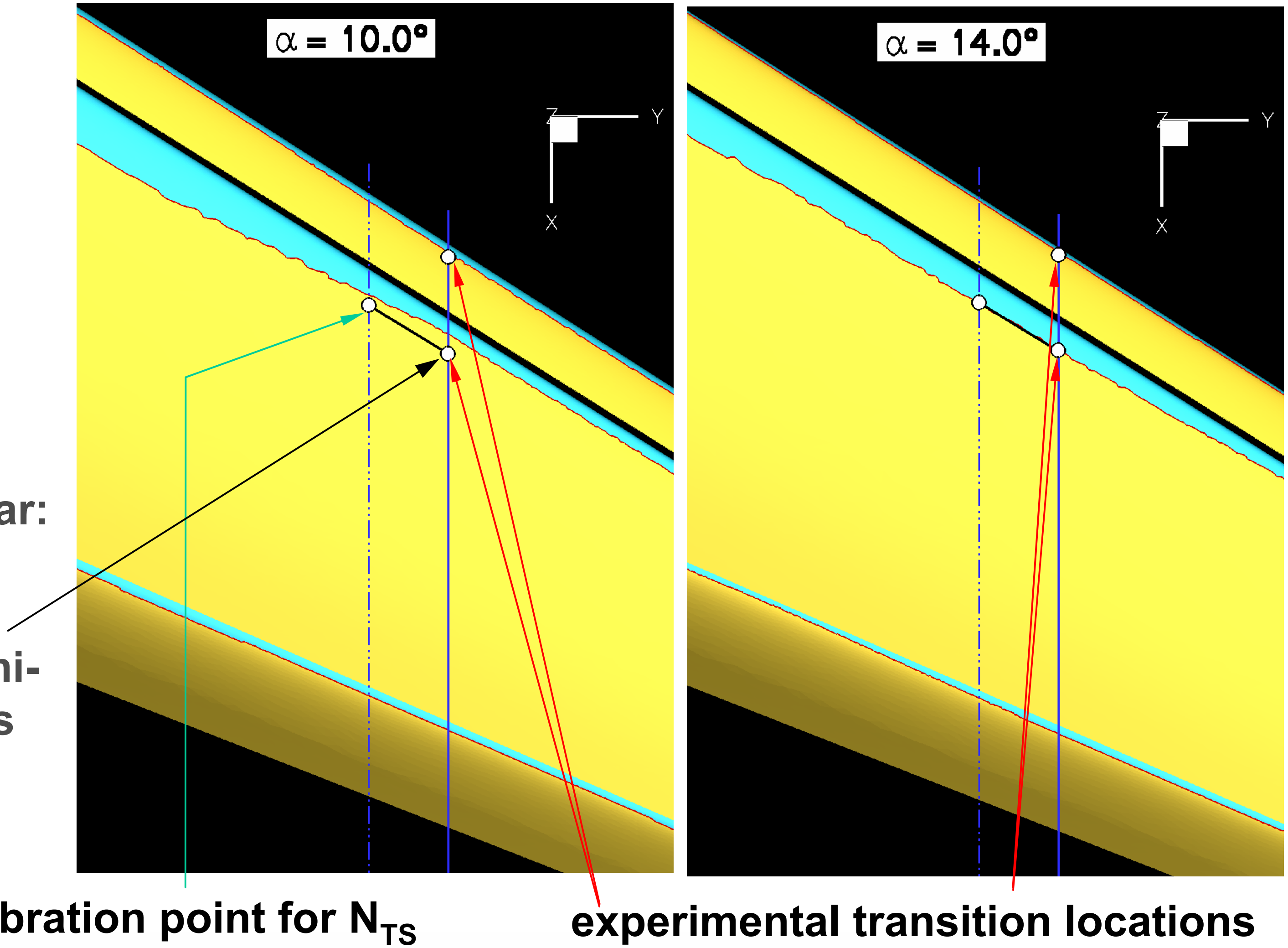
α = 14.0°, upper side: laminar surface regions



Comparison of experimental & predicted transition points

experimental x^T/c

α	10.0°	14.0°
slat	21%	11%
main	8%	5%

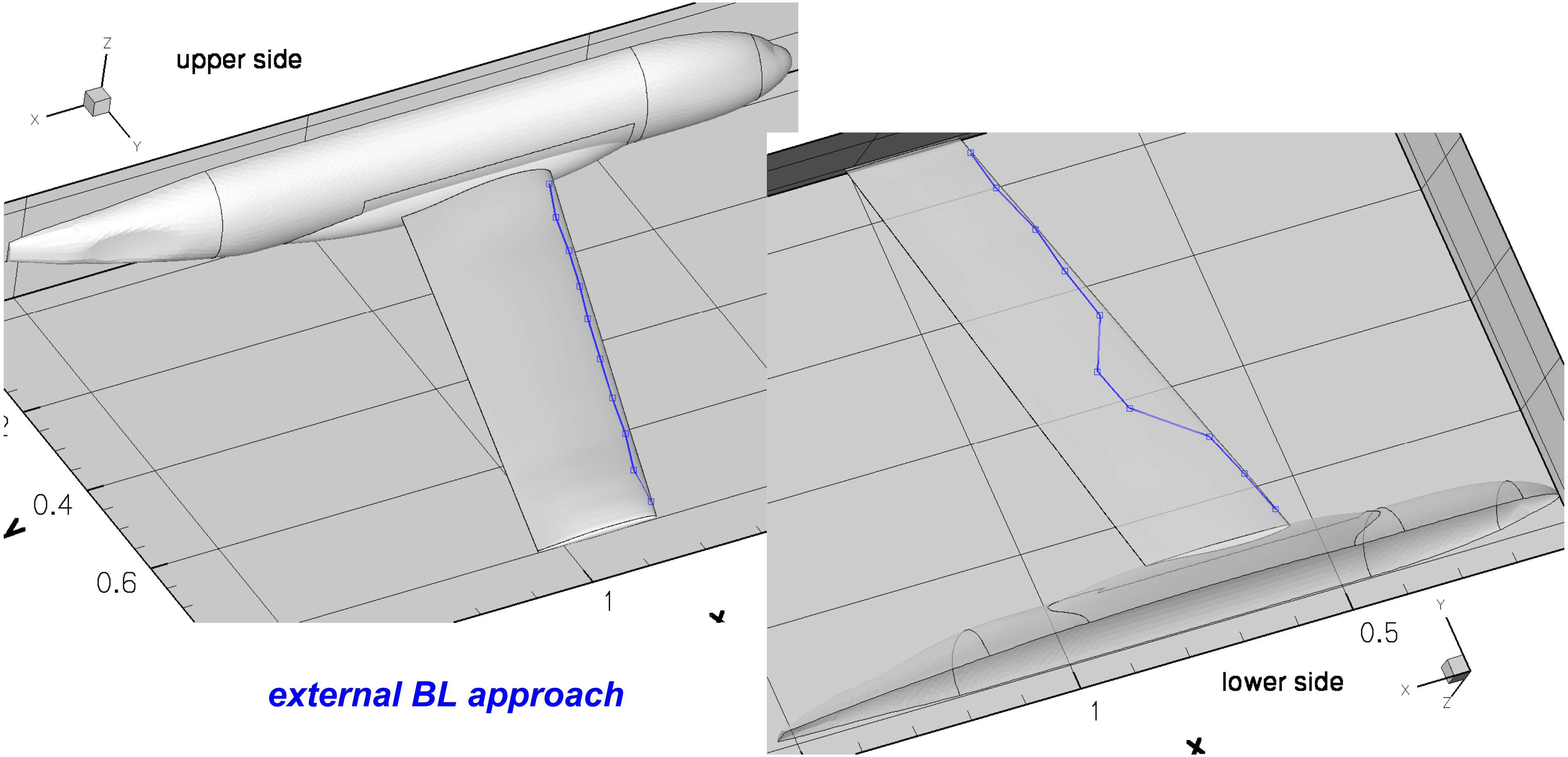


deviation still unclear:

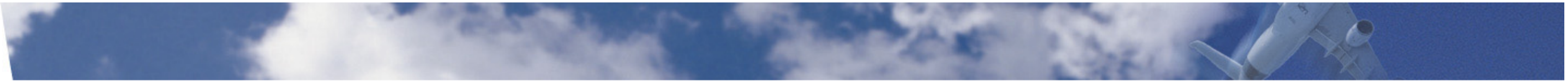
maybe criterion for transition inside laminar separation helps

Wing-body configuration with laminar wing:

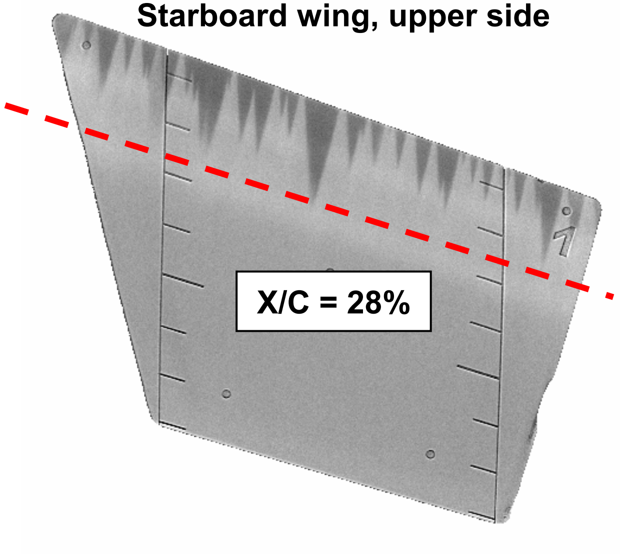
- **PATHFINDER wing from EU project TELFONA**
- **M = 0.78, Re = 20.0×10^6, α = 0.44°, N_{TS} = 12.0, N_{CF} = 9.0** (→ free flight conditions)



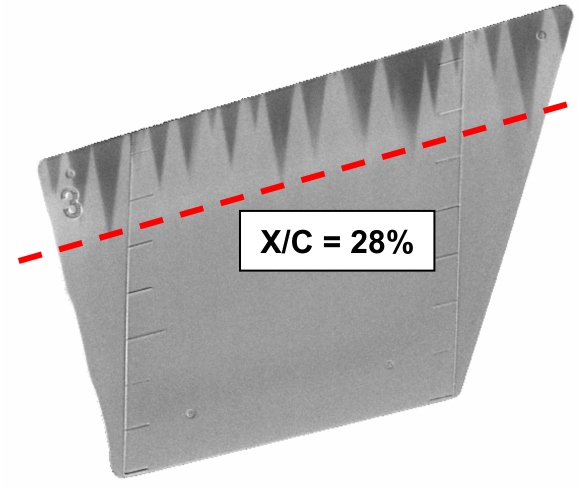
external BL approach



Starboard wing, upper side



η = 0.33   η = 0.67

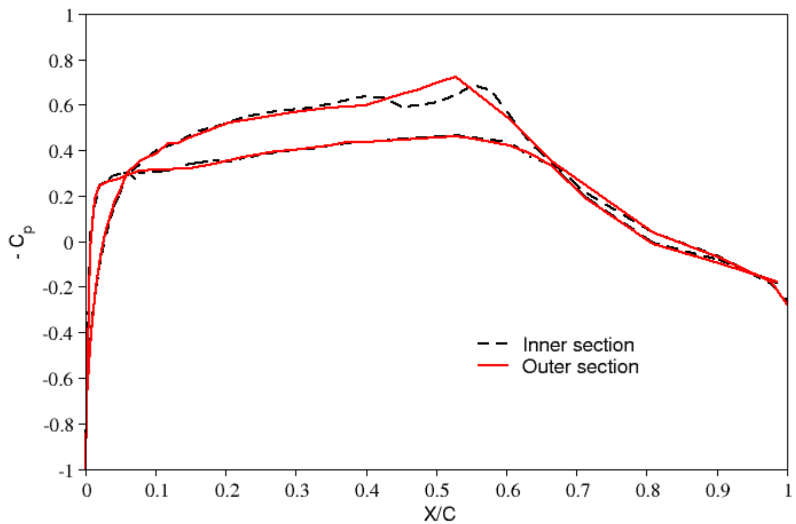


Starboard wing, lower side

Re_bar (<245)		φ_{eff}
Inner	164	18.8º
Outer	173	19.6º

	N_{CF}	N_{TS}
P081PUI	8.3	3
P081PUO	7.6	2
P081PLI	3.1	8.8
P081PLO	3	8.4
P081SUI	9	3.7
P081SUO	9	4
P081SLI	3	9
P081SLO	3	8

P081 Stb M = 0.78 R = 20 MIO C_L = 0.1

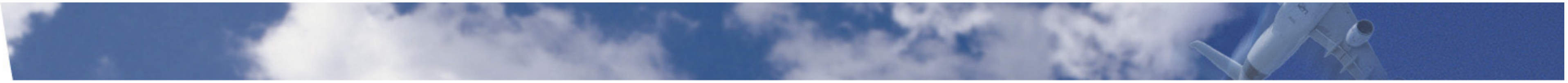


C_P	TSP	Mach	Re	T [K]	C_L	β
P081	P085	0.78	20 mio	175	0.1	0º

P081S: similar zigzag pattern in TSP image on upper side and on lower side, even though upper side is CF and lower side is TS.

Does this mean that transition occurs further downstream?

Results from G. Schrauf, Airbus

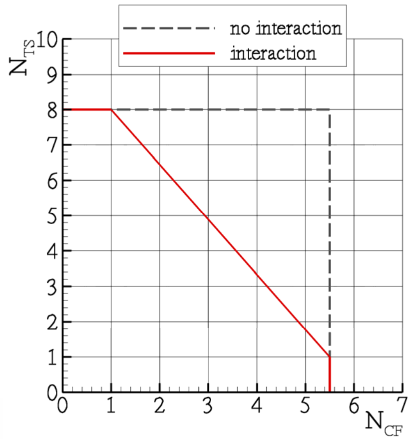


Validation

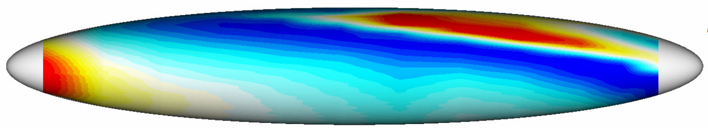
Prolate spheroid (simple representation of an a/c fuselage):

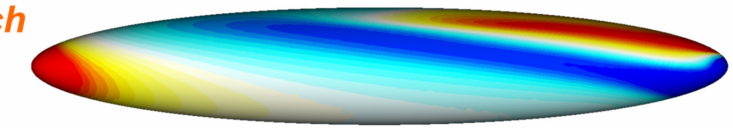
- α = 10.0°, *Re* = 1.5 x 10^6, *Ma* = 0.03
- hybrid grid, 2.8 x 10^6 points
- 40 – 90 grid points in lam. BL normal to wall
- experimental c_f with numerical transition line (left), numerical c_f (right)
- TS dominated transition (CF present)

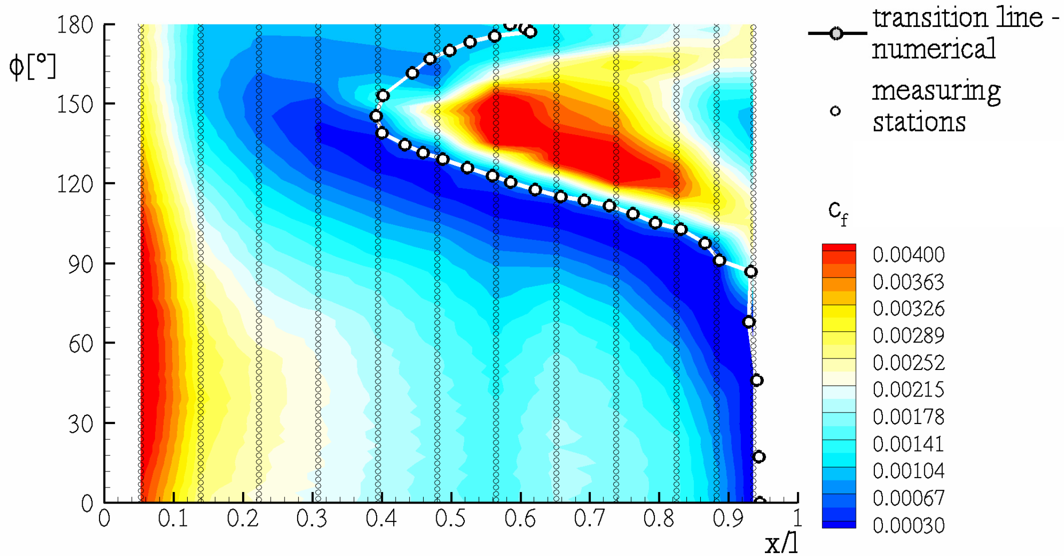
- by H. W. Stock (DLR)*
- modeling of the interaction of TS and CF waves (cannot be treated by local linear stability theory)
- $N_{TS,crit}$ =8.0, $N_{CF,crit}$ =5.5

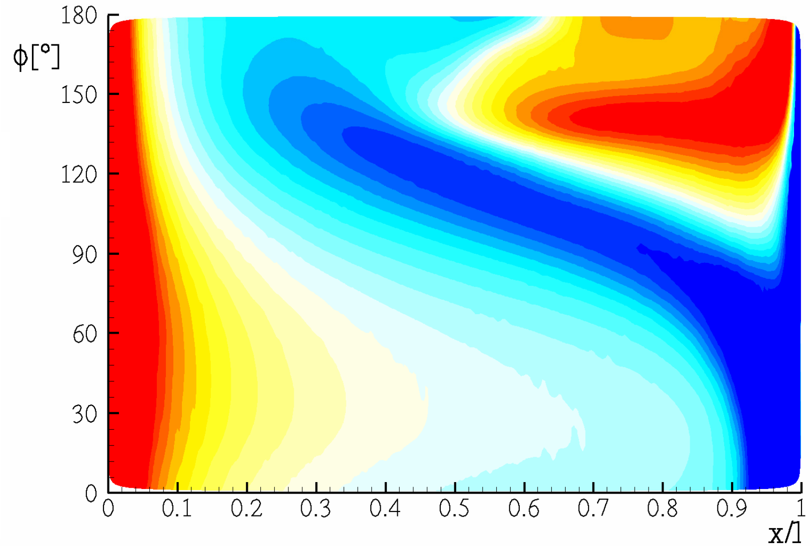


internal BL approach









DLR
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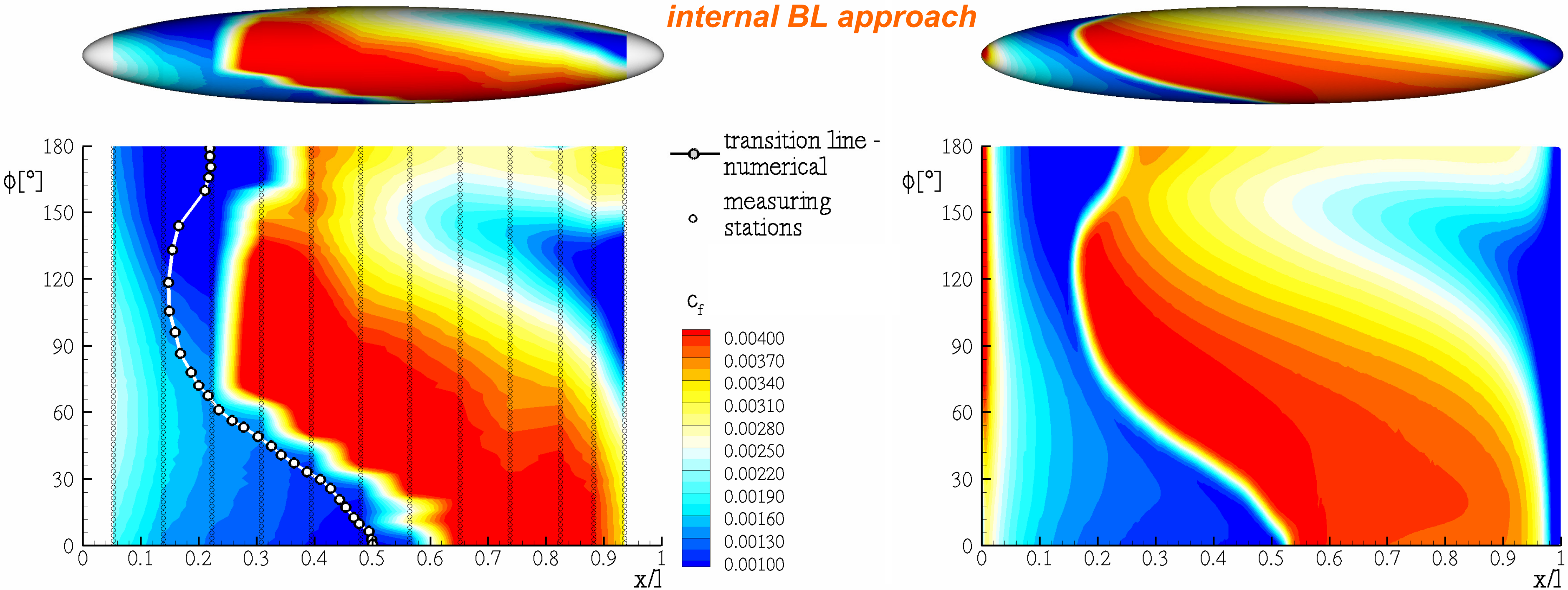
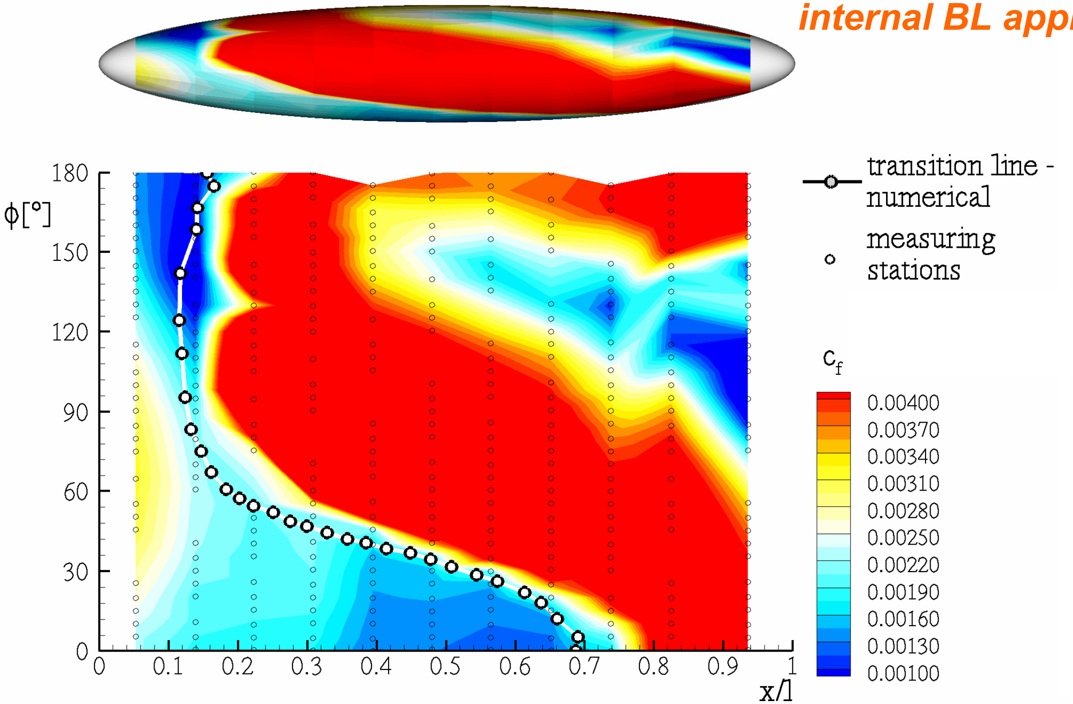
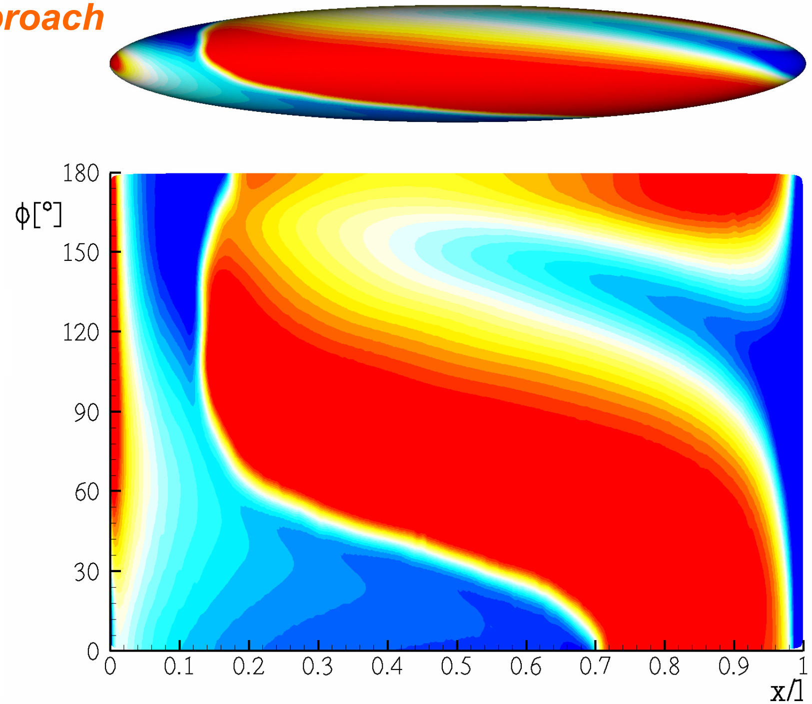
- α = 10.0°, *Re* = 6.5 x 10^6, *Ma* = 0.13
- hybrid grid, 2.8 x 10^6 points
- 40 – 90 grid points in lam. BL normal to wall
- experimental c_f with numerical transition line (left), numerical c_f (right)
- interacting TS and CF transition



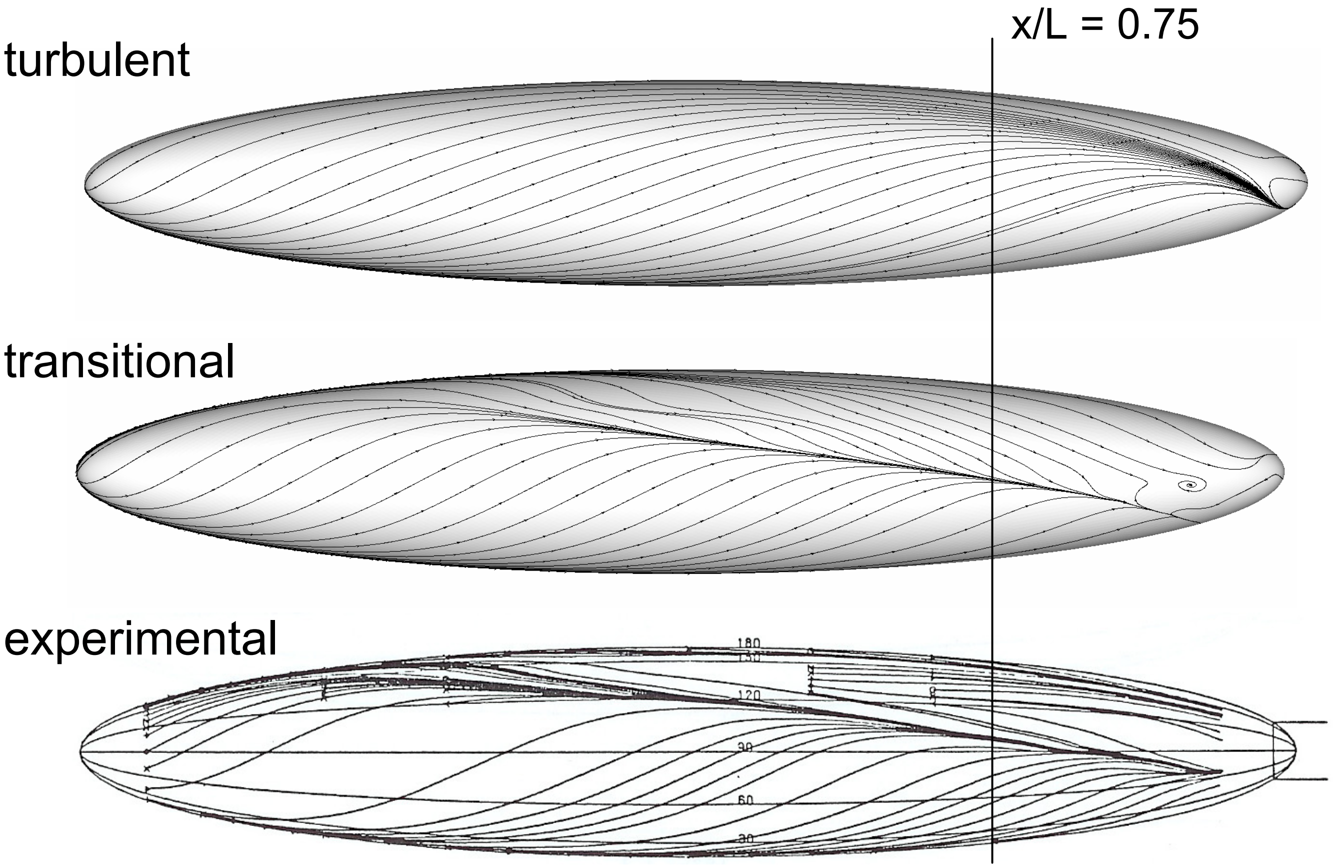
- α = 15.0°, *Re* = 6.5 x 10⁶, *Ma* = 0.13
- hybrid grid, 2.8 x 10⁶ points
- 40 – 90 grid points in lam. BL normal to wall
- experimental c_f with numerical transition line (left), numerical c_f (right)
- CF dominated transition

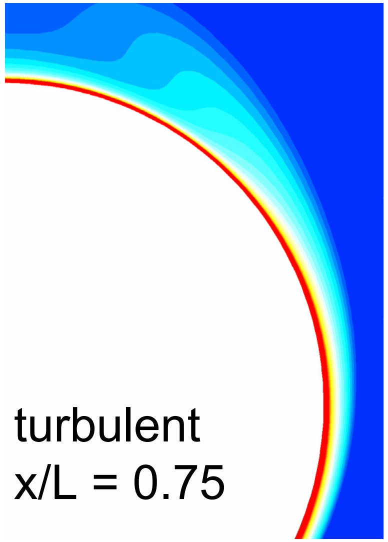


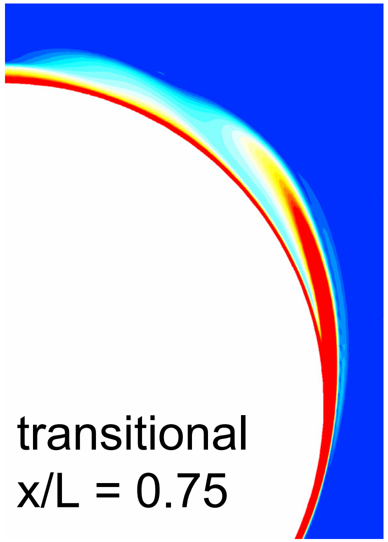
internal BL approach



- $\alpha = 10.0°$, $Re = 1.5 \times 10^6$, $Ma = 0.03$
- free vortex separation in experiment is only matched for transitional computation
- skin friction lines (below) and vorticity contours (right)







Conclusion

- **The complete coupled system (RANS solver & transition prediction module) was succesfully applied to a variety of 3D aircraft configurations.**
- **The technical feasibility was shown for all configurations and first validation steps have been made with:**
  - **good results for wing-body high-lift configuration**
  - **very good results for a prolate spheroid**
- **For the high-lift case, the predicted transition lines are qualitatively alike and quantitatively very similar to those obtained with a block-structured coupled system.**
- **It seems that attachment line transition plays role and that transition inside laminar separation bubbles may be of importance.**
- **Attachment line transition, by-pass trasition & transition inside laminar separation bubbles** (with BL code approach) **must be applied to the high-lift case.**
- **Much, much more validation on complex configurations is necessary.**
- **Reliable experimental transition data from W/T tests is a severe problem.**

Outlook

- Extensive testing on big cluster systems & validation
- Investigation of ALT on swept cylinder
- Testing of the empirical transition criteria
- Setup of Best Practice guidelines
- Implementation of a transition prediction method for unsteady flows
- Implementation of transport equation approaches

Thank you!