DLRK 2022

Deutscher Luft- und Raumfahrtkongress

27.-29. September 2022 - Dresden

CFD-based Transition Modeling for the NASA Common Research Model with Natural Laminar Flow

A. Krumbein[+], S. Helm[#], N. Krimmelbein[+], M. Fehrs[#], D. G. François[+]
Deutsches Zentrum für Luft- und Raumfahrt
Institute of Aerodynamics and Flow Technology[+], Institute of Aeroelasticity[#]

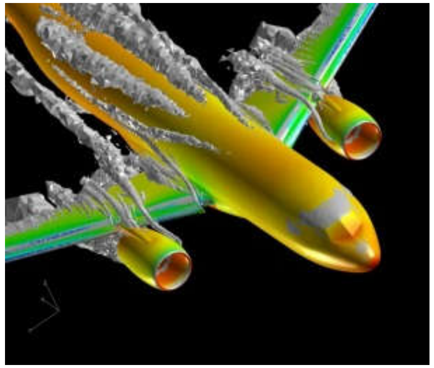
28.9.2022

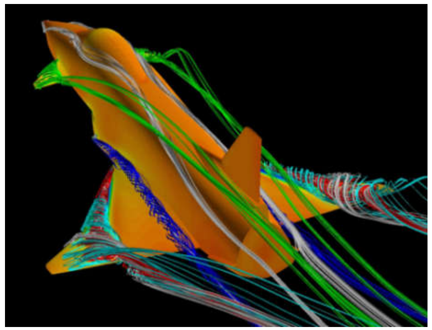
DLR

Transition Prediction Capabilities in CFD

Fundamental Requirements

- Applicable to **complex configurations**
- High level of **automation**, usable within multi-disciplinary simulation frameworks
- All major transition mechanisms/modes
  - **Crossflow, Tollmien-Schlichting, separation-induced, by-pass transition**
- **Accuracy** of simulation results
  - Impact on major flow quantities and properties: c_p, c_f, heat flux, separation/reattachment lines and size of separation, …
  - Point of transition onset, interaction with turbulence model, …
- **Stability** and **robustness** of implementation/procedure
  - Steady RANS, unsteady RANS
  - Rotating systems, e.g. propellers, helicopter rotors, …
  - Scale-resolving simulations (hybrid RANS-LES methods, …)
- **Broad application range**
- **User acceptance**

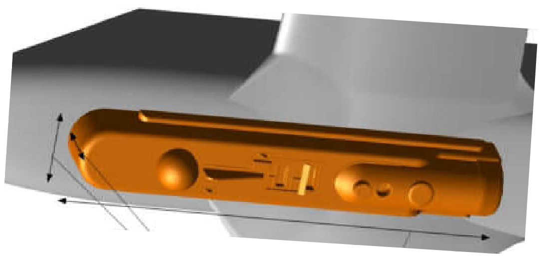




Transition Prediction Capabilities in CFD

Fundamental Requirements

- **More than one method necessary** to satisfy the wide range of requirements.
- DLR TAU code → **Streamline-based** approach using a **two-N-factor strategy + e^N method**
  → **Transition Transport Models** (TTM) using partial differential equations
- **Complementary use** of the different approaches for different applications, for example
  - *Two-N-factor strategy*
    → Design and analysis of laminar flow wings/components
    → Configurations of moderate complexity
    → Weak unsteady flows (e.g. gusts, maneuvers, …)
  - *Transition Transport Models*
    → Massively unsteady flows (e.g. propellers, rotors, dynamic stall, SRS, …)
    → Very complex geometrical configurations

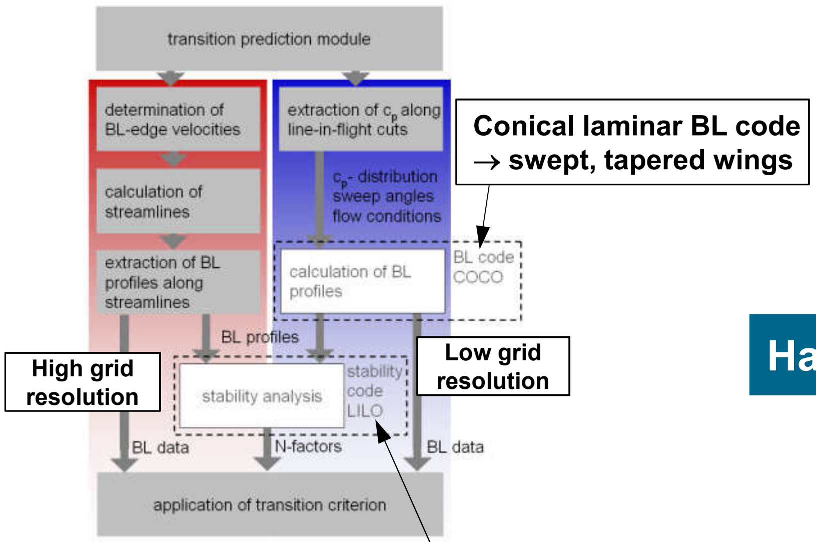


Aircraft with belly-pod

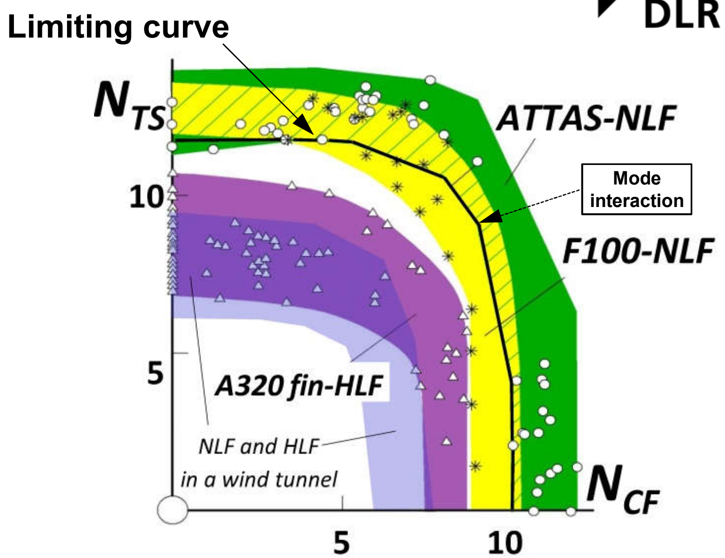
Transition Prediction Capabilities in CFD

Two-N-factor strategy + e^N method

- **Classic approach**
  - Local, linear stability analysis
  - Tollmien-Schlichting (T-S) waves → N_{TS}
  - Stationary crossflow (SCF) waves → N_{CF}

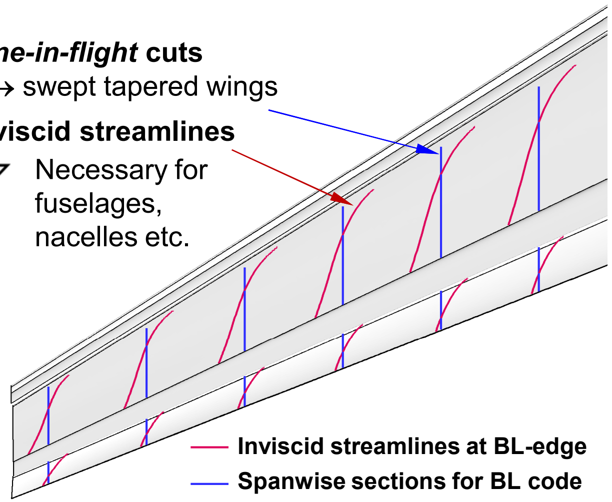


Automated local, linear stability code
→ **frequency estimator** for approximate range of frequencies f
→ **wave length estimator** for approximate range wave lengths λ



Handling of integration paths

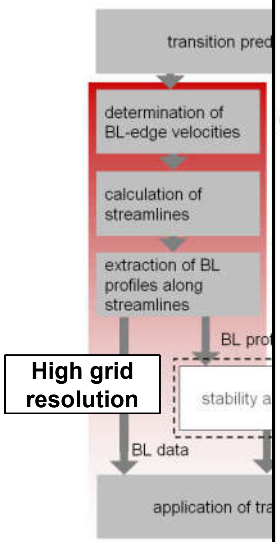
- ***Line-in-flight* cuts**
  → swept tapered wings
- **Inviscid streamlines**
  - Necessary for fuselages, nacelles etc.



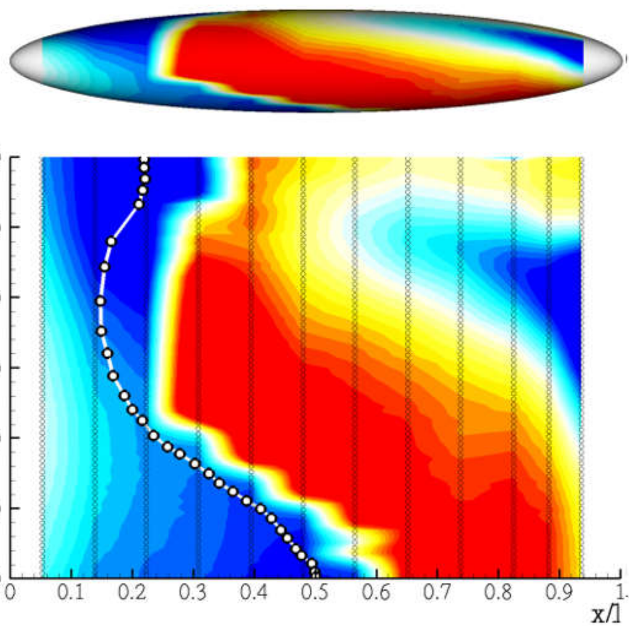
Transition Prediction Capabilities in CFD

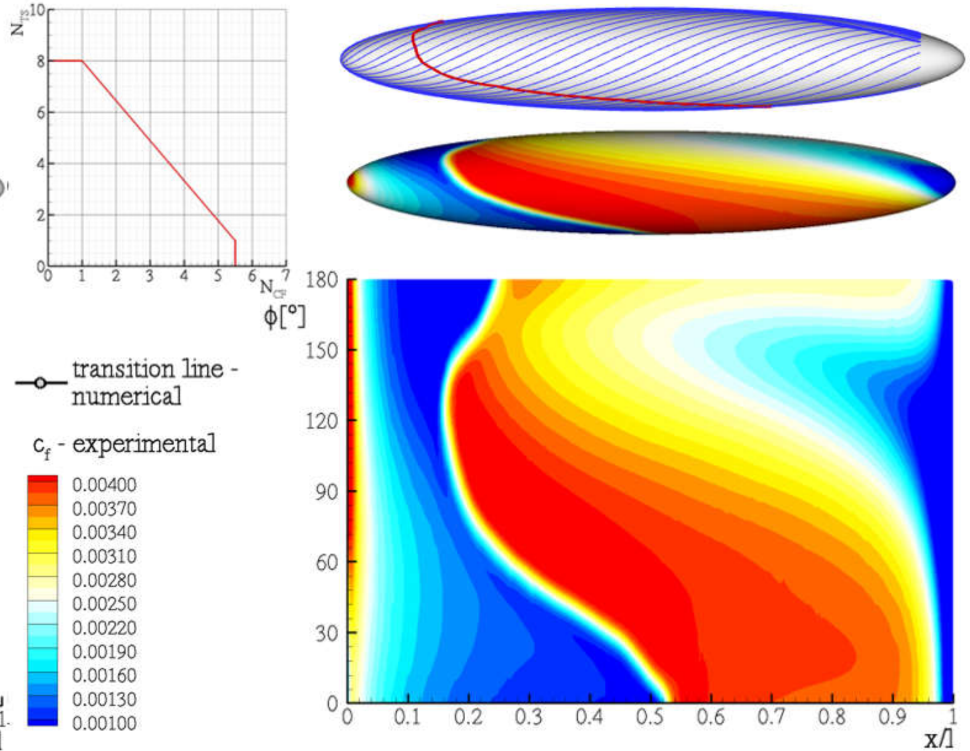
Two-N-fa

- **Classic**
  - L
  - T
  - S

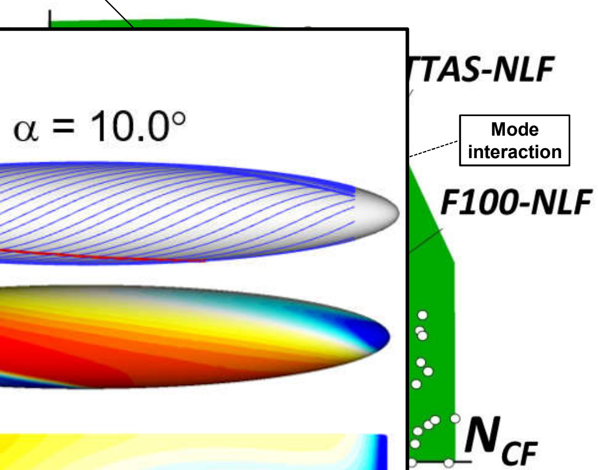


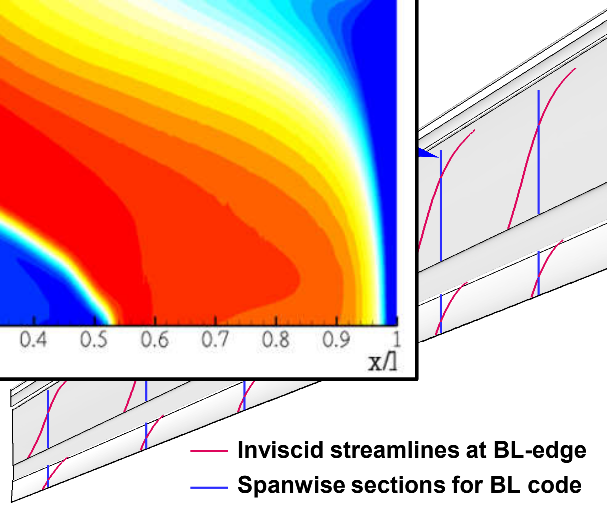
- **Validation**
  - Inclined prolate 6:1 spheroid: Re = 6.5×10^6, Ma = 0.13, α = 10.0°
  - Mixed T-S/CF transition





Limiting curve





Automated local, linear stability code
→ **frequency estimator** for approximate range of frequencies f
→ **wave length estimator** for approximate range wave lengths λ

Transition Prediction Capabilities in CFD

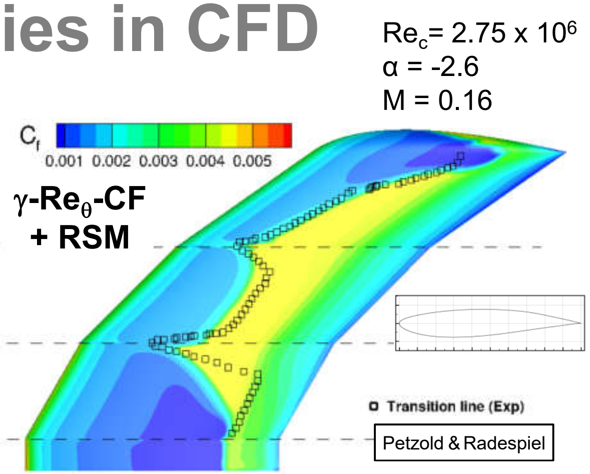
Transition Transport Models

- γ**-Re**$_\theta$ *:* Langtry/Menter → streamwise transition
- γ**-Re**$_\theta$ **– CF***:* DLR AS-CAS development for crossflow transition

Transition Prediction Capabilities in CFD

Transition Transport Models

- **γ-Re$_\theta$***:* Langtry/Menter → streamwise transition
- **γ-Re$_\theta$ – CF***:* DLR AS-CAS development for crossflow transition



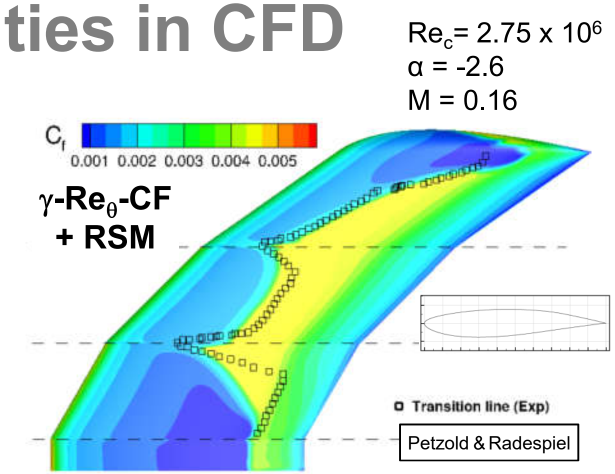
Transition Prediction Capabilities in CFD

Transition Transport Models

- **γ-Re$_\theta$** *:* Langtry/Menter → streamwise transition
- **γ-Re$_\theta$ – CF***:* DLR AS-CAS development for crossflow transition

Problem with γ-Re$_\theta$

- **Limited applicability range**



Transition Prediction Capabilities in CFD

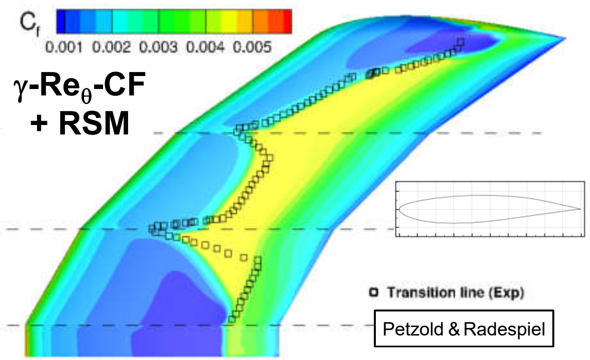
Transition Transport Models

- **γ-Re$_\theta$** *:* Langtry/Menter → streamwise transition
- **γ-Re$_\theta$ – CF***:* DLR AS-CAS development for crossflow transition

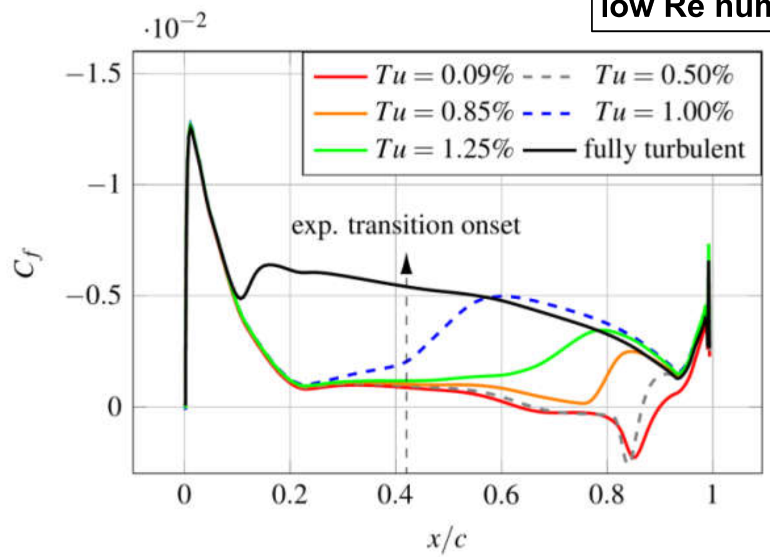
Problem with γ-Re$_\theta$

- **Limited applicability range**
  - Deviations at low Re (~ 10^5)

$Re_c = 2.75 \times 10^6$
α = -2.6
M = 0.16



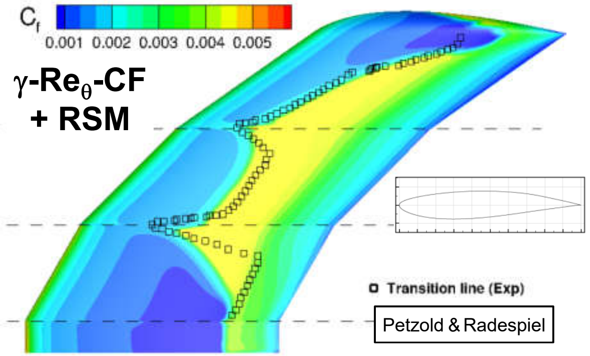
low Re number



DSA-9A, Re$_C$ = 300.000

Transition Prediction Capabilities in CFD

$Re_c = 2.75 \times 10^6$
$\alpha = -2.6$
$M = 0.16$



Transition Transport Models

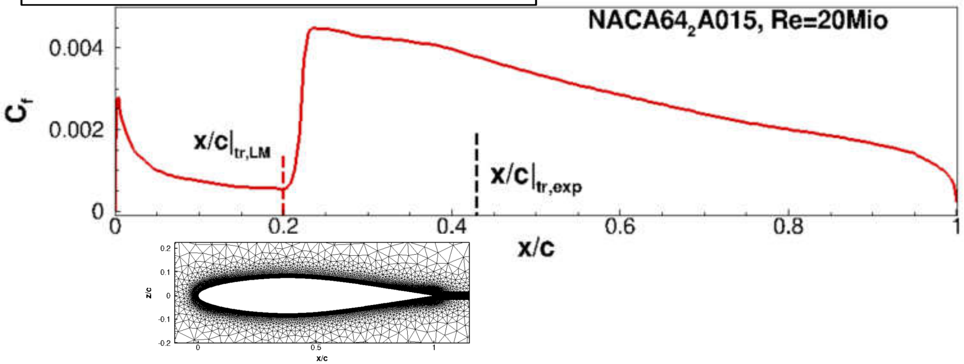
- **γ-Re$_\theta$** *:* Langtry/Menter → streamwise transition
- **γ-Re$_\theta$ – CF***:* DLR AS-CAS development for crossflow transition

Problem with γ-Re$_\theta$

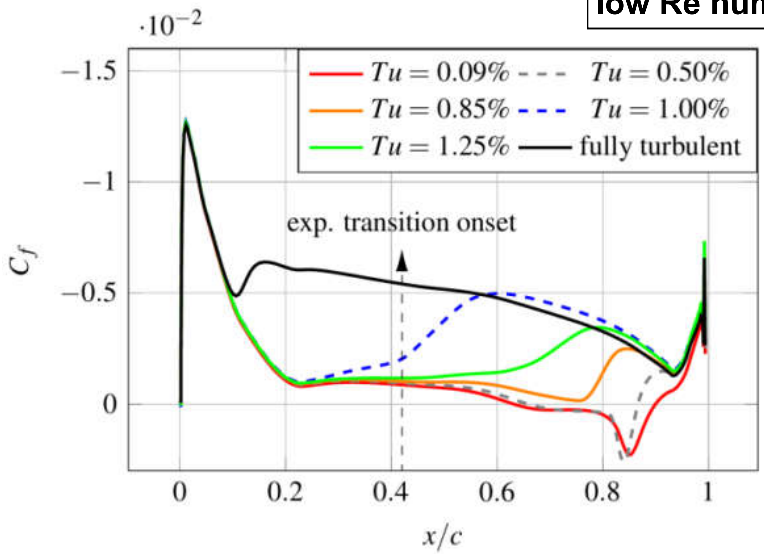
- **Limited applicability range**
  - Deviations at low Re (~ 10^5)
  - Deviations at high Re (~ 10^7)

NACA 642-A-015, Re_C = 20×10^6

high Re number



low Re number



DSA-9A, Re_C = 300.000

Transition Prediction Capabilities in CFD

DLR

Alternative approach to solve the problem

- **Simplified Stability-Based Transport Model**
  - ***γ-based one-equation model***
  - Strongly simplified formulation of AHD criterion
  - Currently coupled with Menter SST k-ω turbulence model
  - Coupling with SA-neg turbulence model currently underway

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

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

$$F_{onset} = f\left(\frac{Re_\theta}{Re_{\theta t}}\right)$$ ***Transition Onset Switch***

$$Re_\theta = \frac{\theta \cdot u_e}{\nu_e} \qquad Re_{\theta t}(\lambda_\theta, TI, Ma) \longrightarrow$$ Simple-AHD criterion

Local Approximation of Integral Quantity

$$Re_\theta^* = \frac{Re_\nu}{\pi(H_{12})} \qquad H_{12} = f(\lambda_\theta) \qquad \lambda_\theta = \frac{\theta^2}{\nu_e}\frac{du_e}{ds}$$

Transition Criterion

$$Re_{\theta t} = -\left(177 \cdot M_e^2 - 22 \cdot M_e + 210\right) \cdot ln\left((7 \cdot M_e + 4.8) \cdot \frac{TI_\infty}{100}\right) \cdot exp\left((5 \cdot M_e + 27) \cdot \lambda_\theta\right)$$

$$H_{12} = \begin{cases} 4.02923 - \sqrt{-8838.4 \cdot \lambda_\theta^4 + 1105.1 \cdot \lambda_\theta^3 - 67.962 \cdot \lambda_\theta^2 + 17.574 \cdot \lambda_\theta + 2.0593}, & if \lambda_\theta \geq 0.0 \\ 2.072 + \frac{0.0731}{\lambda_\theta + 0.14}, & if \lambda_\theta < 0.0 \end{cases}$$

FPG

APG

D. G. François et al., "Simplified Stability-Based Transition Transport Modeling for Unstructured Computational Fluid Dynamics", AIAA 2022-1543

NASA CRM-NLF Configuration

Common Research Model with Natural Laminar Flow (CRM-NLF)

- **Main Test Case from the 1st AIAA Transition Modeling and Prediction Workshop**
- **Flow Conditions**
  - M ≈ 0.85
  - $Re_{MAC} \approx 15\times10^6$
  - AoA ≈ 1.5°, 2.0°, 2.5°, 3.0°
  - $Tu_{free\text{-}stream} = 0.24\%$

transitionmodeling.larc.nasa.gov/wp-content/uploads/sites/109/2020/10/TransitionMPW_Flyer_v7.pdf

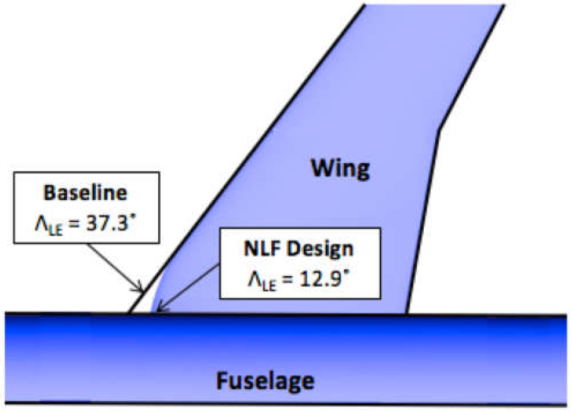
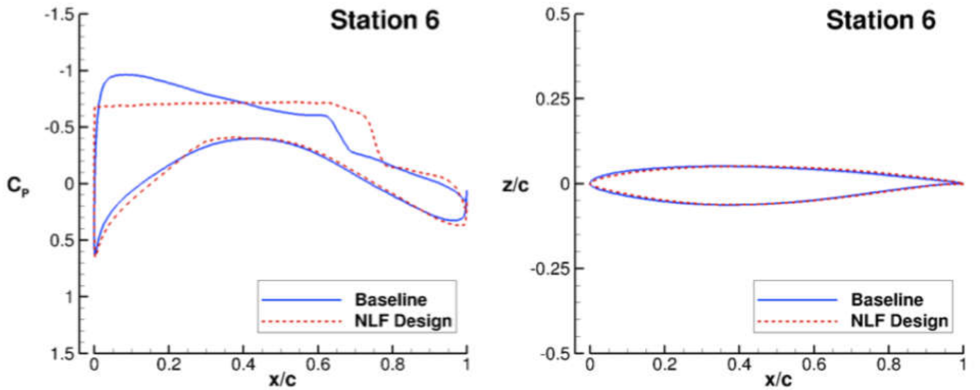


Figure 5. Planform view of the wing-fuselage juncture showing the reduced leading-edge sweep (Λ_{LE}) of the NLF Design, which is used to control attachment line contamination.



c) Station 6 pressure distribution (left) and airfoil geometry (right).

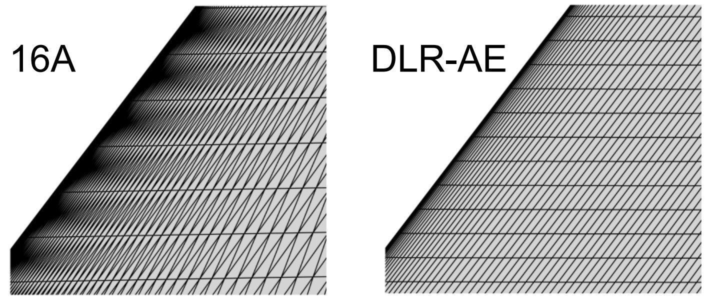
Figure 8. Comparison of the Baseline (blue, solid) and the NLF Design (red, dashed) configurations, showing pressure distributions (left) and airfoil geometry (right), analyzed at M=0.85, C_L=0.5, Re_{mac}=30x10^6.

M. N. Lynde et al., "Computational Design and Analysis of a Transonic Natural Laminar Flow Wing for a Wind Tunnel Model", AIAA 2017-3058

NASA CRM-NLF Configuration

Computational Grids

- Custom unstructured, DLR-AE*
- SeriesA P-T
- Requirement for LST with boundary-layer data from RANS for T-S: $n_{BL,edge} = 48$ / $n_{streamwise} = 128$



surface grids

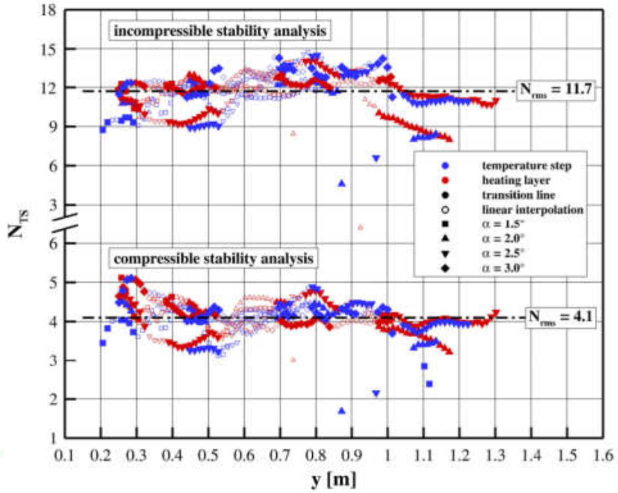
Name	$n_{BL,edge}$	$n_{streamwise}$	n_{TE}	grid size	grid size orig.
DLR-AE*	***48-64***	***300***	***3***	***29547824***	***n/a***
16A	36-48	200	16	21334613	21034665
14A	32-40	180	14	14513793	14308390
12A	28-36	150	12	9324119	9192505
10A	24-28	125	10	5546826	5467478
8A	20-24	100	8	2959216	2914797

*created and provided by Michael Fehrs, DLR, Institute of Aeroelasticity

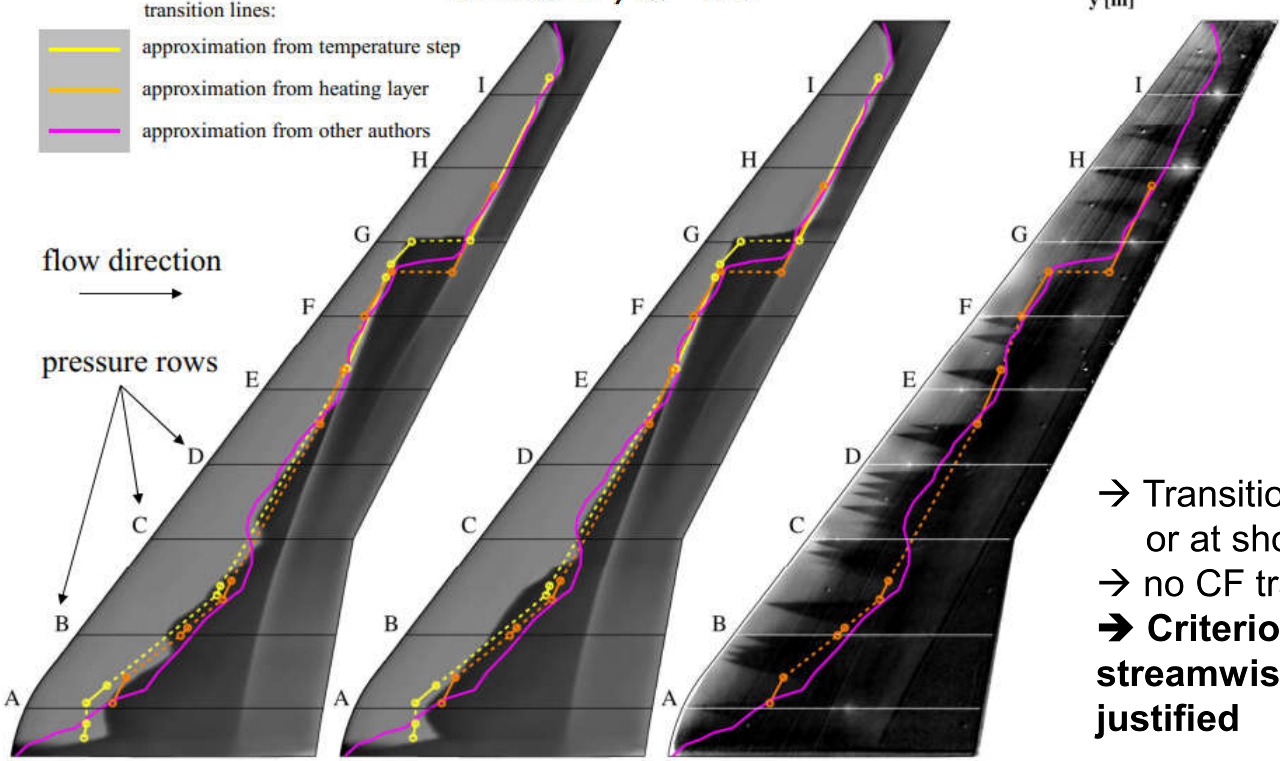
NASA CRM-NLF Configuration

Results from the Two-N-factor Strategy

- **TAU Transition Module Results (LST): N_{CF}^{crit}= 6.0, N_{TS}^{crit}** →



Re 15x10^6, α = 1.5°



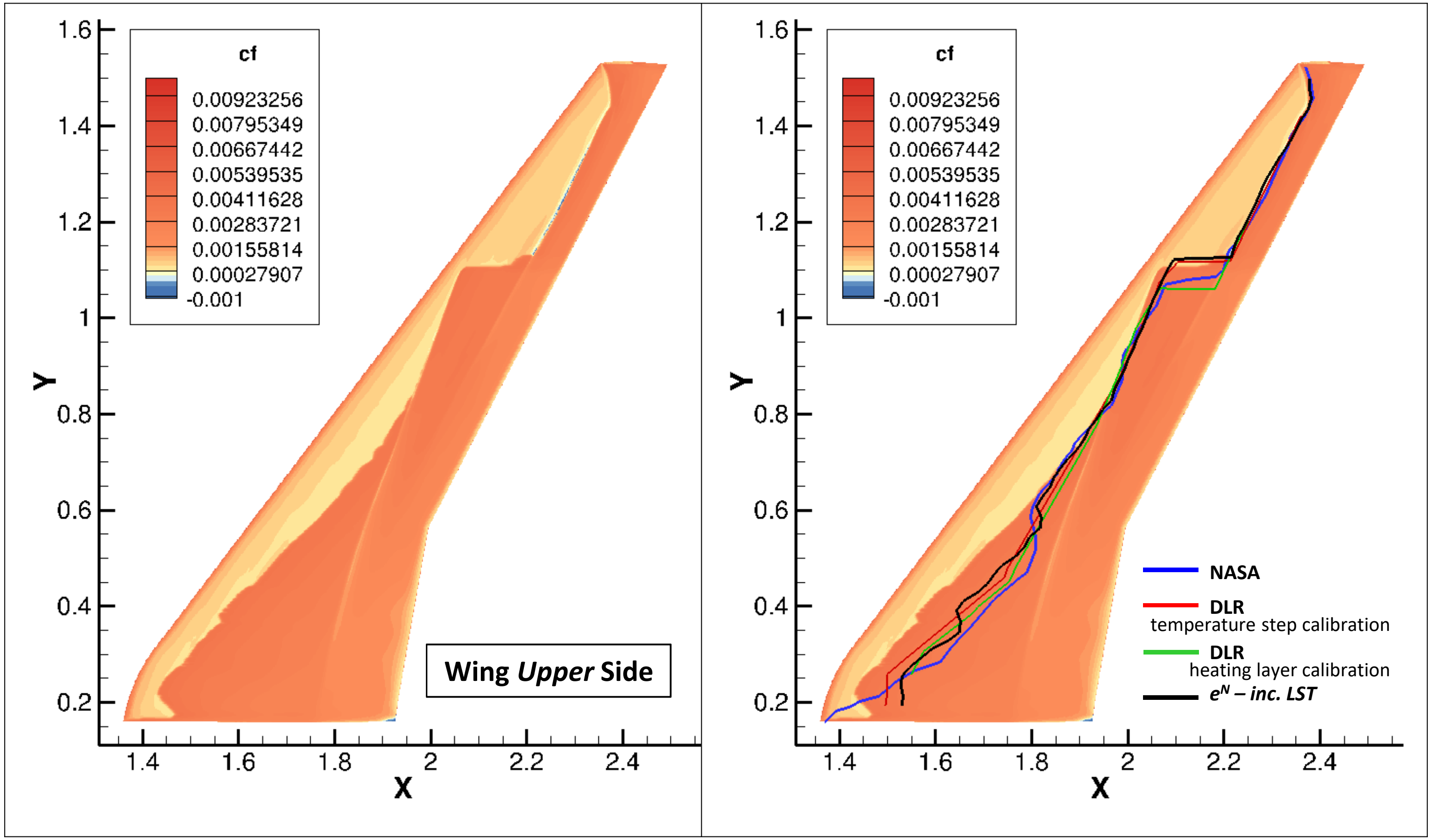
→ Transition due to T-S waves or at shock location
→ no CF transition found
➔ Criterion for pure streamwise transition justified

N. Krimmelbein et al., "Determination of Critical N-factors for the CRM-NLF Wing", Notes on Numerical Fluid Mechanics and Multidisciplinary Design 151 • New Results in Numerical and Experimental Fluid Mechanics XIII, Contributions to the 22th STAB/DGLR Symposium 2020, 2021

NASA CRM-NLF Configuration

Simulation Results and Comparison to Transition Lines derived from the Experiments

- **New γ model**
- **AoA = 1.5°**

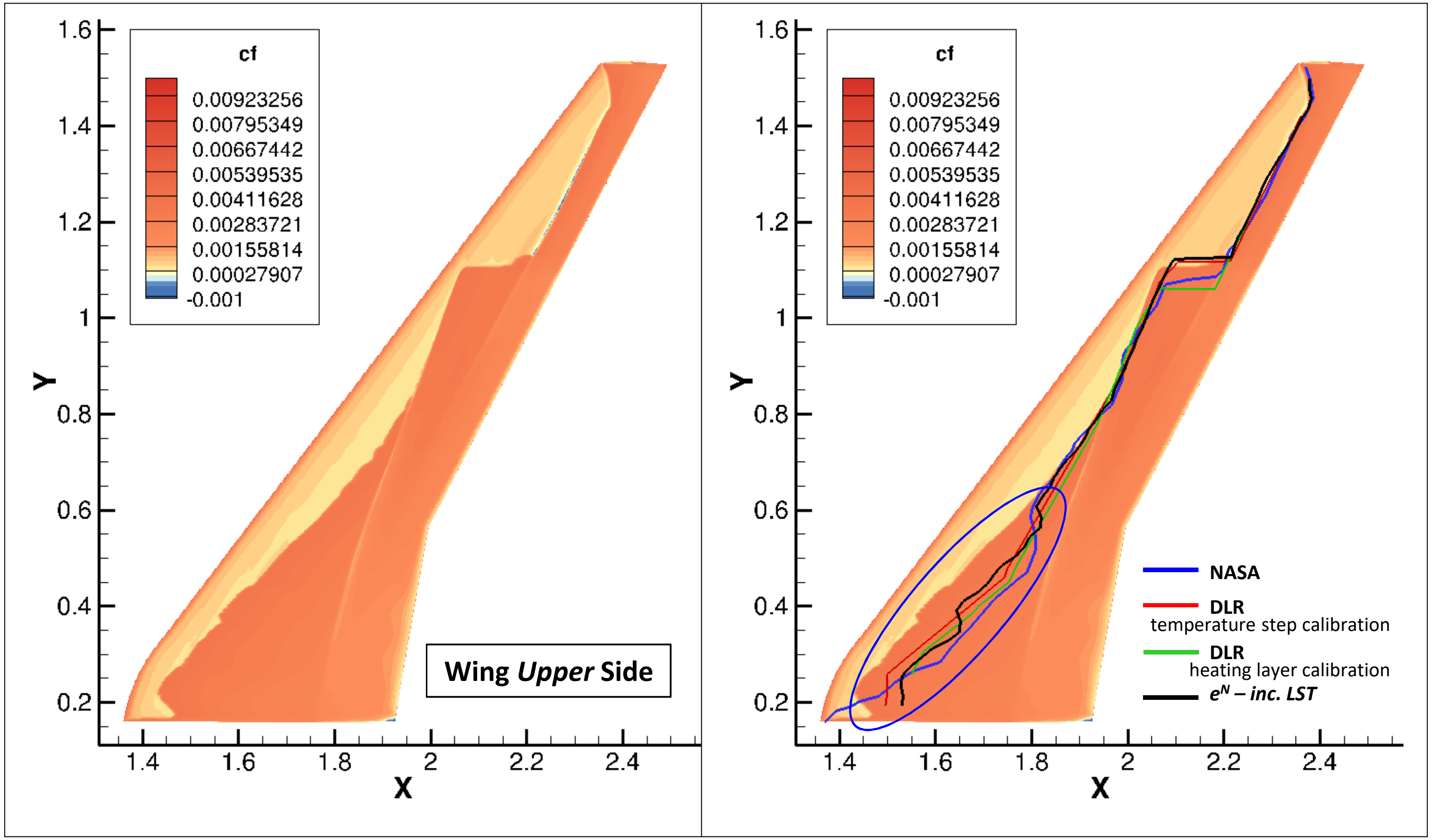


A. Krumbein et al.,"Transport-based Transition Prediction for the Common Research Model Natural Laminar Flow Configuration", Journal of Aircraft, July 2022; AIAA 2022-1541

NASA CRM-NLF Configuration

Simulation Results and Comparison to Transition Lines derived from the Experiments

- **New γ model**
- **AoA = 1.5°**

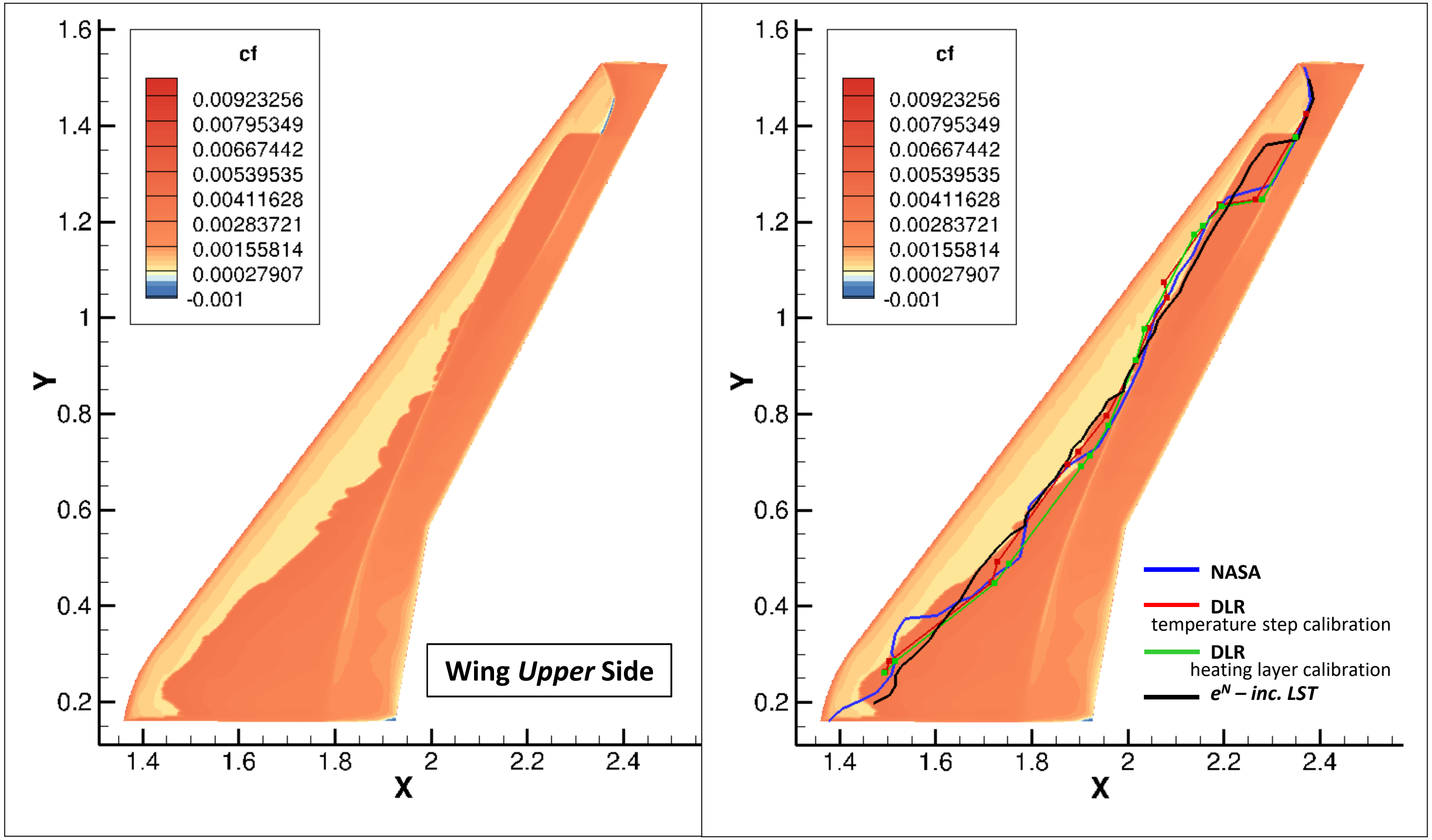


A. Krumbein et al.,“Transport-based Transition Prediction for the Common Research Model Natural Laminar Flow Configuration”, Journal of Aircraft, July 2022; AIAA 2022-1541

NASA CRM-NLF Configuration

Simulation Results and Comparison to Transition Lines derived from the Experiments

- **New γ model**
- **AoA = 2.0°**

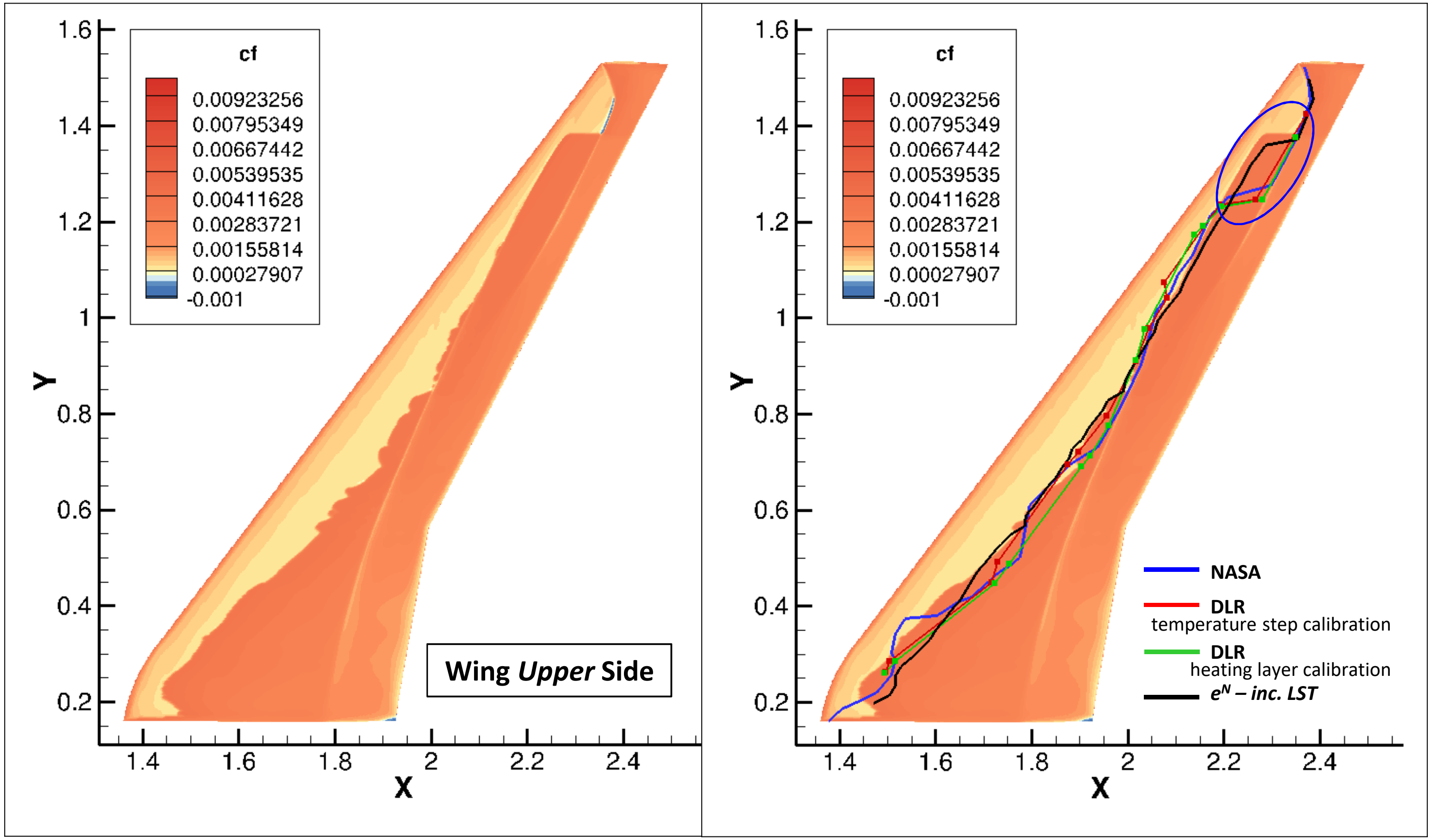


A. Krumbein et al.,"Transport-based Transition Prediction for the Common Research Model Natural Laminar Flow Configuration", Journal of Aircraft, July 2022; AIAA 2022-1541

NASA CRM-NLF Configuration

Simulation Results and Comparison to Transition Lines derived from the Experiments

- **New γ model**
- **AoA = 2.0°**

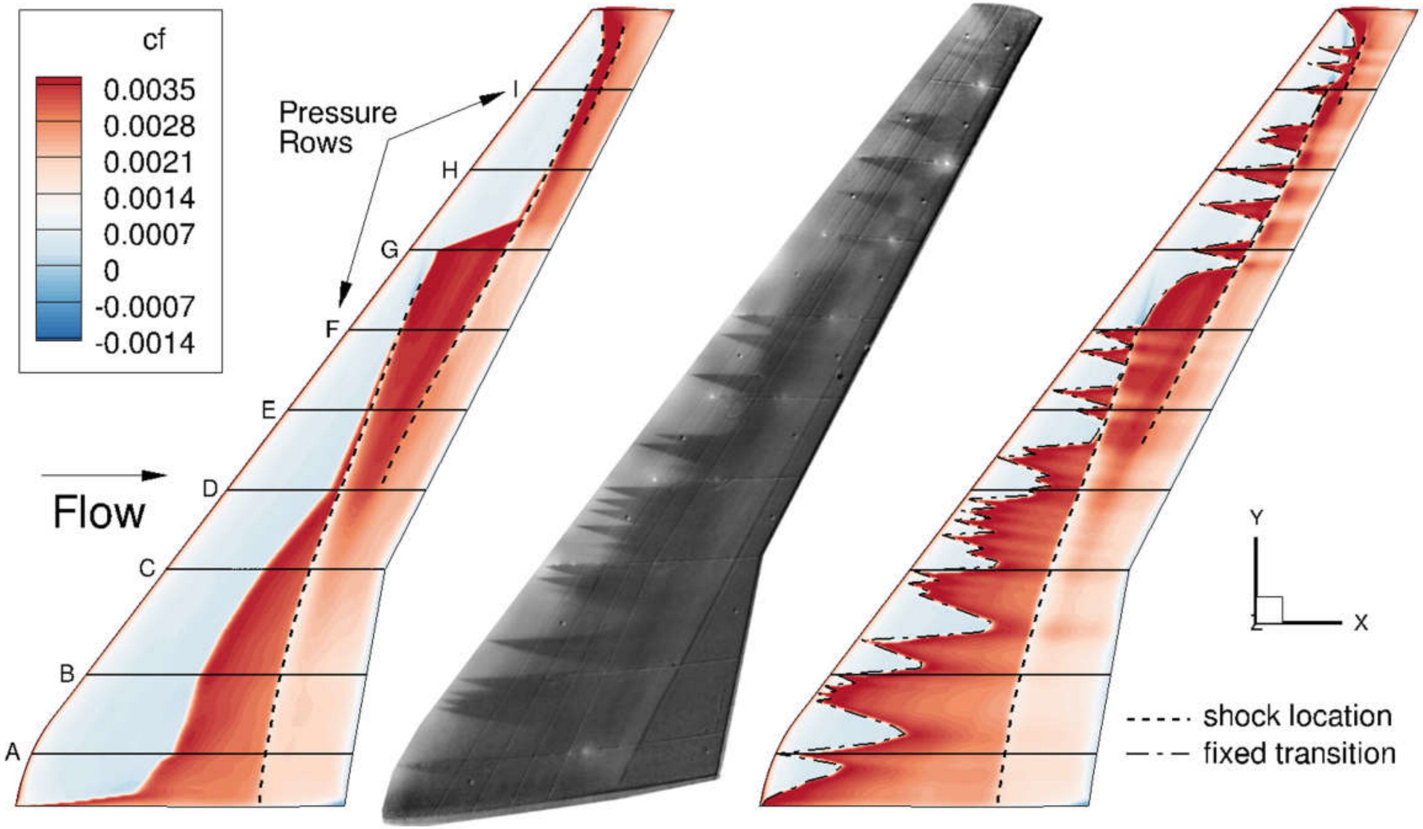


A. Krumbein et al.,"Transport-based Transition Prediction for the Common Research Model Natural Laminar Flow Configuration", Journal of Aircraft, July 2022; AIAA 2022-1541

NASA CRM-NLF Configuration

Influence of turbulent wedges

- **Simulations with fixed transition**
- **AoA = 1.5°**

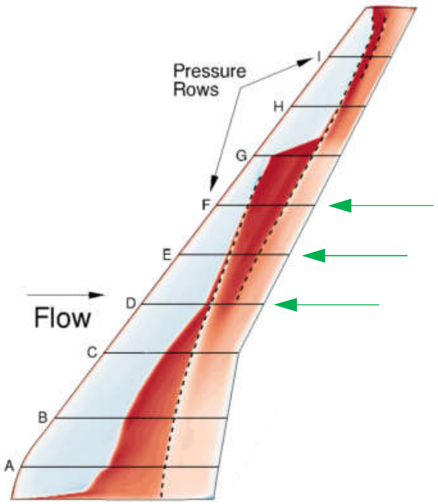


S. Helm et al., "Transition Prediction and Analysis of the CRM-NLF wing with the DLR TAU Code", Notes on Numerical Fluid Mechanics and Multidisciplinary Design 151 • New Results in Numerical and Experimental Fluid Mechanics XIII, Contributions to the 22th STAB/DGLR Symposium 2020, 2021

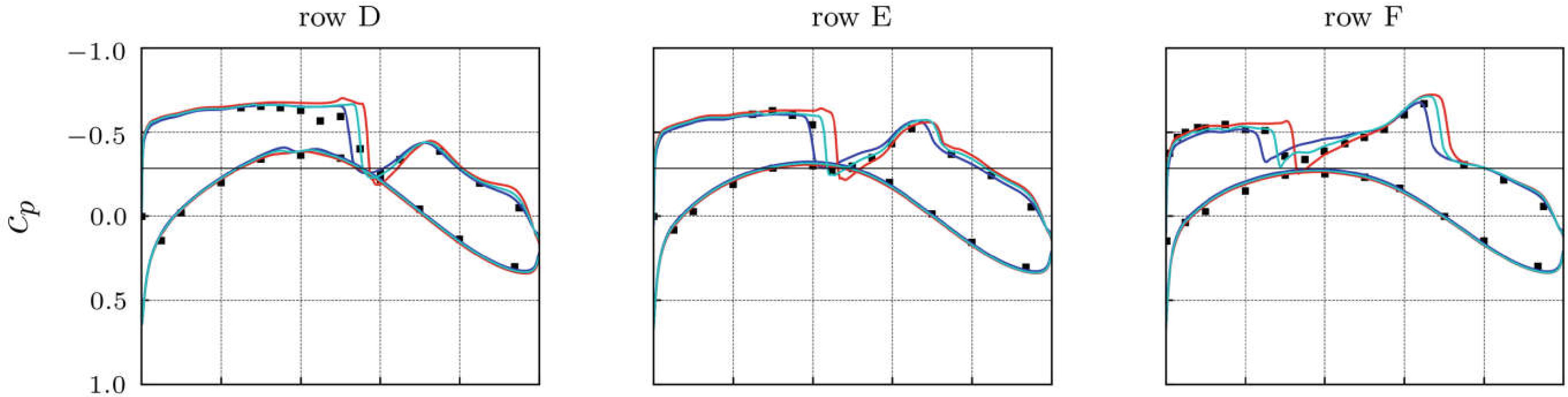
NASA CRM-NLF Configuration

Influence of turbulent wedges

- **Simulations with fixed transition**
- **AoA = 1.5°**



fully turbulent
free transition
fixed with wedges
experiment



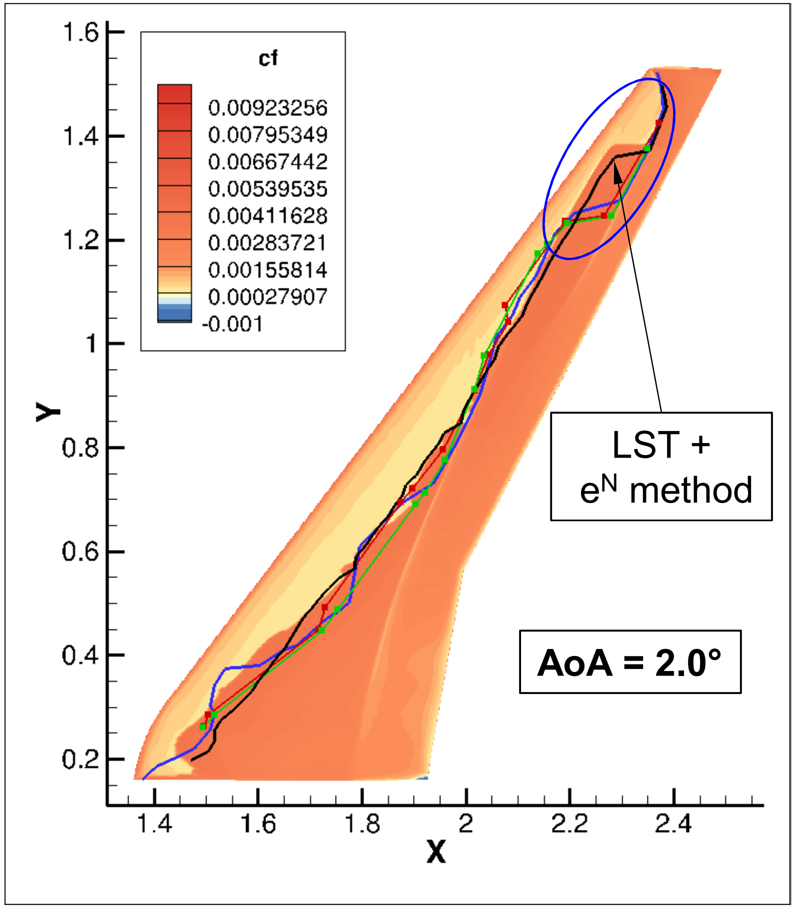
S. Helm et al., "Transition Prediction and Analysis of the CRM-NLF wing with the DLR TAU Code", Notes on Numerical Fluid Mechanics and Multidisciplinary Design 151 • New Results in Numerical and Experimental Fluid Mechanics XIII, Contributions to the 22th STAB/DGLR Symposium 2020, 2021

→ Taking into account the turbulent wedges seems to be crucial for accurate simulation results.

NASA CRM-NLF Configuration

Sensitivity to angle of attack (AoA)

- **Nominal AoA**
  → AoA = 2.0°
- **Slight change of AoA**
  → AoA = 1.8°
- **e^N method vs. new γ model**

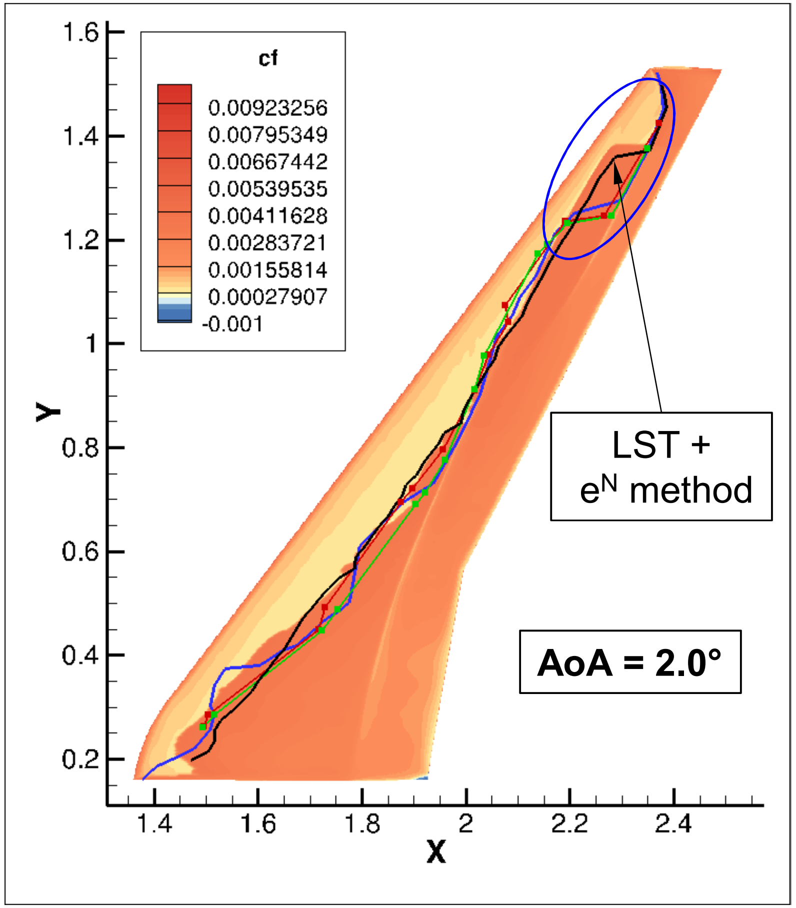


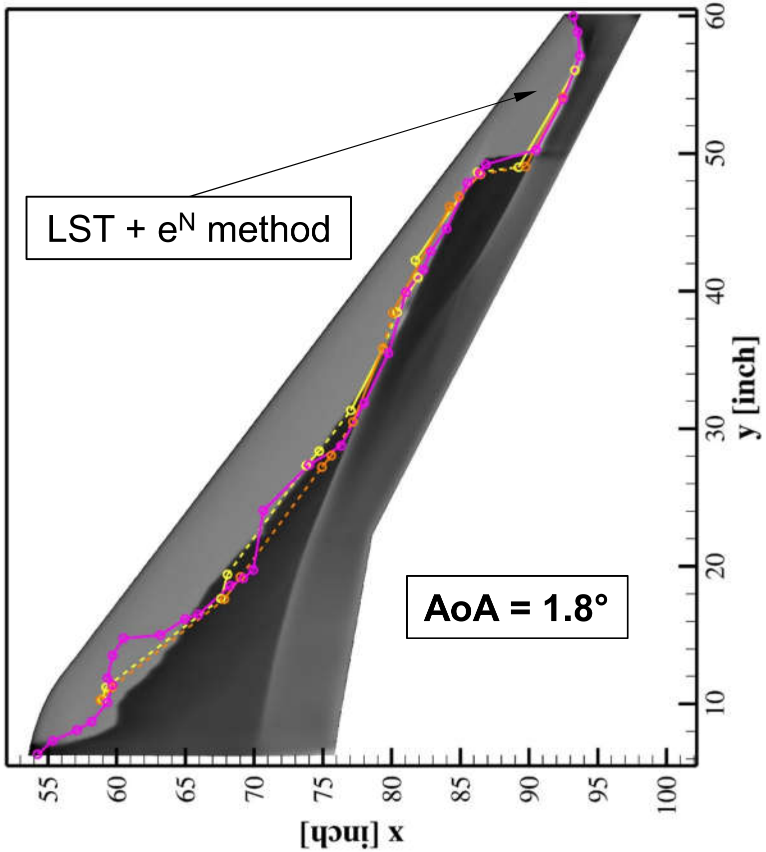
A. Krumbein et al.,"Transport-based Transition Prediction for the Common Research Model Natural Laminar Flow Configuration", Journal of Aircraft, July 2022; AIAA 2022-1541

NASA CRM-NLF Configuration

Sensitivity to angle of attack (AoA)

- **Nominal AoA**
  → AoA = 2.0°
- **Slight change of AoA**
  → AoA = 1.8°
- **e^N method vs. new γ model**



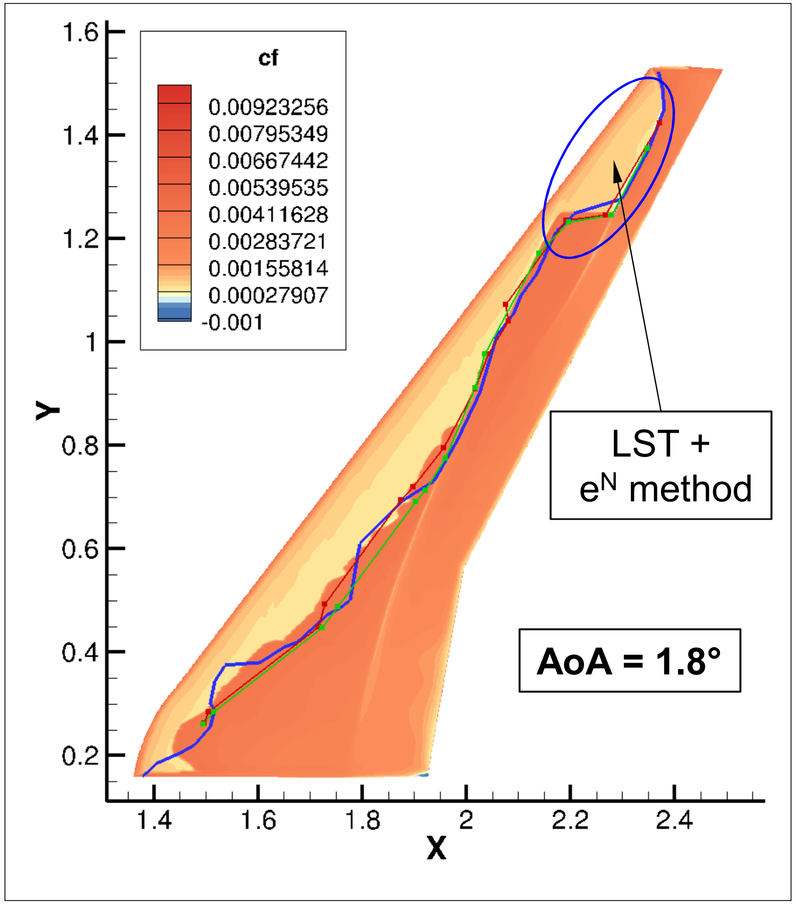


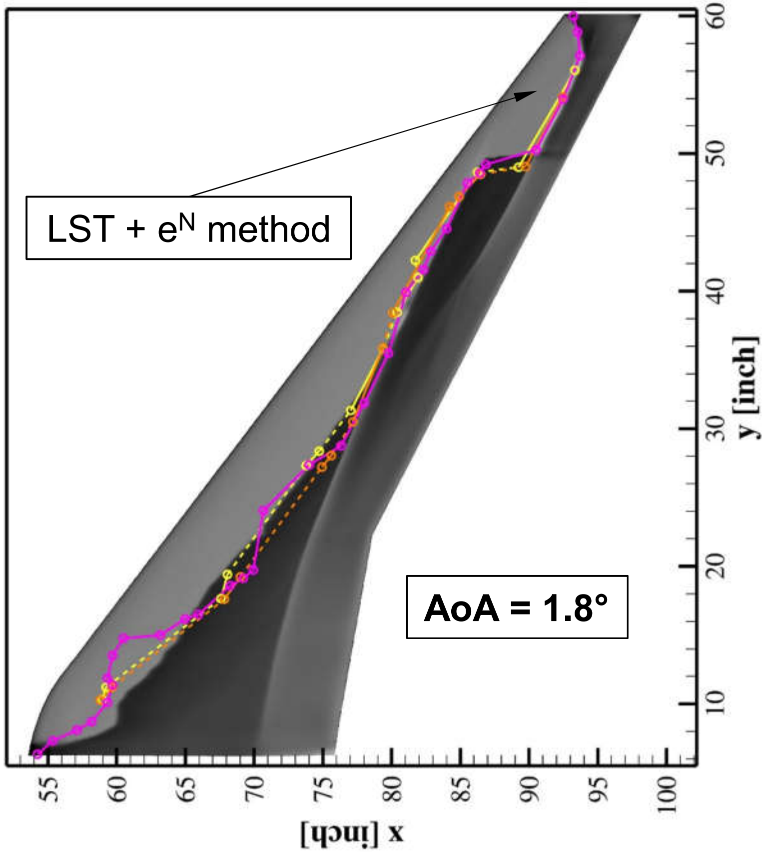
A. Krumbein et al.,"Transport-based Transition Prediction for the Common Research Model Natural Laminar Flow Configuration", Journal of Aircraft, July 2022; AIAA 2022-1541

NASA CRM-NLF Configuration

Sensitivity to angle of attack (AoA)

- **Nominal AoA**
  → AoA = 2.0°
- **Slight change of AoA**
  → AoA = 1.8°
- **e^N method vs. new γ model**
  ➔ *exhibit the same sensitivity at this AoA*





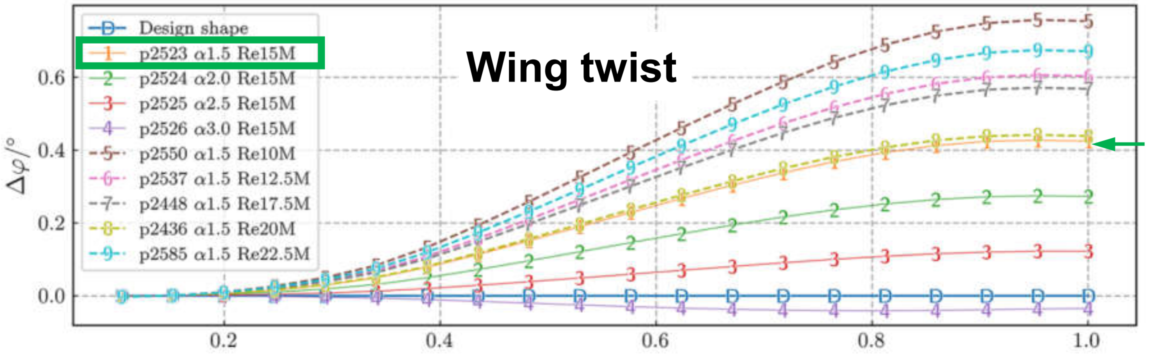
A. Krumbein et al.,"Transport-based Transition Prediction for the Common Research Model Natural Laminar Flow Configuration", Journal of Aircraft, July 2022; AIAA 2022-1541

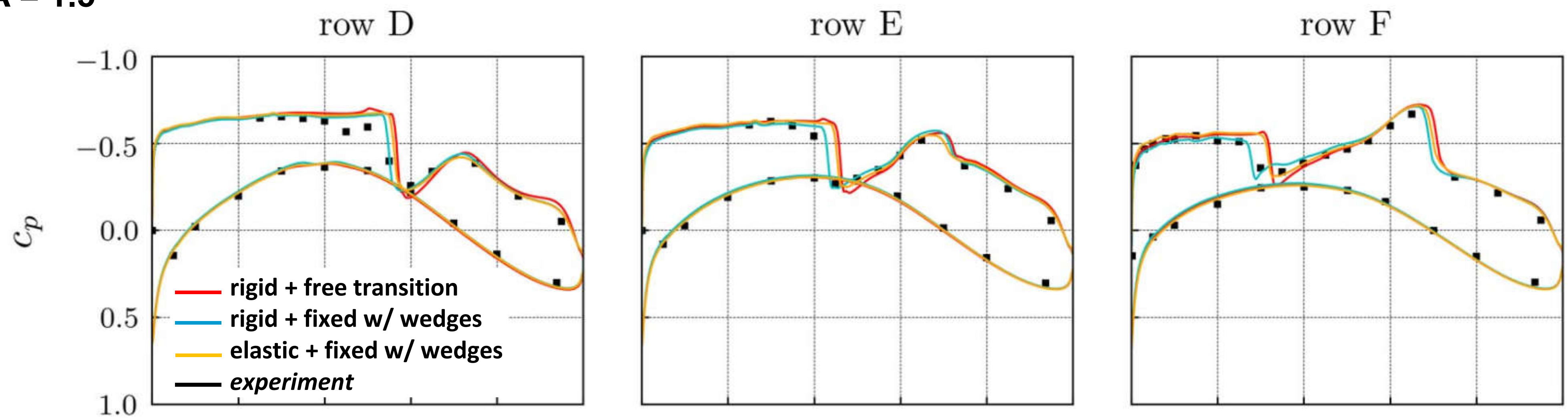
NASA CRM-NLF Configuration

DLR

Wing deformation (CFD-CSM)

- **Simplified structural model**
  - Mass not taken into account
  - Wing-tip bending deflection (design shape vs. jig shape) from model construction was only orientation
- **AoA = 1.5°**





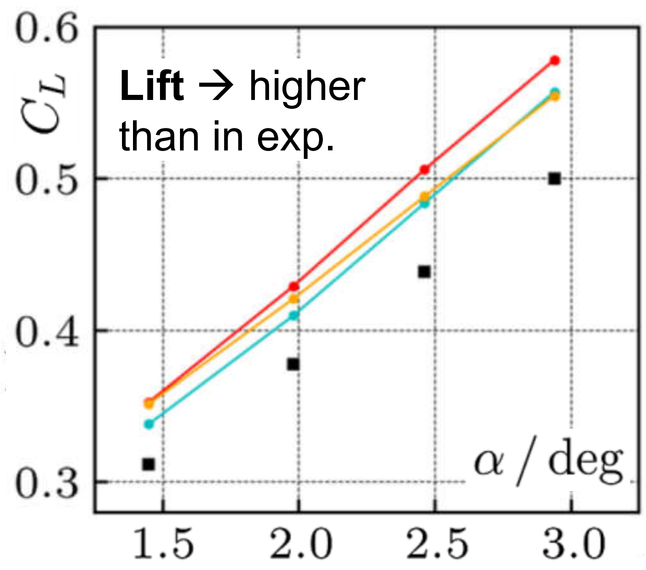
→ Wedges and deformation counteract each other.

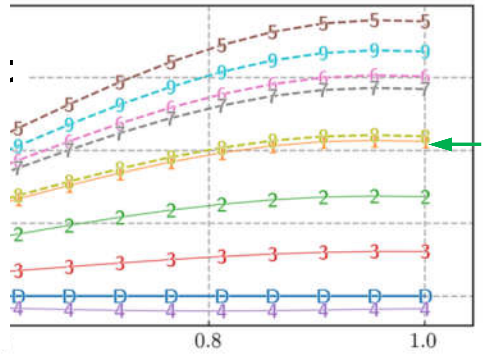
S. Helm et al.,"Numerical Simulation of the Common Research Model with Natural Laminar Flow", Journal of Aircraft, Sep. 2022; AIAA 2021-2503

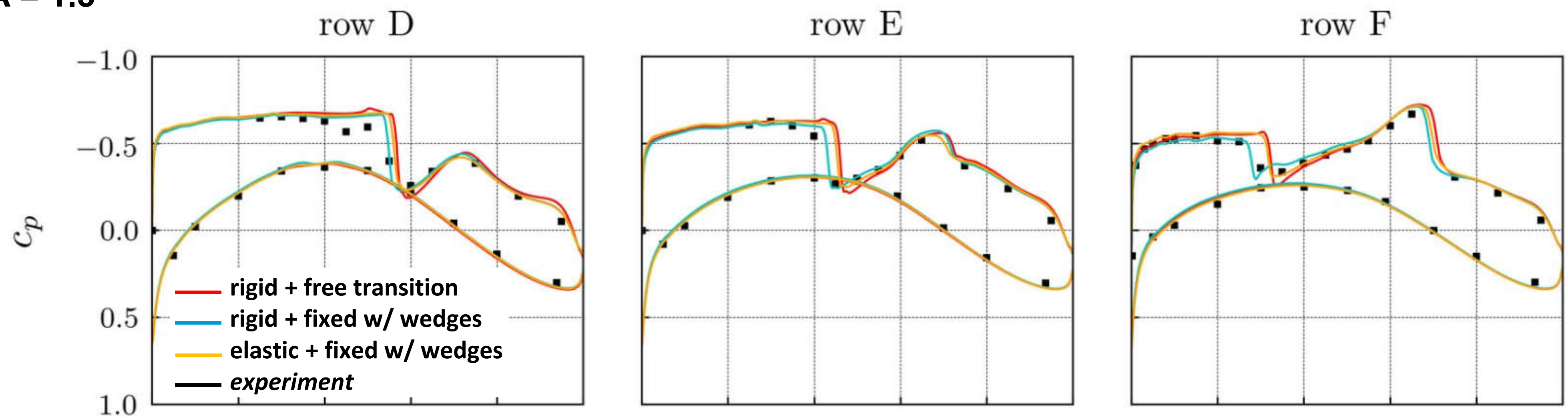
NASA CRM-NLF Configuration

Wing deformation (CFD-CSM)

- **Simplified structural model**
  - Mass not taken into account
  - Wing-tip bending deflection (design shape vs. jig shape) from model construction was only orientation
- **AoA = 1.5°**



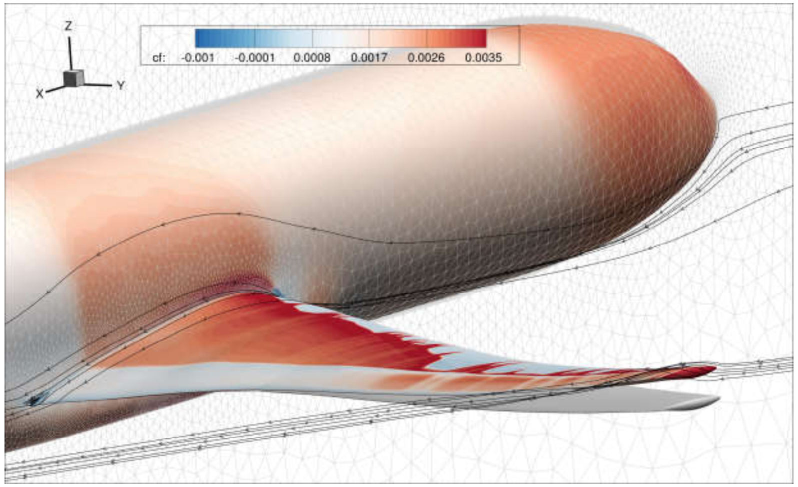




S. Helm et al.,"Numerical Simulation of the Common Research Model with Natural Laminar Flow", Journal of Aircraft, Sep. 2022; AIAA 2021-2503

→ Lift in simulations higher than in experiment → more information and data needed ➔ WT walls, WT corrections, deformed geometry !!!

Conclusions



- New γ-based one-equation transition transport model yields a very close match with
  - Transition fronts derived from the experiments published by different authors using similar but not identical approaches.
  - LST + e^N method
- Both methods indicate CRM-NLF design being dominated by streamwise transition mechanisms, not CF transition
- For validation, consideration of turbulent wedges in the simulation is crucial
- Turbulent wedges and deformation counteract each other
- Lift is higher than in experiment for all refinement steps in the simulations
  ➔ More information and data needed ➔ WT walls, WT corrections, ***deformed geometry***
  - First contacts with NASA: clarification if deformation information can be provided
- Many open questions
  - Visual inspection" of transition fronts → Is the procedure accurate enough?
  - Existence of turbulent wedges at leading edge → What is the reason?