Transition Prediction and Modeling in External Flows Using RANS-based CFD Codes

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Transition Prediction in RANS-based CFD of External Flows

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Introduction
Transition Prediction in RANS-based CFD of External Flows

Current status of transition prediction in RANS solvers

- RANS solvers have become a standard approach for the design and the aerodynamic analysis of aerodynamic configurations.
- Requirement from Aircraft Industry and Research for a long time:
  - RANS solver with integrated general transition prediction functionality
  - Automatic: no intervention of the user
  - Autonomous: as little additional information as possible
- Major aims:
  - Reduction of modeling based uncertainties
  - Improvement of simulation accuracy
- Accuracy of results from fully turbulent computations or from computations with prescribed transition often not satisfactory (e.g. suppression of separation)
- Exploitation of the full potential of advanced turbulence models
- Most important, at present, improved simulation of the interaction between transition locations and separation, especially for high-lift configurations.
Introduction
Transition Prediction in RANS-based CFD of External Flows

Current status of transition prediction in RANS solvers

- Incorporated transition prediction has become a *state-of-the-art* technique for various RANS codes in the last years.
- Details of the concepts are different. They have in common that they are able to be applied to complex geometries: multi-element configurations, full aircraft, high-lift configurations, wind turbines, fuselages, etc.
- Much development and validation work has been carried out and, today, the approaches have gained a high level of confidence.
  - Standard approaches of the transition prediction functionalities regularly used in aircraft industry.
  - Currently, increasing use of advanced approaches at universities and research organizations.
  - Growing computer capacities will allow for more complex geometries and more points.
Introduction
Transition Prediction in RANS-based CFD of External Flows

Currently most commonly used approaches for 3D RANS simulations

- RANS solver + laminar BL code + $e^N$ database methods/empirical criteria
- RANS solver + laminar BL code + automated stability code + $e^N$ methods
- RANS solver + $e^N$ database methods/empirical criteria
- RANS solver + automated stability code + $e^N$ methods
- RANS solver + transition transport equation models
Introduction
Transition Prediction in RANS-based CFD of External Flows

Currently most commonly used approaches for 3D RANS simulations

1. RANS solver + laminar BL code + $e^N$ database methods/empirical criteria

2. RANS solver + laminar BL code + automated stability code + $e^N$ methods
   → standard approach, industrial applications, standard grids can be used: only $c_p$

3. RANS solver + automated stability code + $e^N$ methods
   → advanced approach, accurate in regions where BL codes cannot be applied

4. RANS solver + transition transport equation models
   → $\gamma$-$Re_{\theta,t}$ model by Menter/Langtry works well and yields accurate results for streamwise transition
   → first promising results for CF at infinite swept wings: $\gamma$-$Re_{\theta,t}$-$Re_{52,t}$
Transition Prediction using the $e^N$ method

Structure of the Prediction Approach – Process Chain

- RANS solvers:
  - DLR TAU code
  - DLR FLOWer code
- Transition prescription
- Automatic transition prediction
- 2D and 3D flows
- Parallel
- $e^N$-method (2 N-factor method)
- Various transition criteria
- External codes
  - Stability solver LILO (G. Schrauf)
  - Laminar boundary layer code COCO (G. Schrauf)
Transition Prediction using the e\(N\) method

Structure of the Prediction Approach – Application in 3D

- Transition criteria need laminar boundary-layer data (integral values, velocity profiles)
- Two different approaches:
  - Navier-Stokes data
  - Laminar boundary-layer code
- Application of transition criteria along inviscid streamlines or approximations of streamlines
- Transition points form a polygonal line on a 3D surface of the geometry, the transition line.
- Criteria, for example, AHD, C1, Michel, e\(N\)-method (stability code, envelope methods)

**e\(N\)-method with stability solver LILO**

- 2 N-factors in 3D: TS and CF
- Different strategies
  - Prescribe frequency and propagation direction (TS)
  - Prescribe frequency and wavelength (CF)
- 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 inviscid streamline

Figures: D. Arnal, AGARD AR 709; 1984
Transition Prediction using the $e^N$ method

Structure of the Prediction Approach

Application in 3D

The stability boundary

$N_{TS} \approx 9$

$N_{CF} \approx 12$

Problem for wind tunnels: For most wind tunnels only very limited or no information available which could be used for the validation of transition prediction methods or models

$\rightarrow$ reliable $Tu_\infty$, $N$ factors, transition locations, skin friction distributions, sufficient information on measurement techniques, error bands $\Rightarrow$ high uncertainty level

ELFIN II tests
S1Ma wind tunnel incompressible analysis for transonic flow


Transition Prediction using the $e^N$ method

Structure of the Prediction Approach – Calculation of BL data

- **Internal BL approach**
  - Boundary-layer data from Navier-Stokes solution
  - Projection of BL edge velocities onto surface
  - Integration of edge velocities
  - Inviscid streamlines
  - Moderate (TS) / high (CF) grid resolution
  - Wide range of applications

- **External BL approach**
  - Boundary-layer data from BL code COCO (2.75D)
  - “Line-in-flight” cuts
  - Pressure distribution along cuts
  - Length of inviscid streamline from BL-edge velocities
  - Low grid resolution
  - Limited to high aspect ratio wings
Mapping of transition point information into the computational grid

- **Surface information**
  - Predicted transition line is polygonal line on the surface of the configuration.
  - Linear interpolation for all surface points between two points of a transition line.
  - All points upstream of the transition line are flagged "laminar": $\gamma(P_s) = 0$.
  - All other points are flagged "turbulent": $\gamma(P_s) = 1$.

- **Field information**
  - Every field point knows its distance to the nearest solid wall and its nearest surface point.
  - A crude approximation of the wall-normal extension of the laminar boundary layer is done by generating a laminar zone near the wall.
Transition Prediction using the $e^N$ method

Structure of the Prediction Approach – Laminar Zones

Mapping of transition point information into the computational grid

- An appropriate wall normal distance $d_{\text{lam}}$ for each element of the configuration must be prescribed by the user.
Transition Prediction using the $e^N$ method
Structure of the Prediction Approach – Grid Point Treatment

Treatment of laminar and turbulent points

- **Laminar points**
  - The turbulence model is evaluated also in the laminar regions of the flow field.
  - The source term of any turbulence producing equation is limited for each laminar grid point:
    \[ S(P_{lam}) \leq 0 \]

- **Turbulent points**
  - The unchanged source term of the turbulence model is used.
  - Sudden switch from $\gamma = 0$ to $\gamma = 1$ from one to the next grid point
    \( \Rightarrow \) ‘point transition’

- **Coding**
  - $S^{code} = \min \left[ S, \gamma S \right]$
  - other approaches:
    - $S^{code} = \gamma S$ : source term blanking
    - $S^{code} = \min \left[ P, c D^\gamma \right] - D$: with production limitation, sometimes used for $k-\omega$ models
Transition Prediction using the $e^N$ method

Structure of the Prediction Approach – Parallelization

Parallelization of transition prediction approach

- Major issue in 3D transition prediction: capability to use parallel computation
- Main problem: non-local data is needed $\Rightarrow$ high communication effort

- Parallel computation needed for:
  - Determination of wall normal grid points for the extraction of boundary-layer profiles
  - Calculation of boundary-layer parameters and profiles
  - Calculation of inviscid streamlines and line-in-flight cuts
  - Parallel execution of external, sequential codes (COCO, LILO)

- Parallel computation means: capable to use decomposed solutions, parallel transition analysis whenever possible and reasonable
Transition Prediction using the $e^N$ method
Test Cases & Results – NLF(1)-0416

Natural laminar airfoil

- $M = 0.1$, $Re = 4.0 \times 10^6$, $Tu_\infty = 0.0003 \Rightarrow NT_{Scrit} = 11.0$

- external BL approach
- BL data from BL code
- line-in-flight cuts

Force polars
Transition Prediction using the $e^N$ method
Test Cases & Results – NLF(1)-0416

Natural laminar airfoil

$M = 0.1, \text{Re} = 4.0 \times 10^6, Tu_\infty = 0.0003 \Rightarrow N_{T_{\text{crit}}} = 11.0$

- external BL approach
- BL data from BL code
- line-in-flight cuts

Force polars

Graph showing force polars for different turbulence models:
- experiment – free transition
- fully turbulent – Baldwin-Lomax (FLOWer)
- fully turbulent – Wilcox $k-\omega$ (FLOWer)
Transition Prediction using the $e^N$ method

Test Cases & Results – NLF(1)-0416

Natural laminar airfoil

$\Rightarrow M = 0.1$, $Re = 4.0 \times 10^6$, $Tu_\infty = 0.0003 \Rightarrow N_{T_{crit}} = 11.0$

- external BL approach
- BL data from BL code
- line-in-flight cuts

Force polars

- experiment – free transition
- fully turbulent – Baldwin-Lomax
- fully turbulent – Wilcox $k\omega$
- predicted transition – Baldwin-Lomax
- predicted transition – Wilcox $k\omega$
Transition Prediction using the e^N method

Test Cases & Results – NLF(1)-0416

Natural laminar airfoil

\[ M = 0.1, \, Re = 4.0 \times 10^6, \, T_u = 0.0003 \Rightarrow N_{TS_{crit}} = 11.0 \]
Transition Prediction using the $e^N$ method
Test Cases & Results – NLF(1)-0416

Natural laminar airfoil

$M = 0.1, \ Re = 4.0 \times 10^6, \ Tu_\infty = 0.0003 \Rightarrow N_{T\text{crit}} = 11.0$

Transition locations
Transition Prediction using the $e^N$ method
Test Cases & Results – NLF(1)-0416

Natural laminar airfoil

$M = 0.1, \ Re = 4.0 \times 10^6, \ Tu_\infty = 0.0003 \Rightarrow N_{T\text{crit}} = 11.0$
Transition Prediction using the $e^N$ method

Test Cases & Results – NLF(1)-0416

Natural laminar airfoil

$M = 0.1$, $Re = 4.0 \times 10^6$, $Tu_\infty = 0.0003 \Rightarrow N_{T_{crit}} = 11.0$
Transition Prediction using the $e^N$ method

Test Cases & Results – NLR7301

Two-element airfoil with flap
- $M = 0.185$, $Re = 1.35 \times 10^6$, $\alpha = 6.0^\circ$
- No $T_u \infty$ available $\Rightarrow N_{T_{Scrit}} = 9.0$
- Calibrated by upper main transition point $\Rightarrow N_{T_{Scrit}} = 5.8$

- external BL approach
- BL data from BL code
- line-in-flight cuts

$\Delta c_p$-field and transition locations
Transition Prediction using the $e^N$ method
Test Cases & Results – Swept, tapered wing

Transonic laminar wing
- $M = 0.7$, $Re = 12.0 \times 10^6$, $\alpha = 1.0^\circ$
- $N_{T_{Scrit}} = 11.5$ (free flight)
- feasibility, no validation
- all transition locations slightly downstream of minimum pressure location due to stop of laminar BL code
Transition Prediction using the $e^N$ method
Test Cases & Results

**ONERA M6 wing**
- $M = 0.262$, $Re = 3.5 \times 10^6$

transition lines for 11 wing sections: $\eta = 0.0, 0.11, 0.22, 0.325, 0.42, 0.8, 0.86, 0.9, 0.93, 0.96, 0.975$

*calibration of both $N$ factors for lower side at $\alpha = 5^\circ$:*

- $N_{CF}^{cr} = 5.157 \rightarrow \eta = 0.42$
- $N_{TS}^{cr} = 4.75 \rightarrow \eta = 0.93$

- external BL approach
- BL data from BL code
- line-in-flight cuts
Transition Prediction using the $e^N$ method

Test Cases & Results – DLR F11 (KH3Y)

Wing-Body High-Lift Configuration

- $M = 0.174$, $Re = 1.35 \times 10^6$, $\alpha = 10.0^\circ$, $14.0^\circ$
- $N_{TScrit} = 4.9$, calibration for $\alpha = 10^\circ$ hot film on main wing upper side at 68% span $\rightarrow (x^T/c)_{main} = 0.08$
- no indications for CF $\Rightarrow N_{CFcrit} = N_{TScrit}$

Transition Prediction using the $e^N$ method

- external BL approach
- BL data from BL code
- line-in-flight cuts

Test Cases & Results – DLR F11 (KH3Y)

- external BL approach
- BL data from BL code
- line-in-flight cuts

- block-structured computation
Transition Prediction using the $e^N$ method

Test Cases & Results – DLR F11 (KH3Y)

- external BL approach
- BL data from BL code
- line-in-flight cuts

$c_p$-distributions

$\alpha = 14.0^\circ$

$\eta = 0.20$

$\eta = 0.38$

$\eta = 0.66$

$\eta = 0.88$
Transition Prediction using the $e^N$ method
Test Cases & Results – DLR F11 (KH3Y)

Wing-Body High-Lift Configuration
$M = 0.174, Re = 1.35 \times 10^6, \alpha = 10.0^\circ, 14.0^\circ$

Structured vs. unstructured results

- external BL approach
- BL data from BL code
- line-in-flight cuts

hybrid-unstructured computation

Experiment vs. computation

structured

hybrid

$\alpha = 14^\circ$, upper side

$\alpha = 14^\circ$, upper side

calibration point
for $N_{TS}$

experimental transition locations
Transition Prediction using the e^N method
Test Cases & Results – 6:1 prolate spheroid

Simplified fuselage

- $M = 0.03$
- $Re = 1.5 \times 10^6$
- $\alpha = 10^\circ$

- Determined by numerical investigation
- modeling of the interaction of TS and CF waves
- $N_{TS, crit} = 8.0$, $N_{CF, crit} = 5.5$

TS dominated transition (no interaction of modes)
Transition Prediction using the $e^N$ method
Test Cases & Results – 6:1 prolate spheroid

Simplified fuselage

- $M = 0.13$
- $Re = 6.5 \times 10^6$
- $\alpha = 10^\circ$

- Determined by numerical investigation
- modeling of the interaction of TS and CF waves
- $N_{TS,crit} = 8.0$, $N_{CF,crit} = 5.5$

TS and CF transition (strong interaction of modes)
Transition Prediction using the $e^N$ method

Test Cases & Results – 6:1 prolate spheroid

**Simplified fuselage**
- $M = 0.13$
- $Re = 6.5 \times 10^6$
- $\alpha = 15^\circ$

- Determined by numerical investigation
- Modeling of the interaction of TS and CF waves
- $N_{TS,\text{crit}} = 8.0$, $N_{CF,\text{crit}} = 5.5$

CF dominated transition (slight interaction of modes)
Transition Prediction using the $e^N$ method

Test Cases & Results – Some more examples

Ma = 0.2, Re = 2.3 x 10^6
$\alpha = -4.0^\circ$, $i_h = 4.0^\circ$

Wing-Body with 4-element wing
- 388 cuts overall
- 536 transition predictions per step
- 96 processes

Re = 3.5 x 10^6
Ma = 0.17
$\alpha = 14.0^\circ$

Nacelle of aircraft engine
Re = 3.0 x 10^6
Ma = 0.78
$\alpha = 1.3^\circ$

Wing with winglet
$U_\infty = 50$ m/s
Re = 1.3 x 10^6

Helicopter fuselage
Re = 3.5 x 10^6
Ma = 0.17
$\alpha = 14.0^\circ$
The $\gamma$-Re$_{\theta,t}$ Transport Equation Model
Test Original Model

**Basics of correlation based transition modeling approach**

- Two transport equations with structure similar to turbulence model equation

- A key quantity is the following Reynolds number correlation

$$\frac{Re_{\nu,\text{max}}}{Re_{\theta t}} = 2.193$$

- Correlation of local to non-local quantities

  $$Re_{\nu,\text{max}} = f\left(y, \nu, \frac{du}{dy}\right)$$

  Locally available in a RANS-based CFD Code

  $$Re_{\theta t} = f\left(\theta, \nu, u\right)$$

  Non-local quantity, $\theta$ contains information about transition location

- Approach given by Liepmann (1943) and later by van Driest/Blumer (1963):

  „If the ratio of turbulent stress to viscous stress will reach a certain value in the boundary layer, transition will take place.“
The $\gamma$-$Re_{\theta,t}$ Transport Equation Model
Test Original Model

Basics of correlation based transition modeling approach

\[
\frac{\tau_{\text{turb}}}{\tau_{\text{visc}}} = \frac{\rho u'u'}{\mu \frac{du}{dy}} = \frac{\rho y^2 \left( \frac{du}{dy} \right)^2}{\mu \frac{du}{dy}} = \frac{y^2 du}{\nu \frac{dy}{\nu}}
\]

Uses mixing length approach and the wall distance $y$ as the characteristic mixing length.

- Stress ratio at transition onset

- Usage of Pohlhausen approximation for boundary layer velocity $u$, some transformations and the choice of a suitable transition criterion, e.g.

\[
Re^*_{\theta_t} = f(Tu, \lambda)
\]

lead to

\[
\frac{Re_{\nu,x,max}}{Re_{\theta_t}} = 2.193
\]
The $\gamma$-$Re_{\theta,t}$ Transport Equation Model

Test Original Model

- **Intermittency** transport equation (fraction of time the flow is turbulent compared to a total time, $\gamma = 0$: laminar flow, $\gamma = 1$: turbulent flow)

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

- **Production**
  \[P_\gamma = f \left( F_{\text{onset}}, F_{\text{length}}, \gamma, \rho, S, c_i \right)\]

- **Destruction**
  \[D_\gamma = f \left( F_{\text{turb}}, \gamma, \rho, \Omega, c_i \right)\]

\[F_{\text{onset}} = f \left( Re_\nu / Re_{\theta c}/2.193, \mu_t / \mu \right)\]

\[F_{\text{length}} = f \left( \tilde{Re}_{\theta t} \right)\]

\[F_{\text{turb}} = f \left( \mu_t / \mu \right)\]

triggers $\gamma$ production

defines length of transition region

destroys $\gamma$ values where $\mu_t / \mu$ is very low
The $\gamma$-$Re_{\theta,t}$ Transport Equation Model

Test Original Model

- Transport equation for the Reynolds number based on momentum thickness at transition onset

$$\frac{\partial \left( \rho \tilde{Re}_{\theta t} \right)}{\partial t} + \frac{\partial \left( \rho u_i \tilde{Re}_{\theta t} \right)}{\partial x_j} = P_\theta + \frac{\partial}{\partial x_j} \left[ \sigma_\theta (\mu + \mu_t) \frac{\partial \tilde{Re}_{\theta t}}{\partial x_j} \right]$$

- Production/Destruction

$$P_\theta = f \left( Re_{\theta t}^*, \tilde{Re}_{\theta t}, F_\theta, c_i \right)$$

$F_\theta$: boundary-layer detector switches on/off $P_\theta$ inside/outside BL

$Re_{\theta t}^* = f \left( T_u, \lambda \right)$: empirical transition criterion
The intermittency is coupled to the production and destruction terms of the k-equation of the Menter SST k-ω turbulence model. 

\[ P_k^* = \gamma_{\text{eff}} P_k \]
\[ D_k^* = \min(\max(\gamma_{\text{eff}}, 0.1), 1.0) D_k \]

\[ \gamma_{\text{eff}} = \max[\gamma, \gamma_{\text{sep}}] \]

From a technical point of view, the model is suitable for any type of RANS solver and for arbitrary 3D geometrical configurations and any kind of flow. It covers streamwise transition mechanisms, such as Tollmien-Schlichting-like transition, by-pass transition and separation induces transition. It does not cover cross flow (CF) transition, typical for 3D flows.
The $\gamma$-$Re_{\theta,t}$ Transport Equation Model
Test Cases & Results – AS-A & NLF(1)-0416

- The $\gamma$-$Re_{\theta,t}$ model was implemented into the DLR TAU code and validated on various two-dimensional test cases like the AS-A airfoil and the NLF(1)-0416 airfoil.

AS-A airfoil

NLF(1)-0416 airfoil
The $\gamma$-$Re_{\theta,t}$ Transport Equation Model
Test Cases & Results – 6:1 prolate spheroid

$\triangleright$ $c_f$-distribution for $Re = 1.5 \times 10^6$, $M = 0.03$, $\alpha = 5^\circ$ pure TS transition

$\triangleright$ $c_f$-distribution for $Re = 1.5 \times 10^6$, $M = 0.03$, $\alpha = 10^\circ$ pure TS transition
The $\gamma$-$Re_{\theta,t}$ Transport Equation Model
Test Cases & Results – 6:1 prolate spheroid

- $c_f$-distribution for $Re = 6.5 \times 10^6$, $M = 0.13$, $\alpha = 5^\circ$  
  TS + CF transition

- $c_f$-distribution for $Re = 6.5 \times 10^6$, $M = 0.136$, $\alpha = 15^\circ$  
  pure CF transition
The $\gamma$-$\text{Re}_{\theta,t}$ Transport Equation Model
Extension to Three-dimensional Flows

- The approach of the original model was transferred to the spanwise flow direction.

- As no analytical approximation exists for the velocity profile in crossflow direction, the Falkner-Skan-Cooke (FSC) similarity solution was used to approximate the velocity profiles in three-dimensional boundary layers.

- $C_1$ transition criterion for CF transition: $Re_{\delta_2} = Re_{\delta_2}(H), H = \delta_1/\Theta$

- The same formalism as for the original model leads to:

\[ \frac{Re_{\nu,z,\text{max}}}{Re_{\delta_2}} = f(\vartheta, \text{FSC} - \text{eq.} (\beta_h)) \]

$\delta_1$: displacement thickness of streamwise velocity profile
$\Theta$: momentum loss thickness of streamwise velocity profile
$\delta_2$: displacement thickness of cross flow velocity profile

Local sweep angle of stream line

Hartree parameter of the FSC equations contains the streamwise pressure gradient

Here, two ordinary coupled differential equations – the FSC equations – are solved numerically at each grid point.
The $\gamma$-$Re_{\theta,t}$ Transport Equation Model
Extension to Three-dimensional Flows

ONERA D – infinite swept wing (2.5D)
- Low $M$, $Re = 1.0 \times 10^6$ & $1.5 \times 10^6$, $\alpha = -6^\circ$, $40^\circ < \Phi_\infty < 60^\circ$
- Pure CF transition

![Graphs showing $(x/c)_{tr}$ vs $\Phi_\infty$ for different $Re$ values]
The $\gamma$-$Re_{\theta,t}$ Transport Equation Model
Extension to Three-dimensional Flows

NLF(2)-0415 – infinite swept wing (2.5D)

- Low $M$, $Re = 1.93 \times 10^6$ & $3.7 \times 10^6$, $\alpha = -6^\circ$, $\Phi_{\infty} = 45^\circ$
- For $Re > 2.3 \times 10^6$, transition is dominated by CF instability
Conclusion
Transition Prediction in RANS-based CFD of External Flows

- Two transition prediction approaches for external flows of high potential have been presented
  - $e^N$ method, evaluated along line-in-flight cuts or streamlines using different concepts of calculation of laminar boundary-layer data (1)
  - $\gamma$-$\text{Re}_{0,t}$ transport equation model (2)
- Both can be applied to general, complex geometries in parallel computation environments
  - (1) covering more transition mechanisms and a larger applicability range of the transition criteria
  - (2) offering more flexibility from a technical and practical application point of view
- (1) yielding a high level of maturity and confidence in the method
- (2) having a high potential of being a complementary method for extremely complex configurations in certain flow environments
Outlook
Transition Prediction in RANS-based CFD of External Flows

- (1) with streamline computation and RANS-based BL-data computation not yet push-button-technique for everyday use in industry, but an expert approach.
  - Industrialization has started currently.
- (2) is a rather new approach, still missing comprehensive experience and knowledge on the model behaviour in different situations (flow parameters, grid influence, settings of far-field BCs, numerical stability).
  - $\gamma$-$Re_{\theta,t}$ approach has to be extended to
    - other turbulence models: mid term goal is coupling to RSMs
    - 3D transition mechanisms: CF started, ALT still to be tackled
  - $\gamma$-$Re_{\theta,t}$-$Re_{\delta 2t}$ model to be tested on relevant 3D configurations
    - the ONERA M6 wing
    - the TELFONA (EU project) configurations tested in ETW
  - $\gamma$-$Re_{\theta,t}$-$Re_{\delta 2t}$ model has to be calibrated to a wide range of flows.
  - In aircraft aerodynamics at DLR, the $\gamma$-$Re_{\theta t}$ model only „survives“, if it is able to predict transition due to CF instabilities.