Transition Modeling Activities at AS-C²A²S²E (DLR)

Andreas Krumbein

German Aerospace Center (DLR)
Institute of Aerodynamics and Flow Technology (AS)
*C²A²S²E - Center for Computer Applications in AeroSpace Science and Engineering*

CFD Transition Modeling Discussion Group Meeting
7 June 2017, Denver (CO)
AIAA Aviation 2017
Transition Modeling Activities at C²A²S²E – Chart 2 • AIAA Aviation 2017 • A. Krumbein • 7 June 2017

Overview

- C²A²S²E – Numerical Methods Branch → CFD Code Development
  - **TAU code** – external aerodynamics, compressible
    → air vehicles
  - **THETA code** – internal/external flows, incompressible
    → combustion, wind turbines
  - **Flucs code** – external aerodynamics, compressible/incompressible
    → 2\textsuperscript{nd} order FV branch + HO-DG-branch
    → massive hybrid parallelization
    → development currently ongoing
    → 1\textsuperscript{st} release planned for 12/2019

- Main Customers
  - Internal: Transport Aircraft, Helicopters (incl. Wind Turbines), High-Speed Configurations, Spacecraft
  - External: Airbus Operations
Vision: The Digital Aircraft

Numerical Analysis of Full Flight Envelope

- **Today**, very reliable results for design point applications.
- **Tomorrow**, same reliability needed for complete flight envelope.
  - Strong non-linearities
    - Separated flow regions
    - Strong shocks
    - Shock/boundary-layer interaction
  - Unsteady flows
- In general, all **major physical phenomena** must be captured with sufficient accuracy.
  - Flow separation, BL representation, shock/BL interaction, …
  - Vortices, wakes, free shear layers, engine jets, …
- CFD capabilities growing: discretization schemes, HPC capacities, grid generation, higher resolution, geometrical complexity and details, …
  - **Turbulence** and **transition models** are becoming weakest link in simulation chain.
  - Reliable **models are a key technology** in CFD.

Grey gradient indicates level of confidence in CFD flow solutions
Fundamental Needs

Transition Prediction Capabilities in CFD Codes

- Applicable to **complex configurations**
- High level of **automation**, usable within simulation chains and multi-disciplinary simulation frameworks
  - No interference by code user
  - As little *a priori* knowledge as possible
  - Must be run in parallel on HPC clusters

- Transition mechanisms
  - **Crossflow, Tollmien-Schlichting, separation-induced, by-pass transition**

- **Accuracy** of simulation results
  - Point of transition onset, interaction with turbulence model
  - Impact on major flow quantities and properties: $c_p$, $c_f$, heat flux, separation/reattachment lines, size of separation, …

- **Stability** and **robustness** of implementation/procedure

- **User acceptance**

- **Large application range**
  - Steady RANS, unsteady RANS, rotating systems, SRS
Fundamental Needs

Transition Prediction Capabilities in CFD Codes

- More than one method necessary to satisfy the wide range of requirements.
  - **Streamline-based** approaches using a simplified *two-N-factor strategy* + by-pass criterion
    - Different ways of BL computation
      - Based on RANS solution and RANS grid
      - Laminar BL code
    - $\gamma$-$Re_\theta$ transport equation model + DLR *crossflow (CF) extension*
  - Complementary use of the different approaches for different applications, e.g.
    - Laminar flow design and analysis using *two-N-factor strategy*
    - Massively unsteady flows (e.g. with rotation) using $\gamma$-$Re_\theta$-CF model
**TAU Transition Prediction Module**

**Streamline-based approaches & two-N-factor strategy**

耦合于TAU代码与过渡预测模块
TAU Transition Prediction Module

Streamline-based approaches & two-N-factor strategy

- Internal structure of transition prediction module

**TAU Transition Prediction Module**

- **Streamline-based approaches & two-N-factor strategy**
  - **Internal structure of transition prediction module**

  - **determination of BL-edge velocities**
  - **calculation of streamlines**
  - **BL profiles along streamlines**
  - **extraction of $c_p$ along line-in-flight cuts**
  - **BL profiles**

  - **Calculation of BL profiles**
  - **$c_p$ - distribution sweep angles flow conditions**

  - **BL code COCO**

  - **Conical laminar BL code**
    - **swept, tapered wings**

  - **Line-in-flight cuts** (strip theory)
    - Accurate results for swept tapered wings.
    - Two sides (upper/lower) per cut, divided by stagnation/attachment line point

  - **Inviscid streamlines**
    - Necessary for fuselages, nacelles etc.
    - Start at attachment line
      - Attachment line must be determined too.
    - Suggests separate treatment of upper and lower sides

  - **Execution of the stability code along these lines**
    - One single transition point per cutside/line.
    - Transition line is a polygonal line on the surface.

  - **Fully automated local, linear stability code**
    - Frequency + wave length estimators for automation

- **Internal structure of transition prediction module**

- **Line-in-flight cuts (strip theory)**
  - Accurate results for swept tapered wings.
  - Two sides (upper/lower) per cut, divided by stagnation/attachment line point

- **Inviscid streamlines**
  - Necessary for fuselages, nacelles etc.
  - Start at attachment line
    - Attachment line must be determined too.
  - Suggests separate treatment of upper and lower sides

- **Execution of the stability code along these lines**
  - One single transition point per cutside/line.
  - Transition line is a polygonal line on the surface.

- **Fully automated local, linear stability code**
  - Frequency + wave length estimators for automation
**TAU Transition Prediction Module**

**Streamline-based approaches & two-N-factor strategy**

- Technical feasibility
  - Wing-body configuration with 4-element high-lift wing
  - \( Re = 3.5 \times 10^6, \ Ma = 0.17, \alpha = 14.0^\circ \), only T-S considered
  - 138 cuts@slat 148 cuts@wing, 29/73 cuts@flap
  - 388 cuts overall, 536 transition points (\( \approx 50 \) cuts usually used for these type of configuration)

- 536 calls of BL code and stability code
- 96 processes
- Computations stable and reliable on HPC clusters
TAU Transition Prediction Module

Streamline-based approaches & two-N-factor strategy

- Validation
  - Inclined prolate 6:1 spheroid: Re = 6.5x10^6, Ma = 0.13, \( \alpha = 15.0^\circ \)
  - CF-dominated
TAU Transition Prediction Module

Streamline-based approaches & two-N-factor strategy

- Impact on CFD results
  - DLR A320 D-ATRA high-lift landing configuration
  - Re = 17x10^6, Ma = 0.2
  - Two different grids

\( \alpha = 10.0^\circ \)
TAU Transition Prediction Module

Streamline-based approaches & two-N-factor strategy

- Impact on CFD results
  - DLR A320 D-ATRA high-lift landing configuration
  - Re = $17 \times 10^6$, Ma = 0.2
  - Two different grids

\[ \Delta C_L \text{ between computations: fully-turbulent vs. predicted transition} \]

Impact of transition on $C_L$ in fully-turbulent design @ high lift
\( \gamma\)-Re\(_{\theta}\)-CF Model

**Crossflow extension of \( \gamma\)-Re\(_{\theta}\) model**

- Published 06/2016 in conjunction with Menter SST k-\( \omega \)
- Based on helicity Re number \( Re_{He} = \frac{y^2}{\nu He/||u||} \)
- \( Re_{\delta_2c}(H) \) and \( Re_{He}(H) \) qualitatively very similar
- Calibration of \( Re_{He, tr}(H) \) using ISW standard cases
- Find empirical fully-local correlation function for shape factor \( H \)
\( \gamma-\text{Re}_\theta-\text{CF Model} \)

Crossflow extension of \( \gamma-\text{Re}_\theta \) model

<table>
<thead>
<tr>
<th>( \alpha = 10^\circ )</th>
<th>( \alpha = 24^\circ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M = 0.13, \text{Re} = 6.5 \times 10^6 )</td>
<td>( \text{Ma} = 0.136 )</td>
</tr>
</tbody>
</table>

\( C_f \) vs. \( x/L \)

- \( \gamma-\text{Re}_\theta \) SST
- \( \gamma-\text{Re}_\theta \) SST-CF

Calibrate \( \text{Re}_{\text{He},\text{tr}}(H) \) using ISW standard cases
Find empirical local correlation function for shape factor

\( \text{Re}_{\text{He}} = \frac{y^2}{\nu} \)

\( \text{Re}_{\delta^2c(H)} \) and \( \text{Re}_{\text{He}}(H) \) qualitatively very similar

Compute test cases:
- Inclined prolate 6:1 spheroid
- Different \( M, \text{Re} \) and \( \alpha \)

\( \alpha = 10^\circ \): \( \text{Ma} = 0.136, \text{Re} = 6.5 \times 10^6 \)
Crossflow extension of $\gamma$-$Re_\theta$ model

Until now, direct application of $C_1$ in $\gamma$-$Re_\theta$-CF model only for wing-like components. Development of a modified model variant

Use of helicity

$He = u \cdot (\nabla \times u)$

Definition of helicity $Re$ number

$Re_{He} = \frac{y^2}{\nu}$

$He / ||u||$

$Re_{\delta_2c(H)}$ and $Re_{He(H)}$ qualitatively very similar

Calibrate $Re_{He,tr(H)}$ using ISW standard cases

Find empirical local correlation function for shape factor $H$

Compute test cases:

Inclined prolate 6:1 spheroid

Different $M$, $Re = 6.5 \times 10^6$

$\alpha = 24^\circ$

Still room for improvement.
**γ-\( \text{Re}_\theta \)-CF Model**

**Sickle-shaped wing** (Petzold and Radespiel, 2015)
- Well documented, pressure distributions & transition locations
- Surface roughness and turbulence intensity given
- \( \text{Re}_c = 2.75 \times 10^6, \alpha = -2.6, M = 0.16 \)
♫-Re$_\theta$-CF Model

Sickle-shaped wing

Upper side

Lower side
**γ-\(\text{Re}_\theta\)-CF Model**

**Coupling to SSG/LRR-\(\omega\) DRSM** → PhD thesis just finalized

- \(\gamma\)-\(\text{Re}_\theta\) + \(\gamma\)-\(\text{Re}_\theta\)-CF models: model functions newly calibrated
- 2 publications underway
- MBB VA-2 airfoil: \(M = 0.2, \text{Re} = 2.0 \times 10^6, \alpha = 3.5^\circ \text{ and } 7.5^\circ\)

**Improvement:** Good results for the two angles of attack for \(\gamma\)-\(\text{Re}_\theta\)-RSM using consistent setting of FSTI (identical values) in contrast to \(\gamma\)-\(\text{Re}_\theta\)-SST (different values necessary)
Open Issues & Future Plans

Streamline-based approaches & two-N-factor strategy

- Intermittency function to be implemented
  - Currently only ‘point-transition‘ at point of transition onset
  - Probably, for every turbulence model an individual calibration necessary
- Linear PSE + compressible analysis + curvature: ???
  - Instead of, currently, incompressible analysis using LST
  - Is it possible/reasonable/reliable for more than infinite swept wing?
  - Currently under discussion
- Programming of a ‘new’ python-based version of the transition module
  - Currently available for TAU and THETA, via library
  - Coupling of the new module the multi-disciplinary simulation environment FlowSimulator
    - Couples new transition module to TAU, THETA, Flucs (and potentially other CFD codes)
    - Couples CFD to CSM and Flight Mechanics
  - This will be a major effort!
Open Issues & Future Plans

$\gamma$-$Re_\theta$-CF Model

- Improvement of CF extension
- Rotor applications $\rightarrow$ modifications for rotating systems
- Galilei invariance $\rightarrow$ focus on helicity-based CF extension
- Improvement of the stream-wise criterion for high Reynolds numbers

both approaches

- Extension for Hybrid-laminar Flow Control (HLFC)
  - Started for streamline-based approaches $\rightarrow$ validation of suction BCs
  - For $\gamma$-$Re_\theta$-CF: fully open!
- Incorporation of surface roughness, steps and gaps, waviness
- Coupling, verification, validation, application with scale-resolving simulation methods (HRLM, SAS)
- ...

Transition Modeling Activities at C²A²S²E • Chart 19 • AIAA Aviation 2017 • A. Krumbein • 7 June 2017
CFD Transition Modeling Discussion Group Meeting

Some thoughts

- Verification of implemented models/approaches necessary


- For transport equation approaches: concept could be adopted as is
  - $\gamma$-$Re_\theta$(-CF), AFT, $\gamma$(-CF), laminar kinetic energy, ...
  - Documentation of approaches would be necessary.

- For approaches using a point of transition onset:
  - Numerical treatment of laminar and transitional points in the computational grid must be verified
  - Fixed/prescribed transition
  - $e^N$ methods, empirical criteria, ...
  - Point transition vs. intermittency functions
  - ...
Some thoughts

Before all this: Verification of the turbulence model used in conjunction with any transition model MUST be verified!

Test Cases

Need for cases with sufficient and reliable measurement data relevant for transition

- Point of transition, transition region, end of transition region
- \( c_{-} \)-distribution
- Wind tunnel turbulence intensities including variations in test section
- Measurement uncertainties, error bars
- Definition of the ‘transition point’
- ...

More 3D cases

- JAXA JSM
- HL-CRM
- NLF-CRM
- ...

CFD Transition Modeling Discussion Group Meeting