Validation of intermittency model for transition prediction in a RANS flow solver

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*Presented at AIAA SciTech 2018, 8-12 January 2018, Kissimmee (Florida)
Outline

• Introduction and motivations

• Numerical framework
  ✓ Flow solver
  ✓ Transition model

• Validation
  ✓ Flat plate (ERCOFTAC T3A and T3B)

• Applications
  ✓ S809 Airfoil
  ✓ Prolate Spheroid

• Concluding Remarks
Introduction

• Address the issue of transition phenomenon in RANS simulations
  ✓ Location and region

• Improve simulation capabilities of in-house RANS flow solver
  ✓ Transition prediction
  ✓ Simulation of free-transition flows

• Assessment of transition model
RANS Flow solver

UZEN Code

- Flow Solver for steady and unsteady Euler, and RANS equations
- Spatial Discretization
  - Structured Multi-Block, Finite Volume
  - Cell Centered with blended 2\textsuperscript{nd} and 4\textsuperscript{th} order artificial dissipation
- Dual-Time Stepping for unsteady flows
- Time Advancement for steady flows
  - Runge-Kutta with multigrid, local time-stepping, residual averaging
- Turbulence Models
  - Baldwin-Lomax
  - Spalart-Allmaras
  - Myong-Kasagi, NLEV (Shih formulation) \( \kappa-\epsilon \)
  - \( \kappa-\omega \) : Wilcox, Kok TNT, Menter BSL and SST, SST-LR
  - DES for SA and \( \kappa-\omega \) SST
  - XLES for \( \kappa-\omega \) TNT
Transport equation for intermittency

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

\[P_\gamma = F_{\text{length}} \rho S_\gamma (1 - \gamma) F_{\text{onset}}\]

\[D_\gamma = c_{a2} \rho \Omega \gamma F_{\text{turb}} (c_{e2} \gamma - 1)\]

SST turbulence model interaction

\[
\frac{\partial \rho \kappa}{\partial t} + \frac{\partial \rho U_j \kappa}{\partial x_j} = \gamma P_\kappa + P_{\kappa}^{\text{lim}} - \max(\gamma, 0.1) D_\kappa + \frac{\partial}{\partial x_j} \left[ (\mu + \sigma_\kappa \mu_t) \frac{\partial \kappa}{\partial x_j} \right]
\]

\[P_{\kappa}^{\text{lim}} \] is an additional production term
Transition Model

Triggering functions

\[ F_{\text{onset1}} = \frac{Re_v}{C_{\text{onset}} Re_{\theta c}} \]

\[ Re_{\theta c}(Tu_L, \lambda_{\theta L}) = C_{Tu1} + C_{Tu2} \exp[-C_{Tu3} Tu_L F_{PG}(\lambda_{\theta L})] \]

Original model

\[ C_{\text{onset}} = 2.2 \]
\[ C_{Tu1} = 100.00 \]
\[ C_{Tu2} = 1000.00 \]

Modified model

\[ C_{\text{onset}} = \min \left\{ 4.84, \max \left[ 2.2, 1.388 \ln(Re \times 10^{-6}) + 0.705 \right] \right\} \]
\[ 1 \times 10^6 \leq Re \leq 15 \times 10^6 \]
\[ C_{Tu1} = 163.00 \]
\[ C_{Tu2} = 1002.25 \]

Test cases

• Validation
  - ZPG Flat plate
    - \( \text{\textit{T3A & T3B ERCOFTAC T3 Series}^1} \)

• 2D Flow
  - S809 airfoil\(^2\)
    - Incompressible flow at \( \text{Re}=2.0\times10^6 \) and \( \alpha=1^\circ, 6^\circ, 9^\circ \)

• 3D flow:
  - 6:1 prolate spheroid\(^3\)
    - Incompressible flow at \( \text{Re}=2.0\times10^6 \) and \( \alpha=5^\circ, 10^\circ, 15^\circ \)

1. Coupland, J., “ERCOFTAC special interest group on laminar to turbulent transition and retransition: T3A and T3B test cases,” A309514, 1990
ZPG Flat plate

T3A
- $M = 0.0152$
- $Re = 5.67 \times 10^5$ (on a length $L = 1.6$ m)
- $Tu = 3.3\%$
- $\mu_t/\mu = 12.0$

T3B
- $M = 0.0276$
- $Re = 1.03 \times 10^6$ (on a length $L = 1.6$ m)
- $Tu = 6.0\%$
- $\mu_t/\mu = 90.0$

Grid:
2 blocks structured type
Rectangular domain $\Omega = [-0.2, 1.6] \times [0, 0.3]$ (flat plate starts at $x = 0$)
Three grid levels (40256 cells on fine mesh)
Limiter on turbulence variables

\[ \kappa \geq \kappa_{fs}, \omega \geq 10 \frac{U_{\infty}}{L_{ref}} \]

Both laminar and transition region are missed

Clear improvement in flow computation between “fully turbulent” and “transitional” simulations
Transition detected at about $x=0.6$ ($x/L=0.37$)
Transition detected at about $x=0.6$ ($x/L=0.37$)

$\gamma$ distribution at wall
T3A flat plate

Intermittency function field

Transition detected at about $x=0.6$ ($x/L=0.37$)

$\gamma$ distribution at wall

Effect on eddy viscosity field
T3A flat plate

Effect of free-stream turbulence

Lowering freestream eddy viscosity ratio: delayed transition onset

Lowering freestream turbulence intensity: no transition (fully laminar)
• $M = 0.0276$
• $Re = 1.03 \times 10^6 \text{ (on a length } L = 1.6 \text{ m)}$
• $Tu = 6.0\%$
• $\mu_t/\mu = 90.0$

Transition onset detected downstream
Transition region predicted satisfactorily
Turbulent region well predicted
**S809 Airfoil**

The S809 is a 21\%-thick, laminar-flow airfoil designed for horizontal-axis wind-turbine applications. Short laminar bubbles at high Reynolds number

- $M=0.10$
- $Re=2.00 \times 10^6$ (on a length $L = 1.0 \text{ m}$)
- $\alpha=1^\circ, 6^\circ, 9^\circ$
- $Tu=0.07\%$
- $\mu_t/\mu=0.1$

Grid:

C topology, single block structured type

Farfield set at 1000 chords

Three grid levels (152064 cells on fine mesh)
S809 Airfoil

Good agreement with the experimental data for all grid levels

Laminar bubbles detected on both upper and lower surfaces

Refining the mesh improves the accuracy in modeling the bubble

<table>
<thead>
<tr>
<th></th>
<th>$C_l$</th>
<th>$C_d_{tot}$</th>
<th>$C_m$</th>
<th>$x_{tr}$, upper side</th>
<th>$x_{tr}$, lower side</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXP</td>
<td>0.2673</td>
<td>7.149E-02</td>
<td>-0.0491</td>
<td>0.55</td>
<td>0.50</td>
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<tr>
<td>Coarse</td>
<td>0.2823</td>
<td>6.350E-02</td>
<td>-0.04898</td>
<td>0.53</td>
<td>0.49</td>
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<tr>
<td>Medium</td>
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<td>6.320E-02</td>
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<td>0.48</td>
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<td>6.304E-02</td>
<td>-0.04881</td>
<td>0.54</td>
<td>0.49</td>
</tr>
</tbody>
</table>
Good agreement with the experimental data for all grid levels

Transition on the upper side is predicted downstream with respect to experiments

Delayed transition induces a bubble that is not observed in the experimental data
S809 Airfoil

S809 - $\alpha = 9^\circ$

Slight over-prediction on upper side

A bubble, not clearly visible in the experimental data, is returned by numerical simulation on the leading edge region

<table>
<thead>
<tr>
<th></th>
<th>$C_l$</th>
<th>$C_{d,\text{tot}}$</th>
<th>$C_m$</th>
<th>$x_{tr}$, upper side</th>
<th>$x_{tr}$, lower side</th>
</tr>
</thead>
<tbody>
<tr>
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<td>N/A</td>
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<td>Fine</td>
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<td>0.1474E-01</td>
<td>-0.0569</td>
<td>0.03</td>
<td>0.53</td>
</tr>
</tbody>
</table>
S809 Airfoil

Transition location

Lower side:
- Numerical results match experimental data

Upper side:
- Sudden upstream movement of transition location with \( \alpha \) present in both experiments and CFD
- Original model: good agreement except for \( \alpha = 6^\circ \) and \( \alpha = 7^\circ \)
- Modified model: betters solutions at \( \alpha = 6^\circ \) and \( \alpha = 7^\circ \) but worsens at \( \alpha = 8^\circ \)
$C_d$ and $C_l$ show a shift wrt experimental data

Fully turbulent results (red line) provide a higher drag coefficient than the experimental one

Original transition model (blue line) good comparison up to $C_l=0.8$

Transition model with modification proposed by Colonia et al.$^{1,2}$ (green line) are comparable with the original model.

6:1 Prolate spheroid

- $M=0.13$
- $Re=6.50 \times 10^6$ (on a length $L = 1.0 \text{ m}$)
- $\alpha=5^\circ, 10^\circ, 15^\circ$
- $Tu=0.15\%$
- $\mu_t/\mu=0.1$

Grid:

- C topology, 16 blocks structured type
- Farfield set at 1000 chords
- Approx. $8 \times 10^6$ cells
Transition onset at $\alpha = 5^\circ$ is predicted too far upstream.

Good agreement on leeward side.
Good agreement with experiments, except leeward region $0^\circ \leq \phi \leq 60^\circ$
6:1 Prolate spheroid

Skin friction distribution

Transition is predicted slightly downstream

Good agreement with experiments, except region $0^\circ \leq \phi \leq 60^\circ$
Conclusions

• Transition model based on intermittency function \( \gamma \) implemented in the UZEN in-house developed flow solver

• Assessment for 2D and 3D test cases:
  ✓ satisfactory results
  ✓ ERCOFTAC T3A and T3B test cases
    ▪ Dependence on freestream turbulent variables
  ✓ S809 airfoil
    ▪ Original and a modified version of the model applied
    ▪ Separation bubbles and transition abscissa well predicted
  ✓ 6:1 prolate spheroid
    ▪ Good agreement on leeward side at all incidences
    ▪ Some discrepancies while on windward side
Future Activities

Focus will be:

- simulation of long separation bubbles, e.g. SD7003 airfoil,
- implement correlation functions for the crossflow instabilities\(^1,2\)