Implementation of Two Local Correlation-Based Transition Models in OVERFLOW 2.3e

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  • Test cases
    • T3A, T3A-, Schubauer-Skramstad, NLF-0416
  • Conclusions
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Motivation

• Accurate prediction of laminar-to-turbulent boundary layer transition is important for many applications, such as the design of natural laminar flow wings, unmanned aerial vehicles, and crewed reentry vehicles.
  • Crucial given the push for sustainable aviation and greener air transport technology.
• Availability of an increased variety of transition models within NASA’s OVERFLOW Overset CFD code will help toward efficient and accurate design of these vehicles.

Goal: Implement two different local correlation-based transition models (LCTMs) into OVERFLOW 2.3e and carry out an initial assessment.
Menter Gamma Equation Transition Model

• In 2015, Florian Menter developed an SST-based, one equation, correlation-based transition model.¹

• Removed the $Re_{\theta t}$ equation (from LM2009) and modified terms in the $k$ and $\gamma$ equations.
  • Modified the $F_{\text{onset}}$, $F_{\text{length}}$, and $Re_{\theta c}$
  • In the $k$ equation, the Kato-Launier formulation is used in the production term of $k$ and an additional source term, that only activates under conditions of low Tu and laminar separation bubble, is included.

• New formulation allows for Galilean Invariance - Important for Rotorcraft applications

• However, the original model implementation does not include crossflow.
  • Current available implementations of crossflow will break Galilean invariance.

• A concurrent implementation in FUN3D is ongoing, allowing for a systematic model verification across the two codes.

SA-Based $\gamma$–Re$_{\theta t}$ Transition Model

• Implement an SA-based version of the $\gamma$–Re$_{\theta t}$ (Langtry-Menter/LM) transition model.

• Importance of model development:
  • SA-based models tend to converge quicker and easier than SST-based models.
  • One less equation to solve.
  • SA is used in a majority of aerospace applications.

• M. Piotrowski and D. Zingg of the University of Toronto, V. D’Alessandro of Marche Polytechnic University, and S. Medida of the University of Maryland have each developed their own variations of an SA-based $\gamma$–Re$_{\theta t}$ transition model.
  • Used these as references to substitute out terms, while trying to remain close to the original form of LM2009.

• Changes:
  • Model uses freestream value of the turbulence intensity, without accounting for decay.
  • Modified $F_{\text{wake}}$, $F_{\text{length,1}}$, and removed $F_{\text{sublayer}}$, $R_{\omega}$
Gamma Model Results
Flat Plate (Bypass transition)

- T3 series flat plate cases: T3A, and T3A-
- T3A and T3A- cases run on a family of six-to-eight different grids, with a doubling of resolution in both the x and y coordinates across each level.
  - T3A : Flow conditions based on the AIAA 1st CFD Transition Modeling Workshop
  - Mesh level 5: y+ = 0.5 (T3A) and 0.25 (T3A-)

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<tr>
<th>Case</th>
<th>T3A</th>
<th>T3A-</th>
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<tbody>
<tr>
<td>Inlet Velocity (m/s)</td>
<td>69.44</td>
<td>19.8</td>
</tr>
<tr>
<td>Freestream Temperature (K)</td>
<td>300.0</td>
<td>288.17</td>
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<tr>
<td>Unit Reynolds number (/m)</td>
<td>2.00E5</td>
<td>1.328E6</td>
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<tr>
<td>$\mu_t/\mu$ at inlet</td>
<td>11.9</td>
<td>9.0</td>
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<tr>
<td>Tu (%) at inlet</td>
<td>5.855</td>
<td>1.0</td>
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<tr>
<td>Tu (%) at leading edge</td>
<td>3.3</td>
<td>0.875</td>
</tr>
<tr>
<td>Tu (%) at the leading edge in Experiment</td>
<td>3.3</td>
<td>0.875</td>
</tr>
<tr>
<td>Distance from inflow to plate leading edge (m)</td>
<td>0.25</td>
<td>0.15</td>
</tr>
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</table>
T3A: Grid Convergence and Comparisons with Reference Data

\[ h = \sqrt{(N)} \]
T3A-: Grid Convergence and Comparisons with Reference Data

Skin Friction Coefficient

Model Convergence

Model Convergence (Mesh 5)

Drag Coefficient

Transition Region Skin Friction

Turbulent Region Skin Friction

Transition Region
\( (Re_s = 1.55 \times 10^6) \)

Turbulent Region
\( (Re_s = 2.5 \times 10^6) \)
Flat Plate (Natural transition)

- Flow conditions correspond to the experiment by Schubauer and Skramstad (S&S)
- Mesh level 5 ($y^+ = 0.25$) from T3A- case was used for this condition.
  - Detailed mesh convergence study currently under way
- Five Tu levels studied

<table>
<thead>
<tr>
<th>Condition</th>
<th>Condition 1</th>
<th>Condition 2</th>
<th>Condition 3</th>
<th>Condition 4</th>
<th>Condition 5</th>
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<tbody>
<tr>
<td>$\mu_t/\mu$ at inlet</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>5.0</td>
<td>5.0</td>
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<tr>
<td>Tu (%) at inlet</td>
<td>0.0302</td>
<td>0.084</td>
<td>0.141</td>
<td>0.189</td>
<td>0.346</td>
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<tr>
<td>Tu (%) at the leading edge</td>
<td>0.03</td>
<td>0.08</td>
<td>0.125</td>
<td>0.18</td>
<td>0.30</td>
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<table>
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<tr>
<th>Case</th>
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<td>Inlet Velocity (m/s)</td>
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<td>Freestream Temperature (K)</td>
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<td>Unit Reynolds number (/m)</td>
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<td>Distance from inflow to plate leading edge (m)</td>
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</table>
S&S: Influence of Model, Tu, and Comparisons with Reference Data

• Gamma model results (solid line) show narrow variation in transition onset with Tu, but closer to measured onset at Tu = 0.03%; no variation in results for Tu = 0.03 to 0.18%

• LM model (dashed line) predicts transition onset significantly downstream of measured location at Tu = 0.03% (this was one of the improvements in the Gamma model) and shows larger variation in transition onset with Tu.

• Width of transition zone with both models appear to be much narrower than in the experiment.
Flow conditions from AIAA Transition Modeling Workshop:
- Mach = 0.1
- \( Re_c = 4 \times 10^6 \)
- \( \alpha = 5^\circ \)
- \( T_\infty = 300 \text{ K} \)
- Tested on six different grid levels; Mesh level 5: \( y^+ = 0.2 \)
- Separation bubble induced transition on lower surface (data from expt. shown as gray colored bar).
- TS induced transition on upper surface.
Pressure Coefficient

Upper Surface Transition Region

Lower Surface Transition Region
NLF-0416 (Grid Convergence Plots – Selected Metrics)
Meanflow Residual Convergence

NLF-0416 LM2009 vs. Gamma Model

Graph showing the comparison between SST-$\gamma$ and SST-$\gamma$-Re$_h$ models.
Conclusions

• Successfully implemented the SST-based Gamma transition model from Menter et al. (2015) in OVERFLOW.
  • Laid foundation for systematic model verification with FUN3D.

• Test cases:
  • Transition was well predicted for the T3A flat plate case (LM was upstream).
  • In case of T3A-, transition was predicted much earlier than experimental data. LM was closer to the experimental data.
  • For S&S, prediction of transition onset was closer to measured data at $Tu=0.03\%$ than LM; downstream of LM at other conditions
  • For the NLF-0416, pressure coefficient distribution within the transition region was sensitive to grid resolution (need to explore additional grids).

• Benefit of model: Galilean invariance allows model to be well-suited for rotorcraft applications.

• Future work: Accounting for stationary crossflow effects without violating Galilean invariance; additional test cases.
SA-based $\gamma$–$\text{Re}_{\theta t}$ (LM) Results
• Same run conditions as before, except:
  • $T_u \infty = 2.0\%$, based on the condition at the transition location in the experiment.
  • $(\mu_i/\mu_l) \infty = 1 \times 10^{-5}$
• Transition onset from SA-based LM closer to measured onset.
  • Lower $C_D$ than SST-based LM results.
• Unable to predict measured $C_f$ peak near end of transition.
T3A-

• Same run conditions as before, except:
  • $T_u \infty = 0.1\%$
  • $(\mu_r/\mu) \infty = 1 \times 10^{-5}$

• Also ran cases with $T_u \infty = 0.5\%$ ($T_u$ at transition location in experiment) and $T_u \infty = 0.875\%$ ($T_u$ at LE in experiment) for Mesh 5
S&S: Influence of Model, Tu, and Comparisons with Reference Data

Same run conditions as before, except for change of model to SA-LM, where $Tu_{\infty} = Tu$ (leading edge) and $(\mu_t/\mu_l)_{\infty} = 1 \times 10^{-5}$

- SA-based LM model results (solid line) indicate earlier transition onset as opposed to SST-based LM and appear to be closer to measured onset at $Tu = 0.03\%$ and $0.3\%$;
- Width of transition zone with both models appear to be much narrower when compared to that from the experiment.
• Same flow conditions as before: $T_u \infty = 0.15\%$; $(\mu_r/\mu)_\infty = 1 \times 10^{-5}$
• Converged transition location on the lower surface compares well with those from the experiment (shown as gray colored bar). Transition location on the upper surface is unavailable from the experiment.
Verification of SST-LM model detailed in Venkatachari et al. AIAA Paper 2022-3679
Meanflow Residual Convergence
Conclusions

• Implemented an SA-based version of the Langtry-Menter $\gamma$–$Re_{\theta_t}$ transition model.

• Test cases:
  • Variations in freestream turbulence intensity (Tu) have a major effect on solution, especially for bypass cases.
    • Inability to account for Tu decay represents possible limitation to model.

• Benefit of model:
  • SA is generally more robust for external aerodynamic applications.
  • Model has one less equation to solve for.

• Future work:
  • Implementing crossflow.
  • Recalibrating the model to account for natural/bypass transition cases.
Summary

• Implemented two local correlation-based transition models in the NASA OVERFLOW Overset Grid CFD solver.
  • Learned how to understand flow of established CFD codes, add new capabilities, and good programming practices.
• Tested each model with T3A, T3A-, S&S, and NLF-0416 cases.
• Need to implement crossflow into both models.
• Need to test against more cases and grids to better understand outstanding issues.
• Detailed code-to-code verification of various models (including SA-based AFT) using OVERFLOW and FUN3D to be reported at AIAA Aviation 2023.
Acknowledgments

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References


• NASA Langley Turbulence Model Resource
Questions?
Backup
• Limiting $\text{max}(Re_{\theta_t})$ to 1100.0 for zero pressure gradient boundary layers, in the original LM correlations, similar to that in the gamma model, appears to help at $Tu=0.03%$
  • Suggested by Dr. Menter in private communication
  • Unlike in the gamma model, the new source term in the $k$ transport equation for the low $Tu$ cases, has not been added.
# Mesh Dimensions

<table>
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<tr>
<th>Mesh Level</th>
<th>No. of points in streamwise direction</th>
<th>No. of points in wall-normal direction</th>
<th>Points upstream of leading edge</th>
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