Extended OVERFLOW Analysis of the NASA Trap Wing Wind Tunnel Model

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Anthony J. Sclafani, Jeffrey P. Slotnick, John C. Vassberg
The Boeing Company, Boeing Research & Technology
Huntington Beach, California, USA

Thomas H. Pulliam
NASA Ames Research Center
Moffett Field, California, USA

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Outline

- Applying Lessons Learned
- Flow Solver / Computing Platform
- Grid and Run Matrix
- Convergence History
- Results
  - Workshop vs. Extended Study
  - Bracket Effect
  - Transition Effect
- Conclusions

NASA Trap Wing
“Config 1”
Applying Lessons Learned

- Adjust time step for finer grids
- Use grid with bracket clustering for all runs
- Exact wall distance calculation
- SA with rotation and curvature corrections
- Restarts for higher angles-of-attack
- Low Mach preconditioning

New baseline dataset
Flow Solver / Computing Platform

OVERFLOW Version 2.1ad, 2.2c and 2.2e
- No significant differences due to code version
- Default mode of operation
  - upwind differencing
  - SA-RC turbulence model (SA-la with rotation/curvature corrections)
  - full N-S, exact wall distance calculation, low Mach preconditioning
  - restart from lower $\alpha$ solution starting at $21^\circ$

- Transition Study
  - Langtry-Menter version CFX-v-1.1 of the $\gamma$-Re$_{\theta}$ transition model with SST-RC

Linux PC Cluster
- Used for all SA-RC runs
- Bracket-off medium grid required 6.3 hrs of wall clock time per 1000 steps on 24 cores

Pleiades Supercomputer
- Used for all SST-RC runs
- Same grid required 1.8 hrs of wall clock time per 1000 steps on 192 cores
Grid and Run Matrix

- Medium overset mesh with clustering for bracket grids, no wind tunnel walls

<table>
<thead>
<tr>
<th>Grid</th>
<th>Slat/Flap Bracket Clustering</th>
<th>Slat/Flap Brackets</th>
<th>Points (in millions)</th>
<th>Number of Zones</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>no</td>
<td>off</td>
<td>25.0</td>
<td>34</td>
</tr>
<tr>
<td>2</td>
<td>yes</td>
<td>off</td>
<td>47.0</td>
<td>34</td>
</tr>
<tr>
<td>3</td>
<td>yes</td>
<td>on</td>
<td>58.2</td>
<td>62</td>
</tr>
</tbody>
</table>

- Angles-of-attack analyzed:

**SA-RC Turbulence Model**

<table>
<thead>
<tr>
<th>Brackets (grid #)</th>
<th>BASELINE Fully Turbulent</th>
<th>BRACKET EFFECT Fully Turbulent</th>
<th>TRANSITION EFFECT Specify Laminar Regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>off (2)</td>
<td>6° → 37°</td>
<td>6° → 34°</td>
<td>6° → 28°</td>
</tr>
<tr>
<td>on (3)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**SST-RC Turbulence Model**

<table>
<thead>
<tr>
<th>Brackets (grid #)</th>
<th>BASELINE Fully Turbulent</th>
<th>BRACKET EFFECT Fully Turbulent</th>
<th>TRANSITION EFFECT $\gamma$-$Re_\theta$ Transition Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>off (2)</td>
<td>6° → 32°</td>
<td>6° → 28°</td>
<td>6° → 32°</td>
</tr>
<tr>
<td>on (3)</td>
<td></td>
<td></td>
<td>6° → 28°</td>
</tr>
</tbody>
</table>
Convergence History

Lift – Bracket Effect

OVERFLOW Trap Wing Config 1: Lift Convergence Histories
RN = 4.3 mil, Mach = 0.2, Fully Turbulent, SA-RC

Brackets Off

\[\alpha = 13^\circ\]

\[\alpha = 21^\circ\]

\[\alpha = 28^\circ\]

\[\alpha = 32^\circ\]

Brackets On

Iteration (\(x 10^{-3}\))
Lift Coefficient

restart

restart

restart

restart
Results:

*Workshop vs. Extended Study*
Extended Study results are closer to experiment at angles-of-attack near stall.

This is a fully turbulent, bracket-off analysis. Improved correlation is fortuitous.
At $\alpha = 34^\circ$, $\Delta C_L = -0.07$

$\Delta C_L$ due to: Grid $= -0.1$  Turbulence Model $= -0.1$  Initial Condition $= 0.13$
Workshop vs. Extended Study
Surface Streamline Comparison

Trap Wing Config 1 OVERFLOW Solutions
RN = 4.3 mil, Mach = 0.2, $\alpha = 34^\circ$

Workshop Analysis
> SA
> original grid
> freestream i.c.

Extended Analysis
> SA-RC
> refined grid
> restart

➢ Significant difference in skin friction and streamlines seen at the tip.
Workshop vs. Extended Study
Pressure Comparison

Trap Wing Config1 Pressure Comparison
RN_{mac} = 4.3 million, Mach = 0.2, \alpha = 34^\circ

- \eta = .65
- \eta = .41
- \eta = .17
- \eta = .98
- \eta = .95
- \eta = .85

Brackets Off / Fully Turbulent

- LaRC 14x22
- OVERFLOW, Workshop Analysis
- OVERFLOW, Extended Analysis

Extended Analysis Solution Shown

Cp: -9 -8 -7 -6 -5 -4 -3 -2 -1 0 1

X (inches)
Results:

Bracket Effect
Bracket Effect
Lift Curve Comparison

Trapp Wing Config 1 Lift Comparison: Bracket Effect
Mach = 0.2, Medium Grid, Fully Turbulent, Free Air

- Brackets reduce $C_L$ by indicated amounts.
- Early stall behavior with brackets-on not well understood, may be grid related.
Bracket Effect
Pressure Comparison

Trap Wing Config1 Pressure Comparison
RN_{mac} = 4.3 million, Mach = 0.2, \alpha = 13^\circ

Bracket Effect: SA-RC / Fully Turbulent

LaRC 14x22 Test 513 R105
- OVERFLOW, Brackets Off
- OVERFLOW, Brackets On

\eta = .65

\eta = .41

\eta = .17

\eta = .98

\eta = .95

\eta = .85

X (inches)

Cp: -5 -4 -3 -2 -1 0 1

X (inches)
Results:

Transition Effect
The Trap Wing was analyzed with transition using two methods.


<table>
<thead>
<tr>
<th>Brackets</th>
<th>SA-RC Turbulence Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BASELINE</td>
</tr>
<tr>
<td></td>
<td>Fully Turbulent</td>
</tr>
<tr>
<td>off</td>
<td>$6^\circ \rightarrow 37^\circ$</td>
</tr>
<tr>
<td>on</td>
<td></td>
</tr>
</tbody>
</table>

2. Use the Langtry-Menter $\gamma$-$Re_\theta$ transition model (version CFX-v-1.1) which is coupled with the SST turbulence model only.

<table>
<thead>
<tr>
<th>Brackets</th>
<th>SST-RC Turbulence Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BASELINE</td>
</tr>
<tr>
<td></td>
<td>Fully Turbulent</td>
</tr>
<tr>
<td>off</td>
<td>$6^\circ \rightarrow 32^\circ$</td>
</tr>
<tr>
<td>on</td>
<td></td>
</tr>
</tbody>
</table>
Transition Effect: Specified using SA-RC

Lift Comparison

Trap Wing Config 1 OVERFLOW Results
Reynolds Number = 4.3 million, Mach = 0.2

<table>
<thead>
<tr>
<th>BRACKET EFFECT</th>
<th>FIXED TRANSITION EFFECT</th>
</tr>
</thead>
<tbody>
<tr>
<td>alpha (deg)</td>
<td></td>
</tr>
<tr>
<td>brackets off</td>
<td>brackets on</td>
</tr>
<tr>
<td>brackets off C_L</td>
<td>transition</td>
</tr>
<tr>
<td>brackets on C_L</td>
<td>transition</td>
</tr>
<tr>
<td>6</td>
<td>1.525</td>
</tr>
<tr>
<td>13</td>
<td>2.038</td>
</tr>
<tr>
<td>21</td>
<td>2.559</td>
</tr>
<tr>
<td>28</td>
<td>2.903</td>
</tr>
</tbody>
</table>

- Inconsistent trend in bracket-off $\Delta C_L$ with angle-of-attack
  - $13^\circ$ and $21^\circ$ deltas are as expected
  - Reduced lift at $6^\circ$ and $28^\circ$ caused by flap separation

- Reduced lift due to transition for all angles-of-attack with brackets on
Transition Effect: Specified using SA-RC
Surface Streamline Comparison

Trap Wing Config 1 OVERFLOW Results
RN = 4.3 mil, Mach = 0.2, Brackets Off, SA-RC Turbulence Model

\[ \alpha = 6^\circ, \quad C_L = 1.525 \]
Fully Turbulent

\[ \alpha = 13^\circ, \quad C_L = 2.038 \]
Fully Turbulent

\[ \alpha = 28^\circ, \quad C_L = 2.903 \]
Fully Turbulent

\[ \alpha = 6^\circ, \quad C_L = 1.374 \]
Transition Fixed

\[ \alpha = 13^\circ, \quad C_L = 2.069 \]
Transition Fixed

\[ \alpha = 28^\circ, \quad C_L = 2.867 \]
Transition Fixed
Transition Effect: Specified using SA-RC

Turbulence Index

Trap Wing Config 1 OVERFLOW Results: SA-RC Fixed Transition
RN = 4.3 mil, Mach = 0.2, \( \alpha = 13^\circ \)
Transition Effect: Computed using SST-RC

Lift Comparison

- Transition increases lift while brackets decrease lift.
- Early stall predicted with brackets-on. This is consistent with SA-RC results.
Transition Effect: Computed using SST-RC
Pressure Comparison

Trap Wing Config1 Pressure Comparison
\(R_{\text{in}} = 4.3 \text{ million}, \text{ Mach} = 0.2, \alpha = 13^\circ\)

Transition and Bracket Effect: SST-RC

- LaRC 14x22
- SST-RC, fully turbulent, brackets off
- SST-RC, \(\gamma\)-Re\(_{\infty}\) transition, brackets off
- SST-RC, \(\gamma\)-Re\(_{\infty}\) transition, brackets on

\(\eta = 0.65\)

\(\eta = 0.41\)

\(\eta = 0.17\)

\(\eta = 0.98\)

\(\eta = 0.95\)

\(\eta = 0.85\)

\(C_p\) Values:
-5 -4 -3 -2 -1 0 1

X (inches)
Transition Effect: Computed using SST-RC

Turbulence Index for $\alpha = 13^\circ$

Trap Wing Config 1 OVERFLOW Results: SST-RC w/ $\gamma\cdot Re_e$ Transition
RN = 4.3 mil, Mach = 0.2, Medium Grid, Free Air, $\alpha = 13^\circ$

Turbulence Index

laminar 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 turbulent

Brackets Off

Brackets On

Brackets Off

Brackets On
Transition Effect: Computed using SST-RC
Turbulence Index and Skin Friction for $\alpha = 28^\circ$

- Turbulence index
- Skin friction
Conclusions

- After applying all workshop lessons learned, the fully turbulent bracket-off lift curve is in very good agreement with test data through stall.
  - Implies bracket and transition effects may cancel.

- SA-RC results show brackets have expected impact on data, reducing lift for all angles-of-attack analyzed.
  - Early stall at 32° requires further investigation. May be grid related.

- Fixed transition SA-RC results are mixed due to excessive flap separation at 6° and 28°. Lift increments at 13° and 21° show transition does recover the amount of lift lost to brackets.

- Computed transition SST-RC results produce expected incremental lift trends for 6°, 13° and 21°. That is, bracket and transition effects cancel.
  - Brackets-off early stall at 28°.
  - Brackets-on early stall at 21°.
Questions?
Back-Up
Bracket Effect
Drag and Pitching Moment Comparison

Trap Wing Config 1 Drag Polar Comparison: Bracket Effect
Mach = 0.2, Medium Grid, Fully Turbulent, Free Air

Trap Wing Config 1 Pitching Moment Comparison: Bracket Effect
Mach = 0.2, Medium Grid, Fully Turbulent, Free Air
Convergence History
*Lift – Turbulence Model Effect*

OVERFLOW Trap Wing Config 1: Lift Convergence Histories
RN = 4.3 mil, Mach = 0.2, Fully Turbulent, Brackets-Off

![Graphs showing lift coefficient convergence for different angles](image-url)
Turbulence Model Effect
SA-RC vs. SST-RC

Trap Wing Config 1 Lift Comparison: Turbulence Model Effect
Mach = 0.2, Medium Grid, Fully Turbulent, Free Air, Brackets Off

\[ C^L \] vs. \( \alpha \) (deg)

- LaRC 14x22
- SA-RC
- SST-RC
Turbulence Model Effect
SA-RC vs. SST-RC

Trap Wing Config 1 Pressure Comparison
\( R_{\text{max}} = 4.3 \) million, Mach = 0.2, \( \alpha = 28^\circ \)

Turb Model Effect: Brackets Off / Fully Turbulent

SA-RC Solution Shown

\[ \eta = 0.65 \]

\[ \eta = 0.41 \]

\[ \eta = 0.17 \]

\[ \eta = 0.98 \]

\[ \eta = 0.95 \]

\[ \eta = 0.85 \]
Transition Effect: Computed using SST-RC
Velocity Profile Comparison

Trap Wing Config 1 OVERFLOW Results: Velocity Profiles at $\eta = 0.83$

RN = 4.3 mil, Mach = 0.2, $\alpha = 28^\circ$

LaRC 14x22
- SST-RC, fully turbulent, brackets off
- SST-RC, $\gamma Re_{h}$ transition, brackets off

SST-RC $\gamma Re_h$ Solution