NASA Trap Wing Model
OVERFLOW Analysis

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NASA Trap Wing OVERFLOW Analysis

Outline

- Flow Solver / Computing Platform
- Grid Information
- Convergence Histories and Residuals
- Results
  - Test Case 1: Grid Convergence Study
  - Test Case 2: Flap Deflection Prediction Study
  - Test Case 3: Slat and Flap Support Effects Study
- Conclusions
- Future Work
NASA Trap Wing OVERFLOW Analysis
Flow Solver and Computing Platform

OVERFLOW MPI version 2.1ad – *Default Setup for High Lift Studies*

- Roe upwind differencing
- Spalart-Allmaras (SA) turbulence model – version “fv3”
- full Navier-Stokes
- low-Mach preconditioning
- steady state
- all cases run from scratch (i.e., freestream initial condition)

Parallel Processing on a PC Cluster

- Linux 64bit operating system with 1968 CPUs on 578 nodes
  - 120 2.6GHz Opteron dual core nodes with 8GB of RAM
  - 80 3.0GHz Xeon dual dual-core nodes with 12GB of RAM
  - 112 2.2GHz Opteron dual quad-core nodes with 16GB of RAM
- Config 1 medium grid (25 million points) run on 24 processors
  - 18.7 seconds per iteration
  - Full convergence reached after 5000 iterations
  - Roughly 26 hours of wall clock time needed per case
Structured Overset Grid Systems

- 34 zones for Bracket-Off (28 surface abutting)
- 62 zones for Bracket-On (56 surface abutting)

### Config 1 and Config 8 (body-slat-wing-flap)

<table>
<thead>
<tr>
<th>Grid</th>
<th>Points</th>
<th>$1/N^{2/3} \times 10^5$</th>
<th>$1^{st}$ Cell Size</th>
<th>$y^+$</th>
<th>Constant Cells</th>
<th>Growth Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td>10,653,004</td>
<td>2.07</td>
<td>.00017 in</td>
<td>.87</td>
<td>2</td>
<td>1.25</td>
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<tr>
<td>Medium</td>
<td>24,965,818</td>
<td>1.17</td>
<td>.00013 in</td>
<td>.66</td>
<td>3</td>
<td>1.18</td>
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<tr>
<td>Fine</td>
<td>83,302,438</td>
<td>0.52</td>
<td>.00009 in</td>
<td>.44</td>
<td>4</td>
<td>1.12</td>
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<tr>
<td>Extra-Fine</td>
<td>281,560,012</td>
<td>0.23</td>
<td>.00006 in</td>
<td>.29</td>
<td>6</td>
<td>1.08</td>
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</table>

### Config 1 (body-slat-wing-flap-brackets)

<table>
<thead>
<tr>
<th>Grid</th>
<th>Points</th>
<th>$1/N^{2/3} \times 10^5$</th>
<th>$1^{st}$ Cell Size</th>
<th>$y^+$</th>
<th>Constant Cells</th>
<th>Growth Rate</th>
</tr>
</thead>
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<tr>
<td>Medium</td>
<td>58,175,676</td>
<td>0.67</td>
<td>.00013 in</td>
<td>.66</td>
<td>3</td>
<td>1.18</td>
</tr>
</tbody>
</table>
NASA Trap Wing OVERFLOW Analysis

Convergence Histories – Lift

OVERFLOW Convergence Histories - Lift
> Config 1 Medium Grid Solutions
> Slat/Flap Brackets Off
> Fully Turbulent, Free Air
> RN = 4.3 million, Mach = 0.2

\[ \alpha = 34^\circ \]
\[ \Delta C_L = \pm 0.0001 \]

\[ \alpha = 28^\circ \]
\[ \Delta C_L = \pm 0.0005 \]

\[ \alpha = 21^\circ \]
\[ \Delta C_L = \pm 0.0002 \]

\[ \alpha = 13^\circ \]
\[ \Delta C_L = \pm 0.0003 \]
NASA Trap Wing OVERFLOW Analysis

Convergence Histories – Drag

OVERFLOW Convergence Histories - Drag

- Config 1 Medium Grid Solutions
- Slat/Flap Brackets Off
- Fully Turbulent, Free Air
- RN = 4.3 million, Mach = 0.2

\[ \alpha = 34^\circ \quad \Delta C_D = +/- 0.0002 \]

\[ \alpha = 28^\circ \quad \Delta C_D = +/- 0.0002 \]

\[ \alpha = 21^\circ \quad \Delta C_D = +/- 0.0001 \]

\[ \alpha = 13^\circ \quad \Delta C_D = +/- 0.0001 \]
OVERFLOW Convergence Histories - Pitching Moment

> Config 1 Medium Grid Solutions
> Slat/Flap Brackets Off
> Fully Turbulent, Free Air
> RN = 4.3 million, Mach = 0.2

\[
\alpha = 34^\circ \\
\Delta C_M = +/- 0.0002
\]

\[
\alpha = 28^\circ \\
\Delta C_M = +/- 0.0004
\]

\[
\alpha = 21^\circ \\
\Delta C_M = +/- 0.0001
\]

\[
\alpha = 13^\circ \\
\Delta C_M = +/- 0.0001
\]
### Config 1 Force and Moment Plus/Minus “Error Band”

*Given as Percent Total*

<table>
<thead>
<tr>
<th>α</th>
<th>ΔCₗ</th>
<th>ΔCₜ</th>
<th>ΔCₘ</th>
</tr>
</thead>
<tbody>
<tr>
<td>13°</td>
<td>.03</td>
<td>.05</td>
<td>.06</td>
</tr>
<tr>
<td>21°</td>
<td>.02</td>
<td>.03</td>
<td>.03</td>
</tr>
<tr>
<td>28°</td>
<td>.03</td>
<td>.07</td>
<td>.19</td>
</tr>
<tr>
<td>34°</td>
<td>.01</td>
<td>.04</td>
<td>.10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>grid</th>
<th>ΔCₗ</th>
<th>ΔCₜ</th>
<th>ΔCₘ</th>
</tr>
</thead>
<tbody>
<tr>
<td>coarse</td>
<td>.01</td>
<td>.03</td>
<td>.02</td>
</tr>
<tr>
<td>medium</td>
<td>.03</td>
<td>.05</td>
<td>.06</td>
</tr>
<tr>
<td>fine</td>
<td>.06</td>
<td>.13</td>
<td>.16</td>
</tr>
<tr>
<td>extra-fine</td>
<td>1.01</td>
<td>1.45</td>
<td>1.33</td>
</tr>
</tbody>
</table>
NASA Trap Wing OVERFLOW Analysis
Config 1 Residuals

- Slat/Flap Brackets Off
- Fully Turbulent, Free Air
- RN = 4.3 mil, Mach = 0.2
- $\alpha = 13^\circ$
- Higher alpha solutions have similar residuals

Medium Grid  Fine Grid  Extra-Fine Grid

Log10 (L2 norm of RHS)  Log10 (L2 norm of RHS)  Log10 (L2 norm of RHS)

Iteration  Iteration  Iteration

0 2000 4000 6000 0 2000 4000 6000 0 2000 4000 6000 0 10000 12000

-10  -8  -6  -4  -2  0
-10  -8  -6  -4  -2  0
-10  -8  -6  -4  -2  0

body  slat  slat_tecap1  wing_collar  wing_tipcap5  flap  flap_tipcap2  outer_box
NASA Trap Wing OVERFLOW Analysis

Config 1 Turbulence Model Residuals

- Slat/Flap Brackets Off
- Fully Turbulent, Free Air
- RN = 4.3 mil, Mach = 0.2
- $\alpha = 13^\circ$

Medium Grid

Fine Grid

Extra-Fine Grid
When comparing CFD with wind tunnel data, remember the following.

- Brackets
- Transition
- Walls
- Aeroelastics
Test Case 1

Grid Convergence Study
Test Case 1 – Grid Convergence Study

Config 1: Total Lift at $\alpha = 13^\circ$

- Extra-fine grid solution represents a severe break in the grid convergence plot.
  - Extent of inboard flap separation may be related.
  - Extrapolating from medium and fine grid $C_L$s gives 2.023 at the continuum, ~1% less than experiment.
  - Flap TE separation is reduced with grid refinement.

$C_L$ drops by .06 (~3%) going from fine to extra-fine grid.
Test Case 1 – Grid Convergence Study
Config 1 and Config 8: Total Lift at $\alpha = 13^\circ$

 Trap Wing OVERFLOW Results: Total Lift
Mach = 0.2, $R_N = 4.3$ million, $\alpha = 13^\circ$

- Config 8 extra-fine grid solution shows a similar break in lift but the inboard flap separation is relatively small.
- The drop in lift at $\alpha = 13^\circ$ going from the fine grid to the extra-fine grid does not appear to be driven by inboard flap separation.
Test Case 1 – Grid Convergence Study
Section $C_i$ Comparison at $\alpha = 13^\circ$

The extra-fine grid solution has reduced loading across the entire semi-span for all three elements.
Test Case 1 – Grid Convergence Study

Config 1: Total Lift at $\alpha = 28^\circ$

- Surface streamlines show main wing flow separation (early stall).
- The coarse, medium, and fine grid $C_L$ agrees very well with test data.

Extra-fine grid solution represents an extremely large break in the grid convergence plot.
- Surface streamlines show main wing flow separation (early stall).
Extra-fine grid data may represent a second solution at the two alphas analyzed.

- Currently running $\alpha = 13^\circ$ further
- Will try restarting to get to $28^\circ$
Test Case 1 – Grid Convergence Study
Config 1: Total Drag & Pitching Moment

Drag
Coarse, medium, and fine grid drag levels agree reasonably well with experiment.
- At 13°, grid-converged drag is under-predicted by about 45 counts (~1.3%).
- At 28°, grid-converged drag is under-predicted by about 50 counts (~0.8%).

The extra-fine grid data breaks away from the linear trend indicating asymptotic grid convergence is not achieved.

Pitching Moment
Coarse, medium, and fine grid pitching moment data is not linear at 13°.

The extra-fine grid pitch break is nose-up for both alphas.
- At 13°, nose-up break most likely driven by reduced $C_L$.
- At 28°, nose-up break caused by outboard wing separation.
Test Case 1 – Grid Convergence Study
Config 1: Pressure Comparison at $\alpha = 13^\circ$, $\eta = .17$

Trap Wing Config 1 Pressure Comparison
LaRC 14x22 vs OVERFLOW
$RN_{MAC} = 4.3$ million, Mach = 0.2, $\alpha = 13^\circ$

Medium Grid Solution Shown

```
<table>
<thead>
<tr>
<th>Grid Type</th>
<th>$C_l$</th>
</tr>
</thead>
<tbody>
<tr>
<td>coarse</td>
<td>2.013</td>
</tr>
<tr>
<td>medium</td>
<td>2.021</td>
</tr>
<tr>
<td>fine</td>
<td>2.022</td>
</tr>
<tr>
<td>extra-fine</td>
<td>1.962</td>
</tr>
<tr>
<td>LaRC 14x22</td>
<td>2.047</td>
</tr>
</tbody>
</table>
```

$\eta = .17$

$X$ (inches)
Test Case 1 – Grid Convergence Study
Config 1: Pressure Comparison at $\alpha = 13^\circ$, $\eta = .65$

Trap Wing Config1 Pressure Comparison
LaRC 14x22 vs OVERFLOW
$RN_{MAC} = 4.3$ million, Mach = 0.2, $\alpha = 13^\circ$

Medium Grid Solution Shown

$\eta = .98$
$\eta = .95$
$\eta = .85$
$\eta = .70$
$\eta = .65$
$\eta = .50$
$\eta = .41$
$\eta = .28$
$\eta = .17$

$C_p$

$\eta = .65$

$X$ (inches)
Test Case 1 – Grid Convergence Study
Config 1: Pressure Comparison at $\alpha = 13^\circ, \eta = .95$

Trap Wing Config1 Pressure Comparison
LaRC 14x22 vs OVERFLOW
$R_{N_{MAC}} = 4.3$ million, Mach = 0.2, $\alpha = 13^\circ$

Medium Grid Solution Shown

- $\eta = .98$
- $\eta = .95$
- $\eta = .85$
- $\eta = .70$
- $\eta = .65$
- $\eta = .50$
- $\eta = .41$
- $\eta = .28$
- $\eta = .17$

$\eta = .95$

$C_p$ vs $X$ (inches)

<table>
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<td>LaRC 14x22</td>
<td>2.047</td>
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</tbody>
</table>
Test Case 1 – Grid Convergence Study
Config 1: Pressure Comparison at $\alpha = 13^\circ$, $\eta = .98$

Trap Wing Config 1 Pressure Comparison
LaRC 14x22 vs OVERFLOW
$RN_{MAC} = 4.3$ million, Mach = 0.2, $\alpha = 13^\circ$

Medium Grid Solution Shown

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<tr>
<td>LaRC 14x22</td>
<td>2.047</td>
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</table>

$\eta = .98$
Test Case 1 – Grid Convergence Study
Config 1: Pressure Comparison at Flap Forward Span

Trap Wing Config 1 Pressure Comparison
LaRC 14x22 vs OVERFLOW
RN_{MAC} = 4.3 million, Mach = 0.2, \alpha = 13^\circ

Medium Grid Solution Shown

Flap Forward Span

<table>
<thead>
<tr>
<th>Grid Type</th>
<th>Cl</th>
</tr>
</thead>
<tbody>
<tr>
<td>coarse</td>
<td>2.013</td>
</tr>
<tr>
<td>medium</td>
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</tr>
<tr>
<td>fine</td>
<td>2.022</td>
</tr>
<tr>
<td>extra-fine</td>
<td>1.964</td>
</tr>
<tr>
<td>LaRC 14x22</td>
<td>2.047</td>
</tr>
</tbody>
</table>

Flap Forward Span

Y (inches)
Test Case 1 – Grid Convergence Study
Config 1: Pressure Comparison at Flap Aft Span

Trap Wing Config 1 Pressure Comparison
LaRC 14x22 vs OVERFLOW
RN_{MAC} = 4.3 million, Mach = 0.2, \alpha = 13^\circ

Medium Grid Solution Shown
NASA Trap Wing OVERFLOW Analysis

Skin Friction for Config 8, $\alpha = 13^\circ$

Fine Grid

Extra-Fine Grid
Test Case 2

Flap Deflection Prediction Study
Test Case 2 – Flap Deflection Prediction Study

Lift Comparison

C1 LaRC
\( \alpha_{\text{stall}} = 33^\circ \)
\( C_{L\text{max}} = 3.00 \)

C1 OVERFLOW
\( \alpha_{\text{stall}} = 35^\circ \) to \( 36^\circ \)
\( C_{L\text{max}} = 3.06 \)

Trap Wing Lift Curve
Mach = 0.2, Fully Turbulent, Medium Grid (25.0M points), No Brackets

\[ C_L \text{ vs } \alpha \text{ (deg)} \]

\( \Delta = \text{Config1} - \text{Config8} \)

low by \( \sim 0.02 \)
high by \( \sim 0.04 \)
By removing idealized induced drag, a more detailed polar comparison can be made.

- LaRC data show cross-over $C_L$ to be at 1.5, above which Config 8 has higher drag
- OVERFLOW $C_L$ cross-over is at 2.4
- Larger difference seen in Config 8 polar
Test Case 2 – Flap Deflection Prediction Study

Drag Comparison: $C_D$ vs $\alpha$

Trap Wing Drag Polar
Mach = 0.2, Fully Turbulent, Medium Grid (25.0M points), No Brackets

$C_D$ vs $\alpha$ graph showing comparison between LaRC 14x22, Config 1 and Config 8, also comparing OVERFLOW, Config 1 and Config 8. The graph indicates a difference of $\Delta C_D$ with low by $\sim 0.002$ and high by $\sim 0.02$.
Test Case 2 – Flap Deflection Prediction Study

Pitching Moment Comparison: $C_L$ vs $C_M$

Trap Wing Pitching Moment

Mach = 0.2, Fully Turbulent, Medium Grid (25.0M points), No Brackets
Test Case 2 – Flap Deflection Prediction Study
Pitching Moment Comparison: $C_M$ vs $\alpha$

Trap Wing Pitching Moment
Mach = 0.2, Fully Turbulent, Medium Grid (25.0M points), No Brackets

$\Delta C_M$, low by ~0.005, high by ~0.02

$\Delta = \text{Config1} - \text{Config8}$
Test Case 2 – Flap Deflection Prediction Study

Minimum Pressure Comparison: Config 1

Trap Wing Config 1 OVERFLOW Results
RN = 4.3 million, Mach = 0.2, Medium Grid, No Brackets

Using J. P. Mayer’s 0.7 vacuum \( (M^2_\infty C_p = -1) \) presented by A.M.O. Smith

- Slat suction pressure reaches 0.7 vacuum \( (C_p = -25) \) at \( 36^\circ < \alpha < 37^\circ \)
  - Critical semi-span station is \( \eta = 0.8 \)

- Stall appears to be driven by the slat \( \rightarrow \) slat stalls first followed by wing

*Smith, A. M. O., “High Lift Aerodynamics”, 37th Wright Borthers Lecture, Vol. 12 No. 6, JOA, June 1975
Test Case 3

Slat and Flap Support Effects Study
Test Case 3 – Support Effects Study
Config 1 Bracket Grids*

Medium Grid Sizes
• Bracket-off = 25.0 million
• Bracket-off with refined c-mesh grids = 47.0 million
• Bracket-on with refined c-mesh grids = 58.2 million

*Bracket grids built by Leonel Serrano and Neal Harrison
Test Case 3 – Support Effects Study
Lift Comparison

Trap Wing Lift Curve
Mach = 0.2, Fully Turbulent, Medium Grid

- Brackets reduce $C_L$ by ~0.02 at 13° and 21°
- $C_L$ reduction grows to ~0.08 at 28°
- By 32°, bracket-on configuration is stalled
Test Case 3 – Support Effects Study
Drag and Pitching Moment Comparison

Brackets increase drag by 50 to 200 counts depending on $C_L$.
Brackets drive pitching moment less negative (nose-up)
Test Case 3 – Support Effects Study
Skin Friction and Surface Streamline Comparison

Brackets On
$\alpha = 28^\circ$

Brackets Off
$\alpha = 28^\circ$
Test Case 3 – Support Effects Study

Pressure Comparison at $\alpha = 28^\circ$, $\eta = 50\%$

Trap Wing Config1 Pressure Comparison

LaRC 14x22 vs OVERFLOW

$RN_{MAC} = 4.3$ million, Mach = 0.2, $\alpha = 28^\circ$

### Wing Upper Surface Skin Friction

- 0.014
- 0.012
- 0.010
- 0.008
- 0.006
- 0.004
- 0.002
- 0.000

$\eta = .50$

### Pressure Comparison

- **medium** $C_L = 2.904$
- **medium + brackets** $C_L = 2.820$
- **LaRC 14x22** $C_L = 2.896$

$\eta = .50$
Conclusions

Test Case 1 – Grid Convergence Study

- The extra-fine grid produces solutions that appear to be in a different family than the coarse, medium, and fine grid.
  - hysteresis may be the cause … additional runs are being made

- The coarse, medium, and fine grid $C_L$ results are close to linear when plotted against $1/N^{-2/3}$ and agree reasonably well with test data.

- In general, pressures are in good agreement with test data.
  - wing and flap pressures at the tip are the exception
  - flap trailing-edge pressures predicted best by extra-fine grid

Test Case 2 – Flap Deflection Prediction Study

- Config 1 lift, drag, and pitching moment agree well with test data through stall.
  - $C_{L_{max}}$ is over-predicted by 2%

- More discrepancy seen in the Config 8 force and moment data comparison.

Test Case 3 – Slat and Flap Support Effects Study

- Bracket-on results move away from test data indicating the bracket-off data is not as good as it appears.

- As with the extra-fine grid solutions, adding the supports leads to early stall.
Future Work

- Hysteresis, extra-fine grid solutions
- Brackets
- Laminar flow
- Off-body grid refinement at tip
- SA with Rotational and Curvature Correction (SARC)