OVERFLOW Analysis of the NASA CRM WB and WBNP Aero-Elastic Configurations

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Outline

- Flow Solver and Computing Platform
- Overset Grid Summary and Cases Analyzed
- Convergence History
- Results
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  - Case 2: Nacelle/Pylon Drag Increment
  - Case 3: Wing/Body Drag Polar
  - Case 4: Grid Adaptation
- Conclusions
Flow Solver and Computing Platform

OVERFLOW Version 2.2k
- Setup used for past workshops
  - 2nd order central differencing
  - SA-RC turbulence model (SA-noft2 with rotation/curvature corrections)
  - full N-S, exact wall distance calculation
  - free stream initial conditions
  - fully turbulent boundary layer
  - linear vs. nonlinear stress model via QCR

Pleiades Supercomputer
- SGI ICE cluster with >200,000 cores of mixed processor type
- Utilized Ivy Bridge nodes with 2 ten-core processor per node

<table>
<thead>
<tr>
<th>case</th>
<th>grid</th>
<th>points</th>
<th>cores</th>
<th>sec/it</th>
<th>sec/it/grid</th>
<th>iterations</th>
<th>wall clock</th>
</tr>
</thead>
<tbody>
<tr>
<td>WB</td>
<td>medium</td>
<td>24.7M</td>
<td>20</td>
<td>3.1</td>
<td>12.5 x 10^{-8}</td>
<td>10000</td>
<td>9 hrs</td>
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<tr>
<td>WB</td>
<td>ultrafine</td>
<td>82.7M</td>
<td>60</td>
<td>6.2</td>
<td>7.5 x 10^{-8}</td>
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<td>43 hrs</td>
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<td>6.3 x 10^{-8}</td>
<td>10000</td>
<td>7 hrs</td>
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<tr>
<td>WBNP</td>
<td>ultrafine</td>
<td>132.4M</td>
<td>80</td>
<td>4.1</td>
<td>3.1 x 10^{-8}</td>
<td>25000</td>
<td>28 hrs</td>
</tr>
</tbody>
</table>
### Overset Grid Summary and Cases Analyzed

#### Wing/Body (WB) and Wing/Body/Nacelle/Pylon (WBNP) Grid Family

<table>
<thead>
<tr>
<th>Grid Level</th>
<th>Points (million)</th>
<th>Viscous Spacing</th>
<th>~y+</th>
<th>Const Cells at Wall</th>
<th>Max Stretching</th>
</tr>
</thead>
<tbody>
<tr>
<td>WB</td>
<td>WBNP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tiny</td>
<td>7.4</td>
<td>11.9</td>
<td>0.001478”</td>
<td>1.02</td>
<td>4</td>
</tr>
<tr>
<td>Coarse</td>
<td>14.4</td>
<td>23.0</td>
<td>0.001182”</td>
<td>0.80</td>
<td>5</td>
</tr>
<tr>
<td>Medium</td>
<td>24.7</td>
<td>39.5</td>
<td>0.000985”</td>
<td>0.67</td>
<td>5</td>
</tr>
<tr>
<td>Fine</td>
<td>39.1</td>
<td>62.6</td>
<td>0.000845”</td>
<td>0.58</td>
<td>6</td>
</tr>
<tr>
<td>X-fine</td>
<td>58.2</td>
<td>93.2</td>
<td>0.000739”</td>
<td>0.50</td>
<td>7</td>
</tr>
<tr>
<td>U-fine</td>
<td>82.8</td>
<td>132.4</td>
<td>0.000657”</td>
<td>0.45</td>
<td>8</td>
</tr>
</tbody>
</table>

#### Cases

- **Case 1**: SA, QCR-off
- **Case 2**: SA-RC, QCR-off
- **Case 3**: SA-RC, QCR-on
- **Case 4**: SA-RC, QCR-off

**Case 1**: SA, QCR-off
- SA-RC, QCR-off
- SA-RC, QCR-on
- WB medium grid

**Case 2**: SA-RC, QCR-off
- SA-RC, QCR-on
- WB and WBNP

**Case 3**: SA-RC, QCR-on
- WB medium grid

**Case 4**: SA-RC, QCR-off
- WB coarse grid
Convergence History

Residuals for Mach 0.85, $C_L = 0.5$
Shutting multi-grid off improved convergence for ultrafine grid and shifted force levels.
Results

Test Case 1

Verification Study
Case 1: Verification Study

Drag Convergence

OVERFLOW v2.2k
- Central differencing
- Matrix dissipation
- SA turbulence model
- Rotation and Curvature (RC) corrections on/off
- QCR on/off
- Multi-grid on except for finest grid level

Continuum Drag
- SA, QCR-off 0.012276
- SA-RC, QCR-off 0.011737
- SA-RC, QCR-on 0.011782

2D NACA 0012 OVERFLOW Results
Mach = 0.15, Re = 6.0 million, α = 10°, Fully Turbulent

Total Drag

SA, QCR-off
SA-RC, QCR-off
SA-RC, QCR-on

Continuum Drag
Results

Test Case 2

Nacelle/Pylon Drag Increment
Case 2: Nacelle/Pylon Drag Increment  
Effect of Wing Twist on WB Drag Level

- Fairly constant drag shift of about 5 cts due to wing washout
- Similar WB drag level computed using different grid topologies
Case 2: Nacelle/Pylon Drag Increment

Effect of Grid Resolution and QCR

QCR increases drag by ~2 cts due to AoA increase of ~0.04°

<table>
<thead>
<tr>
<th>Grid Level</th>
<th>QCR-off</th>
<th>QCR-on</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>23.2</td>
<td>23.0</td>
</tr>
<tr>
<td>2</td>
<td>22.8</td>
<td>22.6</td>
</tr>
<tr>
<td>3</td>
<td>22.4</td>
<td>22.2</td>
</tr>
<tr>
<td>4</td>
<td>22.3</td>
<td>22.1</td>
</tr>
<tr>
<td>5</td>
<td>22.0</td>
<td>21.9</td>
</tr>
<tr>
<td>6</td>
<td>21.9</td>
<td>21.8</td>
</tr>
</tbody>
</table>

NP drag increment predicted to be 22 to 23 cts at the design condition depending on grid level.
Case 2: Nacelle/Pylon Drag Increment
Pressure and Skin Friction Drag Comparison

Pressure drag at the continuum:
- WB = 0.01427, WBNP = 0.01471

Skin friction drag at the continuum:
- WB = 0.01117, WBNP = 0.01285

$\Delta C_D^{\text{PR}} = 4.4 \text{ cts}$

$\Delta C_D^{\text{SF}} = 16.8 \text{ cts}$
Case 2: Nacelle/Pylon Drag Increment

Test Data vs. OVERFLOW

CRM Idealized Drag Polars
Mach = 0.85, $R_N = 5.0$ million

<table>
<thead>
<tr>
<th>Source</th>
<th>$(\Delta C_D)_{NP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>OVERFLOW-L3</td>
<td>22.2 cts</td>
</tr>
<tr>
<td>OVERFLOW-continuum</td>
<td>21.2 cts</td>
</tr>
<tr>
<td>Ames</td>
<td>22.4 cts</td>
</tr>
<tr>
<td>NTF</td>
<td>23.3 cts</td>
</tr>
</tbody>
</table>
Test Case 3

Wing/Body Drag Polar
Case 3: WB Drag Polar
Idealized Drag Polar Comparison

Adding the model support system to the CFD model changes wing, tail and aft body pressures and decreases drag by ~25 counts at $C_L = 0.5$ for the Wing-Body-Tail configuration.

OVERFLOW Data:
- Medium (L3) Mesh
- Fully Turbulent
- SARC-central-QCRon

Slope change means a different viscous e.
Case 3: WB Drag Polar
Pitching Moment Comparison

AIAA 2012-0707, M. Rivers and C. Hunter
“Support System Effects on the NASA Common Research Model”

Adding the model support system to the CFD model changes wing, tail and aft body pressures and increases $C_M$ by $\sim 0.035$ at $C_L = 0.5$ for the Wing-Body-Tail configuration.
Test Case 4

Wing/Body Grid Adaption
Case 4: WB Grid Adaption

Background Information on Overset Grid Adaption

References

- Feature-based adaption – not driving integrated forces such as drag
- Sensor function is the undivided 2nd difference of flow variables (truncation error in flow gradient regions)
- Isotropic grid refinement (all 3 directions) where neighboring grids differ by 2x
- Parametric cubic interpolation of original near-body grid
Case 4: WB Grid Adaption

Approach and Drag Results

<table>
<thead>
<tr>
<th>Case</th>
<th>Initial Grid</th>
<th>Adaption Parameters</th>
<th>Total Points</th>
<th>Increase in WingSrf Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>L6, ufine</td>
<td>n/a none n/a n/a n/a</td>
<td>82.8M</td>
<td>156.3K</td>
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<tr>
<td>B</td>
<td>L2, coarse</td>
<td>n/a none n/a n/a n/a</td>
<td>14.4M</td>
<td>50.3K</td>
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<tr>
<td>C</td>
<td>L2, coarse</td>
<td>1 gradient wing, wake 100M 3</td>
<td>98.3M</td>
<td>387.6K</td>
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<tr>
<td>D</td>
<td>L2, coarse</td>
<td>1 uniform all zones n/a 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 uniform wing n/a 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 gradient wing, body 400M 3</td>
<td>388.9M</td>
<td>895.1K</td>
</tr>
</tbody>
</table>

Notes:
- Existing near-field and far-field box grids were used.
- Gradient-based adaption used undivided 2nd difference for sensor function.
- NB = near-body, OB = off-body.

Modified grid topology to satisfy boundary condition limitations → coarse grid point count and drag level changed.

Tracked number of surface grid points on the wing (S) instead of total number of points (N).
SOB separation is insensitive to grid refinement at the design condition even with QCR-off.
Case 4: WB Grid Adaption

Wing Pressure Contours

- Wing shock structure is better defined in adapted solutions (C & D).
Case 4: WB Grid Adaption

Wing Pressure Contours – Tip Region

- Wing tip shock structure characterized by a forward-swept lambda shape.
- This feature is not captured well by the ultra-fine grid suggesting uniform grid family refinement can fail to resolve some areas of the flow field.
This surface grid comparison illustrates how feature-based adaption refines in high gradient regions as opposed to the uniform refinement done in Case A.
Case 4: WB Grid Adaption

Wing Pressure Cut Comparison

Adapted solutions yield similar trends at the shock as the uniform grid family except at the tip where a lambda shock system is predicted in Case D.

RN = 5.0 million
Mach = 0.85
C_L = 0.5

Station = 232.444
(\eta = 0.201)

Station = 581.148
(\eta = 0.502)

Station = 840.704
(\eta = 0.727)

Station = 1098.926
(\eta = 0.950)
Case 4: WB Grid Adaption

Wing Pressure Cut Comparison

RN = 5.0 million
Mach = 0.85
C_L = 0.5

AIAA 2015-6851, M. Rivers, J. Quest and R. Rudnik, "Comparison of the NASA Common Research Model European Transonic Wind Tunnel Test Data to NASA Test Data (Invited)"

Station = 1098.926
(\eta = 0.950)
Verification Study
- Rotation and curvature corrections reduced continuum drag level by 5.4 counts (4.4%).

Nacelle/Pylon Drag Increment
- The 1° of wing washout between the designed and tested wings is predicted to increase drag by 5 counts at the design condition.
- OVERFLOW predicts a 21.2 count drag increase at the continuum due to the addition of the NP.
  - roughly 80% of this increment is skin friction drag
  - good agreement with Ames and NTF data

Wing/Body Drag Polar
- Modeling the as-tested wing twist pushes the computed data closer to experiment.

Wing/Body Grid Adaption
- Feature-based adaption can be better than uniform grid refinement in terms of resolving all shock features.
Thank You!
Back-Up
Case 4: WB Grid Adaption

Pressure Contours

Case A

Case B

Case C

Case D

ufine

course

course Adapted 100M

course L2 Uniform Adapt + L3 NB Adapt
Case 4: WB Grid Adaption

Wing Pressure Contours – OB Region

- Complex OB wing shock structure more evident with extreme grid resolution in Case D.