Computational Analysis of the External Aerodynamics of the Unpowered X-57 Mod-III Aircraft

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Seung Y. Yoo
NASA Armstrong Flight Research Center

Jared C. Duensing
NASA Ames Research Center
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• NASA Armstrong Team
  – Mike Frederick, Nicholas Johnson, Trong Bui, Thomas Matthews

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  – Daniel Maldonado, Jeffrey A. Housman, James C. Jensen, Cetin C. Kiris

• NASA Langley Team
  – Karen A. Deere, Jeffrey K. Viken, Melissa B. Carter, Sally A. Viken
Outline

• Introduction
• Method
• Results
• Conclusion
• Questions
Introduction

- **X-57 Program**
  - Separated into multiple phases, denoted as “MOD”, to demonstrate various technologies
    - Electrical power-plant
    - Optimized high aspect ratio wing and high lift nacelle
    - Tip cruise motor for reducing induced drag
- **Study focused on unpowered MOD-III**
  - Flow physics
  - Differences in flow solution between CFD solvers
- **Purpose of the study**
  - Aerodynamic database generation for pilot-in-the-loop simulation
  - Understanding of the aerodynamics of the vehicle for flight safety
  - Baseline performance for powered simulation
Method

• STAR-CCM+ (v13.04.10)
  – Used extensively at NASA AFRC for airworthiness analysis
  – Grid
    • Unstructured polyhedral mesh
    • Half-span with symmetry boundary condition for symmetric flow, full-span for asymmetric flow simulation
  – Solver
    • Steady state RANS
    • 2\textsuperscript{nd} order Roe flux differencing scheme with algebraic multigrid solver with Gauss-Siedel relaxation scheme
    • Fully turbulent assumption, Spalart-Allmaras with rotational correction

• Launch Ascent Vehicle Analysis Framework
  – Versatile NASA ARC developed framework consisting of multiple solvers
  – Grid
    • Overset, structured, curvilinear grids
    • Full-span for all simulations
  – Solver
    • Steady state RANS structured curvilinear solver
    • Second-order convective flux with Koren limiter
    • Fully turbulent flow assumption, Spalart-Allmaras turbulence rotational correction and quadratic constitutive relationship
Result

- Grid Refinement Study
- Angle of attack sweep
- Sideslip angle sweep
Result – Grid Refinement Study

- **Atmospheric Condition**
  - Altitude 2500 ft, Mach 0.139, freestream velocity = 153.87 ft/s
  - Density $2.2078 \times 10^{-3} \text{kg/m}^3$, static pressure = 1931.9 lbf/ft$^2$, static temperature 283.2K
  - Reynolds number $9.21 \times 10^5$
  - Angle of attack = 10°, Sideslip angle = 20°

- **Aircraft configuration**
  - Aileron = -25°
  - Flap = 30°
  - Rudder = -28°
  - Stabilator = -15°
  - Pitch trim tab = -18°
• STAR-CCM+ Polyhedral Grid (coarse grid shown for clarity)

Result – Grid Refinement Study

- high lift nacelle
- flap deflection
- pitch trim tab on stabilator
- stabilator
- rudder deflection
Result – Grid Refinement Study

• LAVA structured overset curvilinear grid (coarse grid shown for clarity)

- pitch trim tab on stabilator
- flap and rudder deflection
- high lift nacelle
- stabilator
Result – Grid Refinement Study

• STAR-CCM+
  – 3 resolutions: 45e6 Cells (coarse), 77e6 Cells (medium), 126e6 Cells (fine)
• LAVA
  – 5 resolutions: 60.1e6 nodes (coarse), 95.2e6 nodes (medium), 248.6e6 nodes (fine), 312.6e6 nodes (very-fine), 425.7e6 nodes (extra-fine)
## Result – Grid Refinement Study

<table>
<thead>
<tr>
<th>STAR-CCM+ grid resolution</th>
<th>$C_D$</th>
<th>$C_L$</th>
<th>$C_Y$</th>
<th>$C_l$</th>
<th>$C_m$</th>
<th>$C_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>coarse (45e6 cells)</td>
<td>0.30394</td>
<td>1.46749</td>
<td>-0.61327</td>
<td>0.01631</td>
<td>2.41895</td>
<td>0.12050</td>
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<tr>
<td>medium (77e6 cells)</td>
<td>0.30623</td>
<td>1.47778</td>
<td>-0.61585</td>
<td>0.02004</td>
<td>2.41327</td>
<td>0.12257</td>
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<tr>
<td>fine (126e6 cells)</td>
<td>0.30797</td>
<td>1.47193</td>
<td>-0.61886</td>
<td>0.01982</td>
<td>2.38941</td>
<td>0.12337</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>STAR-CCM+ grid resolution</th>
<th>$C_D$ error, %</th>
<th>$C_L$ error, %</th>
<th>$C_Y$ error, %</th>
<th>$C_l$ error, %</th>
<th>$C_m$ error, %</th>
<th>$C_n$ error, %</th>
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</thead>
<tbody>
<tr>
<td>coarse (45 mil. cell)</td>
<td>-1.1</td>
<td>-0.3</td>
<td>-0.9</td>
<td>-17.7</td>
<td>1.2</td>
<td>-2.3</td>
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<td>medium (77 mil. cell)</td>
<td>-0.5</td>
<td>0.4</td>
<td>-0.5</td>
<td>1.1</td>
<td>1.0</td>
<td>-0.6</td>
</tr>
</tbody>
</table>

Although relative error $C_l$ is large, the values are small and coarse mesh chosen to accommodate the large number of runs for limited computing resource.
## Result – Grid Refinement Study

<table>
<thead>
<tr>
<th>LAVA grid resolution</th>
<th>$C_D$</th>
<th>$C_L$</th>
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<th>$C_{l}$</th>
<th>$C_m$</th>
<th>$C_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>coarse (60.1 mil. nodes)</td>
<td>0.3024</td>
<td>1.57</td>
<td>-0.6053</td>
<td>0.0135</td>
<td>2.396</td>
<td>0.1119</td>
</tr>
<tr>
<td>medium (95.2 mil. nodes)</td>
<td>0.29838</td>
<td>1.55</td>
<td>-0.595</td>
<td>0.016</td>
<td>2.404</td>
<td>0.1117</td>
</tr>
<tr>
<td><strong>fine (248.6 mil. nodes)</strong></td>
<td><strong>0.30036</strong></td>
<td><strong>1.56</strong></td>
<td><strong>-0.5876</strong></td>
<td><strong>0.0181</strong></td>
<td><strong>2.398</strong></td>
<td><strong>0.1106</strong></td>
</tr>
<tr>
<td>very-fine (312.6 mil. nodes)</td>
<td>0.30265</td>
<td>1.56</td>
<td>-0.5844</td>
<td>0.0226</td>
<td>2.402</td>
<td>0.1121</td>
</tr>
<tr>
<td>extra-fine (425.7 mil nodes)</td>
<td>0.30237</td>
<td>1.56</td>
<td>-0.582</td>
<td>0.0239</td>
<td>2.401</td>
<td>0.1126</td>
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<tr>
<th>LAVA grid resolution</th>
<th>$C_D$ error, %</th>
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</tr>
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<tbody>
<tr>
<td>coarse (60.1 mil. nodes)</td>
<td>-0.01</td>
<td>-0.64</td>
<td>-4.00</td>
<td>43.51</td>
<td>0.21</td>
<td>0.62</td>
</tr>
<tr>
<td>medium (95.2 mil. nodes)</td>
<td>1.32</td>
<td>0.51</td>
<td>-2.23</td>
<td>33.05</td>
<td>-0.12</td>
<td>0.80</td>
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<tr>
<td><strong>fine (248.6 mil. nodes)</strong></td>
<td><strong>0.66</strong></td>
<td><strong>-0.26</strong></td>
<td><strong>-0.96</strong></td>
<td><strong>24.27</strong></td>
<td><strong>0.12</strong></td>
<td><strong>1.78</strong></td>
</tr>
<tr>
<td>very-fine (312.6 mil. nodes)</td>
<td>-0.09</td>
<td>-0.32</td>
<td>-0.41</td>
<td>5.44</td>
<td>-0.04</td>
<td>0.44</td>
</tr>
</tbody>
</table>
Result – Grid Refinement Study

LAVA (248.6 mil. nodes)
STARCCM+ (45e6 cells)
Result

• Grid Refinement Study
• Angle of attack sweep
• Sideslip angle sweep
### Result – Angle of attack sweep

- 3 flap settings – 0° (cruise), 10° (take-off), 30° (landing)
- Control surfaces in neutral position (no deflection)

<table>
<thead>
<tr>
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<th>Flap = 0°</th>
<th>Flap = 10°</th>
<th>Flap = 30°</th>
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<tbody>
<tr>
<td>Altitude, ft</td>
<td>8000</td>
<td>2500</td>
<td>2500</td>
</tr>
<tr>
<td>Mach</td>
<td>0.233</td>
<td>0.149</td>
<td>0.139</td>
</tr>
<tr>
<td>Density, slug/ft³</td>
<td>1.8628E-3</td>
<td>2.20782E-3</td>
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<tr>
<td>Static pressure, lbf/ft²</td>
<td>1571.9</td>
<td>1931.9</td>
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<tr>
<td>Static temperature, K</td>
<td>272.3</td>
<td>283.2</td>
<td>283.2</td>
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<tr>
<td>Coefficient of viscosity, slug/ft/s</td>
<td>3.57532E-7</td>
<td>3.68708E-7</td>
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<tr>
<td>Reynolds number</td>
<td>1.32E6</td>
<td>9.875E5</td>
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Result – Angle of attack sweep

- Lift dependency on flap deflection
  - Lift increases with increase in flap deflection angle
  - Angle of attack for maximum lift decreases with increase in flap deflection

- Differences in solver
  - Lift at high angle of attack
  - Increase in discrepancy with increase in flap deflection angle at linear region
Result – Angle of attack sweep

• Increase in solution discrepancy in lift with increase in flap deflection angle at linear region

• STAR-CCM+ solution show flow separation at outboard wing that is not show in LAVA for 10° and 30° flap deflection
Result – Angle of attack sweep

- Increase in solution discrepancy in lift at high angle of attack
- STAR-CCM+ solution show larger region of separated flow at higher angle of attack compared to LAVA
Result – Angle of attack sweep

- Higher pitching moment with higher flap deflection angle
- Sharp increase in pitching moment for 0° flap angle at 20° angle of attack
Result – Angle of attack sweep

Angle of attack = 22°, surface pressure contour

- Large flow separation shown on the upper surface of stabilator for 0° flap deflection configuration
- Flow separation shown on the upper surface of stabilator on 10° flap deflection configuration located to inboard and trailing edge
Result

- Grid Refinement Study
- Angle of attack sweep
- Sideslip angle sweep
Result – Sideslip angle sweep

• 3 flap settings – 0° (cruise), 10° (take-off), 30° (landing)
• Control surfaces in neutral position (no deflection)

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• Lift, drag, side forces all decrease with increasing sideslip angle
• Drag decreasing because it is in stability axis (increases when computed in wind axis)
• Rolling moment - 30° flap produces least amount of rolling moment
• Pitching moment - sharp increase in at 15° for all flap deflections
• Yawing moment - 30° flap produces least amount of rolling moment
Result – Sideslip angle sweep

surface pressure coefficient, Angle of attack = 22°

- Increasing separation at leading edge of right wing root with increasing flap deflection
- Separated region at the leading edge of rudder
Conclusion

• Unpowered X-57 MOD-III configuration analyzed
• Angle of attack sweep and sideslip angle sweep presented
• STAR-CCM+ and LAVA solution comparison
  – flow visualization show that solution compare well at low angle of attack
  – Difference in predicted separation behavior at higher angle of attack
QUESTION?