STAR-CCM+ Hypersonic Validation of a 70° Sweep Slab

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Purpose

- Desired to do validation runs of STAR-CCM+ to wind tunnel for Hypersonic flow
  - Wind Tunnel data from NASA Report R-153
    - Comparison of 70° Sweep Slab Delta Wing in Hypersonic flow to analytical methods
    - Mach 6.8, and 9.6 flows from -2.5° - 45° angles of attack
    - Other Conditions tested but are not compared here
- Desired to attempt a flow adaptive grid refinement
Geometry

- Geometry was created in the STAR-CCM+ CAD package.
- Created two geometries, a sharp and blunted version:
  - Sharp geometry has cylindrical leading edges coming to a point in the front.
  - Blunt geometry has cylindrical leading edges with a hemispherical nose.
- Added pressure monitors to both geometries similar to wind tunnel test (with 0.001” offset from surface).
- No information on the sting was in the report, so no attempt to replicate that was made.
Meshing

• Created an initial Mesh of each of the bodies
  – ~360k Polyhedral Cells
  – 5 Prism Layers, 0.025” thick
• Intent was for a very coarse mesh as a starting point
• Remeshed based on CFD solution
Grid Refinement Field Function

- Created a series of field functions to adapt the existing mesh.
  - **Cell_Size**
    - Current cell size
    - $\text{Pow}(\text{Volume},1/3)$
  - **Mach_Gradient**
    - Gradient of the Mach number
    - $\text{Grad}(\text{MachNumber})$
  - **Max_Cell_Rescaler**
    - Sets a limit to prevent the cell size from changing too much
    - $(\text{\$Position.mag()>0.8)? 1.1: (\text{\$Position.mag()>0.7)? 2 : (\text{\$Position.mag()-0.7)/0.1 + 1.1)})$
  - **Desired_Cell_Size**
    - Cell Size used for remeshing to achieve <0.05 Mach variation across cell. Capped to prevent cell size increase and prevent size reducing too much
    - $\text{Max}(\text{\max}(\text{\min}(1/(\text{\$Mach_Gradient.mag()}+0.0000001*0.05, \text{\$Cell_Size}), \text{\$Cell_Size}/\text{\$Max_Cell_Rescaler}), 0.00015))$
  - **Cell_Scaler**
    - Determine ratio of desired cell size to actual (Diagnostic Only)
    - $\text{\$Desired_Cell_size}/\text{\$Cell_Size}$
Solving Strategy

- Ran to converged solution on initial mesh
- Refine
  - Lower surface mesh targets and minimums
  - Set Desired_Cell_Size to an XYZ_Table, than assign the XYZ table as the mesh size table
- Iterate to a converged solution
- Refine
  - Set Desired_Cell_Size to an XYZ_Table, than assign the XYZ table as the mesh size table
- Iterate to final converged solution
Shock Capture

- Refinement captures Shocks well
  Mach Number

Absolute Pressure
Physics Models

- Physics Models
  - All $y+$ Wall Treatment
  - Coupled Energy
  - Coupled Flow
    - AUSM+ FVS
  - Gas
    - Air
      - Specific heat to Polynomial in $T$
  - Ideal Gas
  - Steady
  - Three Dimensional
  - Reynolds Averaged Navier Stokes
  - Turbulent
  - K-Omega Turbulence
  - SST (Menter) K-Omega
Conditions Tested

- Ran a Angle of Attack sweep from -2.5° – 45° for each case.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Mach</th>
<th>Pstat</th>
<th>Tstat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mach</td>
<td>6.80</td>
<td>18.43</td>
<td>108.28</td>
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<tr>
<td>Pstat</td>
<td>9.60</td>
<td>2.94</td>
<td>85.41</td>
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<tr>
<td>Tstat</td>
<td>(-)</td>
<td>(PSF)</td>
<td>(R)</td>
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<tr>
<td>Reynolds #</td>
<td>258000</td>
<td>87000</td>
<td>(-)</td>
</tr>
</tbody>
</table>
Results: Blunt Body Centerline Pressure Comparisons

- Pressure normalized by stagnation pressure after shock
- Good qualitative agreement, good quantitative agreement for lower angles of attack

Red = Mach 6.8  
Blue = Mach 9.6  
Unfilled = Mach 6.8  
Filled = Mach 9.6
Results: Blunt Body; Mach 6.8
Lift Comparisons

• CFD slightly over-predicts peak L/D
• Matches CL well at lower angles of attack, with more error at higher angles
Results: Blunt Body; Mach 9.6 Lift Comparisons

- CFD slightly over-predicts peak L/D
- Matches CL well at lower angles of attack, higher angle of attack not collected in tunnel due due to shock on tunnel boundary layer interaction
Results: Sharp Body; Mach 6.8

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Drag Comparisons

- CFD did not capture pitching moment trend at high Angle of Attack
- Matches CD well at lower angles of attack, with more error at higher angles
Results: Blunt Body; Mach 9.6 Drag Comparisons

- Pitching Moment near zero for all tested conditions
- Matches CD well at lower angles of attack, higher angle of attack not collected in tunnel due to shock on tunnel boundary layer interaction
Results: Sharp Body; Mach 6.8
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Future Improvements

• Future work would attempt to improve on the current work
  – Add transition model
  – Further mesh refinement
  – An expanded polynomial for specific heat
• Also could explore more real world representative cases
  – More complicated geometry
  – Higher total temperature case
Conclusions

• STAR-CCM+ was able to replicate the behavior of the wind tunnel test for angles of attack below 30° well
  – Peak L/D was a little high
  – Overall a good match
• At angles of attack above 30° the validation was not as good
  – Lift and Drag were both overpredicted
  – Pitching moment behavior did not match well
  – L/D was still a good match
• Several sources for differences
  – No sting in CFD, and no reference to how sting effects were addressed in the report
  – Measurement error / tunnel effects
  – CFD error