Generation of Adaptive Meshes for GMGW1

Todd Michal, Dmitry Kamenetskiy, Josh Krakos
Boeing Research and Technology
PID 04

1st Geometry and Mesh Generation Workshop
Denver, CO  June 3-4, 2017
Summary of grids generated:

<table>
<thead>
<tr>
<th>Case</th>
<th>Grid Code</th>
<th>Starting Geometry Model</th>
<th>Grid Type</th>
<th>Number of Grid Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>HL-CRM full gap, AoA=8</td>
<td>CADfix, MADCAP/AFLR, EPIC</td>
<td>STEP</td>
<td>Adaptive Tetrahedral</td>
<td>16</td>
</tr>
<tr>
<td>HL-CRM full gap, AoA=16</td>
<td>CADfix, MADCAP/AFLR, EPIC</td>
<td>STEP</td>
<td>Adaptive Tetrahedral</td>
<td>18</td>
</tr>
<tr>
<td>HL-CRM partially sealed, AoA=8</td>
<td>CADfix, MADCAP/AFLR, EPIC</td>
<td>STEP</td>
<td>Adaptive Tetrahedral</td>
<td>15</td>
</tr>
<tr>
<td>HL-CRM partially sealed, AoA=16</td>
<td>CADfix, MADCAP/AFLR, EPIC</td>
<td>STEP</td>
<td>Adaptive Tetrahedral</td>
<td>17</td>
</tr>
</tbody>
</table>

Tools Used

Geometry Preparation – CADfix
Initial Mesh Generation – MADCAP/AFLR
Adaptive Mesh Generation - EPIC¹
Flow Solver – GGNS node centered SUPG finite element

EPIC (Edge Primitive Insertion and Collapse)

- Anisotropic metric-based tetrahedral mesh adaptation
- Iterative application of edge operators (collapse, break, reconnect) to coarsen/refine surface and volume mesh to equilibrate error over domain
- Adaptation performed on tetrahedral mesh with optional prismatic BL grid insertion (normal spacing adapted to solver estimate of $y+$)
- Sizing metric derived from Mach Hessian error estimate
Boeing Grid Tools Geometry Preparation Process

Input Model:
(Iges, STEP, native CAD, ... )

CADfix*
- Compute topology
- Modify/defeature
- Analyze
- Compute parametric trim curves

Analysis Model:
Iges (surfaces trimmed by parametric curves) + topology

* Product of International TechneGroup (ITI)
HL-CRM Geometry Preparation Process

HL-CRM STEP Model

CADfix
- Join chains of edges
- Split faces at iso-lines
- Split aft fuselage
- Compute parametric trim curves

IGES + topology file

HL-CRM Geometry Modifications

1. Trim aft fuselage surface with plane

2. Join chains of short edges on slat LE to remove extraneous edge breaks

3. Split surfaces along iso-parametric lines at leading edges and coves

Clock Time: 1 hour, User Time: 1 hour

- Lessons Learned: covered later

Reason: mesh quality
mesh tool grows single BL strand from surface nodes. Adding aft facing face improves quality of BL mesh

Reason: mesh quality
mesh tool preserves edge end points which would unduly constrain mesh resolution

Reason: robustness
adds additional feature curves to guide mesh generation. Edge collapse and geometry projections are constrained from crossing feature edges.
Mesh Generation Summary

Tetrahedral Initial Mesh (MADCAP and AFLR)

- Objective: coarse surface and volume mesh to start adaptation process
- Sizing based on geometry curvature and user input to control spacing along trailing edges
- Few layers of semi-structured volume boundary elements
- Background function used to generate smooth 3D distribution field
- Mesh generation sequence: edges $\rightarrow$ surfaces $\rightarrow$ volume

*Clock Time*: 15 minutes  *User Time*: 15 minutes
Mesh Generation Summary

Adaptive Mesh

- Objective: remesh to match anisotropic sizing field that matches target number of elements and equilibrates error
- Metric sizing field computed from target # elements and flow solution error estimate
- Metric sizing constrained to specified min/max limits, geometric constraints, growth limits, etc.
- Perform edge breaks, collapses, reconnections to drive mesh towards target sizing metric
- Insert near body BL mesh based on local y+ estimate from solution
- Interpolate solution to new mesh
- Clock Time: ~ 4 days (dependent on machine and grid size)  
  User Time: 30 minutes (job set up and monitoring)

File Formats: AFLR binary ugrid (initial mesh), GGNS (adapted mesh)
HL-CRM Adaptive Mesh Sequence
Mach 0.2, Re=3.26M, $\alpha=16^\circ$  Grid Level 0

Initial Grid and Solution

Grid 0, Nodes=1.5M, Cells= 8.1M
HL-CRM Adaptive Mesh Sequence
Mach 0.2, Re=3.26M, $\alpha=16^\circ$  Grid Level 7

Lift Convergence

Grid 7, Nodes=6.6M, Cells= 39.1M
HL-CRM Adaptive Mesh Sequence
Mach 0.2, Re=3.26M, $\alpha=16^\circ$ Grid Level 12

Lift Convergence

Grid 12, Nodes=14.9M, Cells= 88.5M
HL-CRM Adaptive Mesh Sequence
Mach 0.2, Re=3.26M, $\alpha=16^\circ$  Grid Level 18

Lift Convergence

Grid 18, Nodes=38.8M, Cells= 230.9M
HL-CRM Gapped Adaptive Mesh Convergence With Error Indicator Improvements
HL-CRM Adapted Grid Convergence

- Adapted solutions converge to near constant lift (~ 10M DOF)
  - Slight increase in CL with grid resolution continues
  - Consistent seal-gap increment with increasing grid resolution
Difficulties Encountered

- **Issue 1:** High curvature computed on wing/body fairings
  
  Resolution: placed lower limit on curvature refinement size
  
  Lost time: none, modified limit as adaptation job ran

- **Issue 2:** Invalid mesh created on HL-CRM full gap model after 9\textsuperscript{th} grid level for AoA=8° case
  
  Resolution: modified geometry and restarted adaptation from 8\textsuperscript{th} grid level
  
  Lost time: cpu time for 2 grid/solution computations (~8 wall clock hours)

- **Issue 3:** Potential geometry issue discovered when analyzing HL-CRM full gap results
  
  Resolution: reprocessed geometry and reran adaptation (8 and 16 degrees)
  
  Rework time: calendar and cpu time for 2 adaptive solutions (~4 days)
Issue 2: Geometry Problem Leads to Grid Failure
HL-CRM Full Gap Model Side of Inboard Flap

- Untrimmed flap surface
- 0.02" trim curve offset from surface

Invalid adapted mesh resulting from geometry surface mismatch

Invalid Adapted Mesh at AoA=8°
Discovery of 0.01” offset in slat TE trim curves
Issue 3: HL-CRM Full Gap Slat Cove TE Surface Mesh

- Trim curve offset introduced during geometry processing (did not appear in original STEP file)
- Found to be a problem with the export tolerance during preparation
- Model was re-exported and solutions were regenerated – did not impact results
## HL-CRM Adapted Mesh Statistics

<table>
<thead>
<tr>
<th>Geometry Model</th>
<th>Grid Type</th>
<th>Grid Level</th>
<th>Nodes</th>
<th>BFaces</th>
<th>Volume Cells</th>
<th>Solver Residual Convergence</th>
<th>Solver Iterations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>full gap, AoA=8</strong></td>
<td>Adapted Tetrahedral</td>
<td>1</td>
<td>1.5M</td>
<td>375K</td>
<td>8.1M</td>
<td>5.0e-09</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>8.4M</td>
<td>413K</td>
<td>49.6M</td>
<td>1.4e-9</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11</td>
<td>12.9M</td>
<td>541K</td>
<td>76.6M</td>
<td>9.2e-09</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td></td>
<td>16</td>
<td>28.0M</td>
<td>1.1M</td>
<td>166.3M</td>
<td>1.1e-07</td>
<td>149</td>
</tr>
<tr>
<td><strong>full gap, AoA=16</strong></td>
<td></td>
<td>1</td>
<td>1.5M</td>
<td>375K</td>
<td>8.1M</td>
<td>6.1e-10</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>16.0M</td>
<td>707K</td>
<td>95.3M</td>
<td>9.9e-09</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14</td>
<td>39.4M</td>
<td>1.4M</td>
<td>234.3M</td>
<td>1.5e-09</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18</td>
<td>53.6M</td>
<td>1.8M</td>
<td>318.9M</td>
<td>8.5e-09</td>
<td>105</td>
</tr>
<tr>
<td><strong>partially sealed, AoA=8</strong></td>
<td></td>
<td>1</td>
<td>939K</td>
<td>280K</td>
<td>6.6M</td>
<td>1.4e-09</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>12.2M</td>
<td>510K</td>
<td>72.6M</td>
<td>9.8e-10</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13</td>
<td>19.3M</td>
<td>718K</td>
<td>114.9M</td>
<td>6.0e-09</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>30.5M</td>
<td>1.0M</td>
<td>181.6M</td>
<td>3.5e-09</td>
<td>56</td>
</tr>
<tr>
<td><strong>partially sealed, AoA=16</strong></td>
<td></td>
<td>1</td>
<td>939K</td>
<td>280K</td>
<td>6.6M</td>
<td>5.3e-10</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12</td>
<td>15.1M</td>
<td>507K</td>
<td>89.8M</td>
<td>2.8e-09</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14</td>
<td>24.1M</td>
<td>725.6K</td>
<td>143.78M</td>
<td>1.8e-09</td>
<td>81</td>
</tr>
<tr>
<td></td>
<td></td>
<td>17</td>
<td>49.0M</td>
<td>1.2M</td>
<td>292.2M</td>
<td>2.5e-06</td>
<td>149</td>
</tr>
</tbody>
</table>

### Element Metric Quality

#### HL-CRM Gapped Geometry
- **$\alpha=8$, Grid 16**
- **$\alpha=16$, Grid 18**

#### HL-CRM Partially Sealed Geometry
- **$\alpha=8$, Grid 15**
- **$\alpha=16$, Grid 17**
HL-CRM Partial Seal Adapted Mesh, $\alpha=16$

Surface Mesh
Wing Upper Surface
HL-CRM Partial Seal Adapted Mesh, $\alpha=16$

Surface Mesh
Wing Lower Surface
HL-CRM Partial Seal Adapted Mesh, $\alpha=16$

Surface Mesh - Wing Slat LE at Root
HL-CRM Partial Seal Adapted Mesh, $\alpha=16$

Surface Mesh - Wing Flap TE at Root
HL-CRM Partial Seal Adapted Mesh, $\alpha=16$

Surface Mesh - Wing Tip LE
HL-CRM Partial Seal Adapted Mesh, $\alpha=16$

Surface Mesh - Wing Tip TE
HL-CRM Partial Seal Adapted Mesh, $\alpha=16$

Flap Gap Upper Surface

Partial Seal Model

Full Gap Model
HL-CRM Partial Seal Adapted Mesh, $\alpha=16$

Volume Mesh Cut at $y=277.5$
HL-CRM Partial Seal Adapted Mesh, $\alpha=16$

Volume Mesh Cut at $y=638$
HL-CRM Partial Seal Adapted Mesh, $\alpha=16$

Volume Mesh Cut at $y=1050$
Mesh Evaluation

- Meshes were evaluated based on
  - Validity
    - Consistent volume and boundary element topology
    - Positive face/cell volume
    - Ability to compute implied element Metric determinant
  
  - Conformance to metric sizing field
    - Edge lengths computed in metric space
    - Cell quality metric (computed in metric space)

- Ultimately evaluation was based on “fit for purpose”
  - Solver convergence and solution cost (number of iterations)
  - Grid convergence
  - Solution accuracy and cost (both CPU and labor)

$$Q_{cell} = \frac{48}{3^{1/3}} \left(\frac{1}{2} V'\right)^{2/3} \sum_{i=1}^{6} (L'_i)^2$$

where

- $V'$ = transformed volume
- $L'_i$ = transformed edge length
Summary

- **Adaptive meshes generated for HL-CRM**
  - Robustly generated adapted mesh families for full gap and sealed models at 8 and 16 degrees angle of attack
  - Meshes were “fit for purpose” - machine zero solution convergence on most meshes and results approached constant lift with grid size for all cases

- **A few geometry related issues were encountered**
  - Gaps between parametric trim curves – introduced during preprocessing
  - High curvature computed for wing/flap fairing
  - Geometry tolerance is particularly important for adaptive meshing

- **Adaptive meshing provided several advantages**
  - Automatic generation of consistent mesh family in days (compared to weeks for fixed grid approach)
  - No a priori solution knowledge required
  - Reduced solution uncertainty due to mesh
Questions?