OVERSET MESH GENERATION FOR THE HIGH-LIFT COMMON RESEARCH MODEL

William M. Chan

Computational Aerosciences Branch

AMS Seminar Series, March 9, 2017
OVERVIEW

1st AIAA Geometry and Mesh Generation Workshop
3rd AIAA High-Lift Prediction Workshop

- Introduction

- Structured overset meshing methods and best practices using Chimera Grid Tools (CGT): AIAA Paper 2017-0362

- Lessons learned
  - Meshing a family of grid systems at different resolutions
  - Grid quality checks

- Summary and conclusions
STRUCTURED OVERSET MESHING USING CGT: METHODS AND BEST PRACTICES
HIGH-LIFT CRM GEOMETRIC CONFIGURATIONS

Full Flap Gap (coarse, medium, fine, extra fine)

Partially-Sealed Flap Gap (medium only)
OVERSET STRUCTURED GRID GENERATION PROCESS AND SCRIPTING FRAMEWORK

Main steps
- Geometry processing
- **Surface grid generation:** featured-based domain decomposition, grid point distribution, mesh fill
- **Volume grid generation:** hyperbolic near-body, Cartesian off-body
- **Domain connectivity:** grid points blanking, donor stencil search
- Input parameters preparation for flow solver:
  - boundary conditions, grid indices for component aerodynamic loads

Develop script that reproduces entire process
- Chimera Grid Tools Script Library (Tcl-based, 200+ macros)
- Component scripts (fuselage, slat, flaps, wing)
- Master script
- Parameterized inputs
  - max stretching ratio (surface and volume)
  - surface grid spacing (max interior, at surface features)
  - volume grid wall normal spacing
  - min number of points on smallest feature
GEOMETRY PROCESSING

- Geometry definition files supplied: native CAD, STEP, IGES
- Create starting point for grid generation script development
  - **Unstructured surface triangulation** (CART3D format)
    - Generated using ANSA software
    - Sufficient resolution at high curvature regions
  - **Surface curves** (PLOT3D format)
    - Generated using Chimera Grid Tools from surface triangulation
    - CAD edges including all surface features
- Identify configuration characteristic lengths
  - component length scale
  - smallest feature size
  - gap size between components

chord
cusp / t.e.
thickness
gap size
GRID POINT DISTRIBUTION MESHING GUIDELINES

Mostly prescribed by High-Lift Prediction Workshop document

Nose spacing

Tail spacing

Maximum interior spacing and stretching ratio

Root spacing

Leading edge spacing

Tip spacing

Wall normal spacing

Wall normal stretching ratio

Number of points across blunt trailing edge/cusp

Streamwise spacing at t.e. (spacing continuity for O-topology)

Trailing edge spacing
WORKSHOP PRESCRIBED MESHING PARAMETERS

Reference spacing $\Delta s_{\text{ref}} = 3\%$ mean aerodynamic chord

<table>
<thead>
<tr>
<th>Resolution Level</th>
<th>Coarse</th>
<th>Medium</th>
<th>Fine</th>
<th>Extra Fine</th>
</tr>
</thead>
<tbody>
<tr>
<td># Points on trailing edge</td>
<td>5</td>
<td>9</td>
<td>13</td>
<td>17</td>
</tr>
<tr>
<td>Span spacing at flap gap</td>
<td>12.5</td>
<td>8.3</td>
<td>6.25</td>
<td>5.0</td>
</tr>
<tr>
<td>cap grids (x $10^{-2}$) *</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max surface spacing</td>
<td>$1.5 \Delta s_{\text{ref}}$</td>
<td>$\Delta s_{\text{ref}}$</td>
<td>$\Delta s_{\text{ref}} / 1.5$</td>
<td>$\Delta s_{\text{ref}} / 1.5^2$</td>
</tr>
<tr>
<td>Wall normal stretching ratio</td>
<td>1.25</td>
<td>1.16</td>
<td>1.1</td>
<td>1.07</td>
</tr>
<tr>
<td>Wall normal spacing (x $10^{-4}$)</td>
<td>17.5</td>
<td>11.7</td>
<td>7.8</td>
<td>5.2</td>
</tr>
</tbody>
</table>

* Not prescribed by workshop

GRID QUALITY CHECKS

All volume meshes are automatically checked for
- Positive Jacobians as computed by target flow solver (OVERFLOW)
- Self intersections with surface mesh
INITIAL CURVES AND SURFACE GRIDS
Fuselage Features: Cockpit Window, Fairing, Wing Intersection

Initial Curves (28)

Cockpit Window
Geometry trimmed by wing intersection curve

Fuselage Fairing

Wing/Fuselage Intersection

Fuselage Side of Wing/ Fuselage Collar Grid

Surface Grids (13)
INITIAL CURVES AND SURFACE GRIDS
Slat and Flap Features: L.E., T.E., Cusp, Root, Tip

Slat Initial Curves (20)

Slat Cap Grids (5 at each root and tip)

Flap Initial Curves (2x12)

Flap Surface Grids (2x10)

Flap Cap Grids (4 at each root and tip)

Flap Gap Region
INITIAL CURVES AND SURFACE GRIDS

Wing Features: L.E., T.E., Root Intersection, Tip, Slat Cove, Flap Cove, Cove Side Walls

Wing Initial Curves (65)

Wing Surface Grids (22)

Wing/Fuselage Junction (3 collars)

Wing Tip

Flap Cove Side Wall

Slat Cove Side Wall
FLAP PARTIAL SEAL SURFACE GRIDS

Re-use grids from full flap gap case for fuselage, slat, wing, and flaps

Partial flap seal against fuselage
Partial flap seal between inboard and outboard flaps

Back and side wall cap split into two grids to avoid double concave corner => easier for hyperbolic volume mesh generation
SLICES OF FUSELAGE, SLAT, FLAP VOLUME GRIDS
SLICES OF WING VOLUME GRIDS

Main Wing

Wing/Fuselage Collar Grids

Slat Cove Side Wall

Flap Cove Side Wall
**WALL-NORMAL GRID POINT DISTRIBUTION**

**Fuselage and Slat**
1. Uniform spacing first two cells ($\Delta s_{\text{wall}}$)
2. Stretched region to outer boundary

**Wing and Flaps**
Need to resolve shear layer from preceding component for accurate drag prediction
1. Uniform spacing first two cells ($\Delta s_{\text{wall}}$)
2. Stretched region
3. Shear layer region
   - Uniform spacing = 100 x $\Delta s_{\text{wall}}$
   - Thickness = 3 in.
   - Distance from wall = 1.5 in.
4. Stretched region to outer boundary
OFF-BODY STRETCHED CARTESIAN VOLUME GRIDS

- Cartesian box grid with uniform core and stretched outer layers
- One box grid around fuselage volume grids
- Three staggered box grids around slat, wing, flaps

- Large stretched box grid encloses all smaller box grids and goes to far field
DOMAIN CONNECTIVITY
Comparison of Two Approaches

Chimera Components Connectivity Program (C3P)

- Inputs: boundary conditions for each mesh, and component ID for each solid wall (low manual effort needed)

- External process performed prior to running OVERFLOW flow solver

OVERFLOW-DCF (DCF)

- Inputs: boundary conditions for each mesh, X-ray map for each hole cutter, list of grids to be cut by each X-ray, constant offset distance for each hole cut instruction (significant manual effort needed)

- Built into the OVERFLOW flow solver
CONSTANT SPAN CUT THROUGH VOLUME MESH
(Wing Trailing Edge, Flap Leading Edge Region)

C3P
(spatially variable offset)

DCF
(constant offset)
VARIOUS VOLUME SLICES FROM C3P CONNECTIVITY

Constant-x cut across flap gap

Constant-x cut at wing/fuselage junction
GRID SCRIPT DEVELOPMENT TIME (MEDIUM MESH)

Two different domain connectivity methods/software

<table>
<thead>
<tr>
<th>Task</th>
<th>Time (hr.)</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry processing</td>
<td>3.75</td>
<td>5.5</td>
</tr>
<tr>
<td>Surface grid generation</td>
<td>56.05</td>
<td>81.7</td>
</tr>
<tr>
<td>Volume grid generation</td>
<td>4.50</td>
<td>6.6</td>
</tr>
<tr>
<td>Domain connectivity (C3P)</td>
<td>1.20</td>
<td>1.7</td>
</tr>
<tr>
<td>Input prep. (flow solver b.c., post-processing)</td>
<td>3.1</td>
<td>4.5</td>
</tr>
<tr>
<td>Total</td>
<td>68.6</td>
<td>100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Task</th>
<th>Time (hr.)</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry processing</td>
<td>3.75</td>
<td>4.7</td>
</tr>
<tr>
<td>Surface grid generation</td>
<td>56.05</td>
<td>69.9</td>
</tr>
<tr>
<td>Volume grid generation</td>
<td>4.50</td>
<td>5.6</td>
</tr>
<tr>
<td>Domain connectivity (DCF)</td>
<td>12.8</td>
<td>16.0</td>
</tr>
<tr>
<td>Input prep. (flow solver b.c., post-processing)</td>
<td>3.1</td>
<td>3.9</td>
</tr>
<tr>
<td>Total</td>
<td>80.2</td>
<td>100.0</td>
</tr>
</tbody>
</table>
GRID SCRIPT DEVELOPMENT FOR DIFFERENT LEVELS OF MESH RESOLUTION AND PARTIALLY-SEAL FLAP GAP

Full flap gap coarse, fine, and extra-fine level grid systems
- Created independently from the medium level system
- Not a redistributed version of medium mesh

Partially-sealed flap gap medium system
- Created by copying fuselage, slat and wing grids, and some flap grids from full gap grid system
- Only need to create grids for partial seals

<table>
<thead>
<tr>
<th>Flap Gap Geometry</th>
<th>Full Gap</th>
<th>Partial Seal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution Level</td>
<td>Coarse</td>
<td>Medium</td>
</tr>
<tr>
<td>Grid script</td>
<td></td>
<td></td>
</tr>
<tr>
<td>development time</td>
<td>10.0 *</td>
<td>68.6 *</td>
</tr>
<tr>
<td>(hr.)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Additional development time beyond medium mesh script
GRID SYSTEM STATISTICS

- Entire process performed on Linux Xeon desktop workstation
- All timings include i/o

<table>
<thead>
<tr>
<th>Flap Gap Geometry</th>
<th>Full Gap</th>
<th>Part Seal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution Level</td>
<td>Coarse</td>
<td>Medium</td>
</tr>
<tr>
<td># Grids</td>
<td>72</td>
<td>72</td>
</tr>
<tr>
<td># Surface grid points (x 10^6)</td>
<td>0.27</td>
<td>0.51</td>
</tr>
<tr>
<td># Volume grid points (x 10^6)</td>
<td>24.1</td>
<td>65.4</td>
</tr>
<tr>
<td>Grid script devel. time (hr.)</td>
<td>10.0</td>
<td>68.6</td>
</tr>
<tr>
<td>Grid script exec. time (min.)</td>
<td>3.25</td>
<td>5.35</td>
</tr>
<tr>
<td>Connectivity (C3P) exec. wall time (min.), mem use (GB)</td>
<td>1.14 (6)</td>
<td>2.85 (13)</td>
</tr>
<tr>
<td>24 OpenMP threads</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Connectivity (DCF) exec. wall time (min.)</td>
<td>0.50</td>
<td>1.52</td>
</tr>
<tr>
<td>24 MPI ranks</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

n/a = not attempted due to extra manual time needed to create special X-ray cutters
OVERFLOW PRELIMINARY RESULTS
(Tom Pulliam)

Grid Sizes
- Coarse: 2.4M
- Medium: 6.5M
- Fine: 189M
- X-Fine: 565M

Connectivity: C3P and DCF

Parameters:
- Mach = 0.2, Alpha = 8 deg,
- Re = 3.26M based on MAC
- 3rd order Roe, SA-RC-QCR2000
LESSONS LEARNED FROM MESHING EXERCISE
GENERATION OF FAMILY OF GRID SYSTEMS AT DIFFERENT MESH RESOLUTIONS (COARSE, MEDIUM, FINE, EXTRA-FINE)

- Grid system at each resolution level is generated independently of each other starting from geometry definition

- Different meshing parameters prescribed for each level (e.g., max stretching ratio, max interior surface grid spacing, grid spacing at surface features, number of points on t.e., volume mesh wall normal spacing)

- Current practices do not provide automatic adjustments of marching distances and smoothing parameters

- Significant grid script execution time at extra-fine level (> 0.5 hr)
PARAMETER ADJUSTMENTS AT DIFFERENT LEVELS OF GRID RESOLUTIONS (1)

Hard coded grid indices for medium mesh script

Splitting locations defined by
- Grid indices => faster one level (medium) mesh development
- Grid coordinates or distance to reference point => slightly slower one level development but works for all levels
PARAMETER ADJUSTMENTS AT DIFFERENT LEVELS OF GRID RESOLUTIONS (2)

Hyperbolic grid marching distances chosen to provide optimal overlap at coarse level (e.g., 5-point overlap for 5-point flow solver stencil)

- Too much overlap at fine and extra fine levels
PARAMETER ADJUSTMENTS AT DIFFERENT LEVELS OF GRID RESOLUTIONS (3)

Finer grid spacing in concave corners in finer levels
- Need to adjust smoothing parameters for hyperbolic marching
GRID QUALITY CHECK UTILITIES
NOT CURRENTLY IN CGT

1. Distance of surface grid points to geometry definition (Native CAD, STEP, IGES)

2. Distance to wall of first grid point normal to viscous wall

3. Cell orthogonality (surface and volume)

Need min/max and distribution of grid attribute statistics => Histogram and color map display
GRID QUALITY CHECK UTILITIES IN CGT (1)
Jacobians and Cell Volumes

Must pass
1. Jacobian computed using same subroutine as in target flow solver
   OVERFLOW (all > 0)
2. Self-intersection of volume grid points against surface grid (none)

Mostly pass
3. Cell volume using hexahedral decomposition into 6 tetrahedrons
4. Stretching ratio (<= 1.2)
   - Cut into 2 prisms
   - Cut each prism into 3 tets
   - Bad cell if
     1. any tet volume < 0
     2. sum of 6 tet volumes < 0

OVERGRID Diagnostic
GRID QUALITY CHECK UTILITIES IN CGT (2)

Domain Connectivity: Orphan Points

Number, location and spread (OVERGRID)

Total = 25, sparse points away from surface
Domain Connectivity: Fringe Point Donor Stencil Accuracy

Histogram of distance between fringe point and vertex obtained by donor stencil interpolation (*intchk* tool in CGT)

<table>
<thead>
<tr>
<th>Distance</th>
<th>Number of pts</th>
<th>% Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>d &lt; 0.0001</td>
<td>2592370</td>
<td>89.207</td>
</tr>
<tr>
<td>0.0001 &lt;= d &lt; 0.001</td>
<td>127886</td>
<td>4.401</td>
</tr>
<tr>
<td>0.001 &lt;= d &lt; 0.01</td>
<td>128241</td>
<td>4.413</td>
</tr>
<tr>
<td>0.01 &lt;= d &lt; 0.1</td>
<td>47312</td>
<td>1.628</td>
</tr>
<tr>
<td>0.1 &lt;= d &lt; 1.0</td>
<td>10167</td>
<td>0.350</td>
</tr>
<tr>
<td>1.0 &lt;= d &lt; 10.0</td>
<td>49</td>
<td>1.7E-03</td>
</tr>
<tr>
<td>10.0 &lt;= d</td>
<td>0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Set *NORFAN* carefully in OVERFLOW for viscous stencil repair.

Donor stencil with NORFAN = 25

Point obtained using interpolation coefficients on 8 corners of donor cell.
GRID QUALITY CHECK UTILITIES IN CGT (4)
Domain Connectivity: Donor Stencil Attributes Compatibility

Compatibility of cell attributes between fringe point and donor stencil
- Cell volume ratio histogram table (intchk) and location map (OVERGRID)
- Bad ratio => gradients cannot be transferred accurately between grids

Other attributes that could be checked
- Cell aspect ratio, orientation

<table>
<thead>
<tr>
<th>Volume ratio</th>
<th># Pts.</th>
<th>% Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 &lt;= C &lt;= 1.0</td>
<td>2714268</td>
<td>48.26</td>
</tr>
<tr>
<td>0.2 &lt;= C &lt; 0.5</td>
<td>1705036</td>
<td>30.32</td>
</tr>
<tr>
<td>0.1 &lt;= C &lt; 0.2</td>
<td>670232</td>
<td>11.92</td>
</tr>
<tr>
<td>0.01 &lt;= C &lt; 0.1</td>
<td>525048</td>
<td>9.34</td>
</tr>
<tr>
<td>0.001 &lt;= C &lt; 0.01</td>
<td>9631</td>
<td>0.17</td>
</tr>
<tr>
<td>C &lt; 0.001</td>
<td>21</td>
<td>0.37E-03</td>
</tr>
</tbody>
</table>

Volume ratio < 0.01
GRID QUALITY CHECK UTILITIES IN CGT (5)

Domain Connectivity: Conversion to Lower Fringe Layers

- Insufficient grid overlap to support double fringe locally
- Option to convert from double fringe to single fringe
  => full 5-point differencing stencil not supported in flow solver
     (lower accuracy, robustness)
GRID QUALITY CHECK UTILITIES IN CGT (6)
Domain Connectivity: Donor Stencil Quality

Histogram table (intchk) and location map (OVERGRID)

<table>
<thead>
<tr>
<th>Stencil Quality</th>
<th>Number</th>
<th>% Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q = 0.0</td>
<td>0</td>
<td>0.0000</td>
</tr>
<tr>
<td>0.0 &lt; Q &lt; 0.1</td>
<td>0</td>
<td>0.0000</td>
</tr>
<tr>
<td>0.1 &lt;= Q &lt; 0.2</td>
<td>0</td>
<td>0.0000</td>
</tr>
<tr>
<td>0.2 &lt;= Q &lt; 0.3</td>
<td>4858</td>
<td>0.1672</td>
</tr>
<tr>
<td>0.3 &lt;= Q &lt; 0.4</td>
<td>12120</td>
<td>0.4171</td>
</tr>
<tr>
<td>0.4 &lt;= Q &lt; 0.5</td>
<td>14660</td>
<td>0.5045</td>
</tr>
<tr>
<td>0.5 &lt;= Q &lt; 0.6</td>
<td>14054</td>
<td>0.4836</td>
</tr>
<tr>
<td>0.6 &lt;= Q &lt; 0.7</td>
<td>19504</td>
<td>0.6712</td>
</tr>
<tr>
<td>0.7 &lt;= Q &lt; 0.8</td>
<td>24788</td>
<td>0.8530</td>
</tr>
<tr>
<td>0.8 &lt;= Q &lt; 0.9</td>
<td>23280</td>
<td>0.8011</td>
</tr>
<tr>
<td>0.9 &lt;= Q &lt; 1.0</td>
<td>45317</td>
<td>1.5594</td>
</tr>
<tr>
<td>Q = 1.0</td>
<td>2573858</td>
<td>88.5697</td>
</tr>
</tbody>
</table>

Stencil quality < 0.26
Domain Connectivity: Hole Boundary Location & Smoothness

Avoid

Good

Irregular hole boundaries?

Visualization in OVERGRID

SUMMARY AND CONCLUSIONS (1)
Workshop Baseline Meshes

- Grid systems generated and scripted using Chimera Grid Tools
  - Full flap gap geometry (coarse, medium, fine, and extra fine levels)
  - Partially-sealed flap gap (medium only)

- Workshop guidelines are mostly consistent with current overset grid generation best practices

- Surface grid generation is the most time consuming step

- Some adjustments needed in developing grid scripts for different levels of grid resolution => ideas for further automation development

- Total development time for all 5 systems ~ 121 man hours

- Grid script execution time ~ a few minutes (coarse, medium, fine), half hr.+ (extra-fine)

- Preliminary solutions have been computed using OVERFLOW for all 5 grid systems
SUMMARY AND CONCLUSIONS (2)

Grid Quality Checks

- Effective evaluation using histograms and location maps

- Wish list
  - Distance to geometry
  - Distance of first volume grid point to wall
  - Cell orthogonality

- Must-pass grid quality checks
  - Jacobians and self-intersection on surface

- Mostly-pass grid quality checks
  - Cell volumes
  - Various domain connectivity statistics
  - Need study on how flow solution is affected
    - Accuracy
    - Convergence
    - Robustness / Stability
ACKNOWLEDGEMENTS

- This work has been partially funded by NASA’s Transformational Tools and Technologies (TTT) Project of the Transformative Aeronautics Concepts Program under the Aeronautics Research Mission Directorate

- The author wishes to thank
  - Jeff Housman (NASA Ames) for help in ANSA
  - Tom Pulliam (NASA Ames) for computing preliminary OVERFLOW solutions on all the grid systems