KHI computed results using Cflow for HiLiftPW-2

Taku Nagata, Yosuke Ueno, Akio Ochi
Aerospace Company
Kawasaki Heavy Industries, LTD.
Presentation Outline

- Introduction
- KHI in-house CFD tool, “Cflow”
- KHI independently-generated grid by “Cflow”
- Results
  - Comparison between Cflow grid and committee provided grid
- Conclusion
Kawasaki Heavy Industries, LTD. (KHI) is a Japanese manufacturer of a variety of transportation equipment (ships, rolling stock, aircraft, motorcycle), plant, and general machinery.

Main Products of Kawasaki Group

Achieving new heights in technology

Main Products of Aerospace Company

Airplanes

Helicopters

Space-related

quote from http://www.khi.co.jp/
History of CFD Engineering in KHI

- Since 1980s KHI has developed in-house CFD tools and used them for aircraft design

KHI CFD tools (UG3 + PUFGG) show a close correlation with flight test data in actual developing aircraft.
Early studies of Cflow

- KHI developed Cflow to meet growing needs for computation of *highly complicated configuration* or *unsteady analysis* about *aeroacoustic problem*, wake interaction, etc.
  - Landing gear of aircraft
  - Pantograph of high speed train

- Next target is to steady/unsteady computation about aircraft configuration (*high aspect ratio* wing, *sweptback* and *dihedral* angle)

![Cartesian base grid achieved promising result](image)
Motivation and KHI computed cases

- Validation and verification of KHI in-house CFD code
- Benchmark new CFD tool “Cflow” for a 3D high lift configuration and clarify the issues

<table>
<thead>
<tr>
<th>Case1</th>
<th>Grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow Solver</td>
<td>Cflow</td>
</tr>
<tr>
<td></td>
<td>Cflow</td>
</tr>
<tr>
<td></td>
<td>UG3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case2a,2b</th>
<th>Grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow Solver</td>
<td>Cflow</td>
</tr>
<tr>
<td></td>
<td>Cflow</td>
</tr>
<tr>
<td></td>
<td>UG3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case4</th>
<th>Grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow Solver</td>
<td>Cflow</td>
</tr>
<tr>
<td></td>
<td>Cflow</td>
</tr>
<tr>
<td></td>
<td>UG3</td>
</tr>
</tbody>
</table>

*Submitted data were inappropriate in outflow boundary condition. Revised data will be submitted.
Distinctive point of Cflow Grid

- Cflow conducts automatic Cartesian based grid generation
  - with octree Adaptive Mesh Refinement (AMR)
  - with Layered grid near surface for boundary layer
- In addition, “Non-Orthogonal Initial Grid” was developed to increase flexibility for high aspect ratio and sweptback configuration

**NOBLU (Non-orthogonal Octree Boundary-fitted Layer Unstructured) Grid**

- NOBLU Grid concept has been applied to NASA-CRM configuration (AIAA-2012-1259)
Cflow Grid Generation Procedure

- User prepare surface grid (STL) and initial grid (Cartesian or arbitrary non-orthogonal)
- Cflow automatically generate AMR with layer grid and surface mesh

**Surface Grid**

**Initial Grid**

**Frontal Surface**

**Step 1:** Octree Refinement

**Step 2:** Cell removal near body

**Step 3:** Frontal Surface smoothing

**Step 4:** Projection with feature lines preserving technique and Layer Grid generation
Initial Grid for High Lift Configuration

- A multi-block hexahedral structured grid generated by PointwiseV17
  - Cuboidal block near the fuselage, oblique block along sweptback and dihedral angle around the wing
  - Control grid density and aspect ratio
- Pile-up forming volume grid generated from structured grid boundary surface to far-field boundary

Multi-block structured grid near the body (hexahedron)

Keep hexahedron cells near the body to allow adaptive mesh refinement

Use pyramid, prism, tetra cells at far from the body

X constant plane

Y constant plane

Z constant plane

Arbitrary shaped Initial Grid
Cflow Grid Information

- **Case 1 – Config 2**
  - Cflow generated Coarse and Medium level grid. Fine level grid was not completed

<table>
<thead>
<tr>
<th>Grid Level</th>
<th>Number of Total Nodes</th>
<th>Number of Total Cells</th>
<th>Wall Boundary Nodes</th>
<th>Wall Boundary Faces</th>
<th>Number of BL Layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td>23 million</td>
<td>23 million</td>
<td>0.6 million</td>
<td>0.6 million</td>
<td>32</td>
</tr>
<tr>
<td>Medium</td>
<td>74 million</td>
<td>74 million</td>
<td>1.3 million</td>
<td>1.3 million</td>
<td>52</td>
</tr>
<tr>
<td>Fine</td>
<td>will be about 200 million</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

- **Case 2 – Config 4 (Config 2 + FTF/STF)**
  - Gridding was not completed

**FYI:** Config2_C_uns_mix_medium grid; the number of total cells is 130 million

Need to improve grid generation algorithm / technique / Initial Grid
Grid detail, Wing

Cflow Grid - Coarse  Cflow Grid - Medium  C_uns_mix Grid - Medium
Grid detail, flap-seal

Cflow Grid - Coarse  Cflow Grid - Medium  C_uns_mix Grid - Medium
Grid detail, $\eta=0.288$ (PS 02)

Cflow Grid - Coarse    Cflow Grid - Medium    C_uns_mix Grid - Medium
Grid detail, $\eta=0.681$ (PS 06)
Numerical schemes of flow solver (used in this study)

- Grid System
  - Unstructured hybrid grid (polyhedral cells) with *layered grid*
  - Octree Adaptive Mesh Refinement (*AMR*)
- Governing equation
  - Reynolds-Averaged Navier-Stokes equation (*RANS*)
- Time integration
  - Matrix Free Gauss-Seidel (*MFGS*) implicit method
- Spatial discretization
  - Cell-centered finite volume method
  - Simple Low-dissipation AUSM scheme (*SLAU*)
  - 2nd-order accurate MUSCL with modified Green-Gauss method
- Turbulence model
  - Spalart-Allmaras one equation model (*S-A*)
- Parallel computation
  - domain decomposition method with *MPI*
Results: Case1, Iterative

- Cflow grid got to steady state faster than C_uns_mix grid

![Graphs showing convergence of Cflow grid and C_uns_mix grid for Case1, Medium grid, θ = 7° and θ = 16°.](image)
Results: Case1, Grid Convergence

- Cflow grid shows higher lift and lower drag than that of C_uns_mix grid
- Cflow grid can estimate experimental data with smaller grid size

Grid convergence of $C_L$ at $\alpha=7,16^\circ$

Grid convergence of $C_D$ at $\alpha=7,16^\circ$
Results: Case1, force & moment (1/2)

- most of the CFD results show lower lift than that of ETW data
- $C_L$ of Cflow-Medium grid is in good agreement with ETW data
- high angle of attack cases will be computed
Results: Case1, force & moment (2/2)

- $C_L-C_M$ curve shapes vary widely at lower angle of attack
- Cflow grid has less separation area on the outboard flap than that of C_uns_mix grid
Results: Case 4, Grid Convergence

- Submitted data were inappropriate outflow boundary condition (used free-stream condition)
- Revised computed data (used pressure outflow condition) shows good agreement with NASA codes in converged data.

![Graph showing Cf at X=0.75 for different grid sizes and turbulence models.](image)

![Graph showing CL vs. h for different turbulence models.](image)
Conclusion

- KHI has been developing a new CFD tool “Cflow”
  - consists of Cartesian based grid generator and flow solver
  - “Non-Orthogonal Initial Grid” was developed to increase flexibility such as high aspect ratio and sweptback cells
- Benchmark Cflow for 3D high lift configuration
  - Cflow generated Coarse and Medium level grid. Fine grid was not completed
    - Cflow grid can reduce grid point by controlling initial grid shape and grid density
    - Cflow grid generation algorithm needs more robustness
  - Compared between “Cflow grid” and “C_uns_mix grid” calculated by “Cflow solver”
    - Cflow grid (i.e. NOBLU grid) shows a capability of application to an aircraft with high lift configuration.

- Cflow Grid (CGNS format) and computed results will be submitted
Thank you for your attention.

If you become interested in “Cflow”, you can find more detail information in the bellow papers.


1. Inter-noise, Pantograph
2. AIAA-2012-1259, NASA-CRM configuration
3. AIAA-2012-2284, Landing Gear
Computed time

- **Cflow Grid**
  - Medium grid
  - 128CPU parallel
  - about 4 days
  - CPU: Xeon X5660, 2.8GHz, 2CPU/6cores

- **C_uns_mix Grid**
  - Medium grid
  - use 256CPU
  - about 3 days
  - Xeon E5-2670, 2.6GHz, 2CPU/8cores
CAD modification

- Intersection point of flap-seal and wing lower surface was moved a little forward for easier grid generation
Numerical schemes of flow solver

- Cflow basically implemented proven methods in UG3, furthermore some new schemes

<table>
<thead>
<tr>
<th></th>
<th>Cflow</th>
<th>UG3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Grid Systems</strong></td>
<td>Unstructured hybrid (polyhedral cells)</td>
<td>Unstructured hybrid (hexahedron, prism, pyramid, tetrahedron cells)</td>
</tr>
<tr>
<td></td>
<td>Octree Adaptive Mesh Refinement</td>
<td>Overset Grid</td>
</tr>
<tr>
<td><strong>Governing Equations</strong></td>
<td>Three-dimensional, compressible Euler/Navier-Stokes</td>
<td></td>
</tr>
<tr>
<td><strong>Data Structure</strong></td>
<td>face based</td>
<td>cell based</td>
</tr>
<tr>
<td><strong>Spatial Discretization</strong></td>
<td>Cell-centered finite volume method</td>
<td></td>
</tr>
<tr>
<td><strong>Reconstruction</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interpolation to face value</td>
<td>MUSCL with modified Green-Gauss</td>
<td>MUSCL</td>
</tr>
<tr>
<td>Approximate Riemann Solver</td>
<td>SHUS, SLAU</td>
<td>SHUS, LSHUS, Roe, etc.</td>
</tr>
<tr>
<td>Viscous Term</td>
<td>2nd-order central difference</td>
<td></td>
</tr>
<tr>
<td><strong>Turbulence Models</strong></td>
<td>Spalart-Allmaras (S-A)</td>
<td>S-A, Baldwin-Barth(B-B), Baldwin-Lomax (B-L), etc.</td>
</tr>
<tr>
<td><strong>Unsteady Turbulence Models</strong></td>
<td>DES, DDES</td>
<td>DES, DDES, LES</td>
</tr>
<tr>
<td><strong>Time Integration</strong></td>
<td></td>
<td>MFGS implicit method</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Runge-Kutta explicit method</td>
</tr>
<tr>
<td><strong>Parallelization</strong></td>
<td>domain decomposition method with MPI</td>
<td>domain decomposition method with PVM, MPI, and Open MP</td>
</tr>
<tr>
<td></td>
<td>The number of parallel processing can be determined at the time of execution</td>
<td></td>
</tr>
</tbody>
</table>
Results: Case1, force & moment (1/2)

- most of the CFD results shows lower lift than that of ETW data
- \(C_L\) of Cflow-Medium grid is in good agreement with ETW data
- \(C_L\)-\(\alpha\) slope is less than that of ETW data

[Diagram: Case1 Grid Convergence; \(C_L\)-\(\alpha\)]

What will be the trends post stall?
Results: Case1, force & moment (2/2)

- finer grid overestimate negative pitching moment
Results: Case2 CL-α, C_uns_mix Grid, Medium

Case 2a and 2b are computed using thin layer approximated NS eq.