Application of Novel Hybrid Mesh Generation Methodologies for Improved Unstructured CFD Simulations
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Overview

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- Grid Family
- Adjoint-based Grid Improvements
- Workshop Summary
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Introduction

- NASA common research model; cruise configuration of conventional civil transport aircraft
- WBT-configuration selected as experimental basis for the fourth Drag Prediction Workshop (DPW4)
- “Natural application” of Solar grid generation package due to available philosophy files, which automate the definition of sources
Cases

- Workshop held in San Antonio, TX, on June 20-21 2009
- **case 1** – consisting of two sub-cases
  - 1) grid convergence study at $M = 0.85$, $C_{lift} = 0.5$, $Re = 5 \cdot 10^6$
    - tail incidence angle $iH = 0^\circ$
    - coarse, medium, and fine grids
  - 2) downwash study at $M = 0.85$
    - drag polars for alpha = $0.0^\circ$, $1.0^\circ$, $1.5^\circ$, $2.0^\circ$, $2.5^\circ$, $3.0^\circ$, $4.0^\circ$
    - tail incidence angles $iH = -2^\circ$, $0^\circ$, $+2^\circ$, and tail off
    - medium grid
    - trimmed drag polar derived from polars at $iH = -2^\circ$, $0^\circ$, $+2^\circ$
    - delta drag polar of tail-off vs. tail-on
  - three turbulence models (SAO, SST, RSM)
- **case 3** – Reynolds number effects (WT to flight scaling)
  - Same configuration & settings as case 1.1, but with $Re = 20 \cdot 10^6$
Computational Methods

- DLR **TAU** code (CFD) and ARA/BAE-ATC **Solar** (grid gen.)

- Compressible RANS
- Unstructured, finite volume, node-centered, (Full-NS)
- Central scheme with Jameson-type scalar dissipation; $k_2 = 1/4$, $k_4 = 1/64$
- Backward-Euler, LUSGS
- 4w multigrid / sg
- SA(RC), Menter $k$-$\omega$ SST, SSG/LLR-$\omega$ RSM

- Unstructured, quad/hexa-dominant
- Advancing-layer/front
- Octree-based background grid for steering Delaunay tetra generation
- Anisotropic surface quads
- Adaptive, variable expansion ratio
- No user-specified amount of wall-normal layers
Initial Results

- Initial medium grid (~10 mio. Points) generated in ½ day, using default philosophy files
Initial Results

Wing-fuselage fairing

Field-cut around outboard wing
Initial Results

- Overnight initial results; acceptable solver convergence
Strict application of DPW committee gridding guidelines leads to contracted near-field layer at concave corners.

Cut at x=1400"
Up-Front Grid Improvements

- Increase of surface grid size at junctions mitigates, but does not resolve the problem
Up-Front Grid Improvements

- After initial runs with medium grid, additional anisotropic source added at mid-chord, over entire span, to better resolve shock region
Up-Front Grid Improvements

- Modification of fuselage trailing edge
  - Sharp → blunt; through cut at x=2561.5 inch (bTE: 0.5 inch)
Grid Family

- Starting from medium source distribution, generation of one level of finer and coarser grids
  - Source sizes scaled by a factor of $\sqrt[3]{3} \approx 1.4422$, affecting both surface and volume meshing
  - Influence radii ($r_1$ & $r_2$) not changed, being coupled to geometry
  - Consistent scaling of expansion ratio, to keep the total near-field layer extent similar between grid levels

$$Total\ layer\ thickness = \sum_{i=0}^{n} a \cdot q^i = a \cdot \frac{1-q^{n+1}}{1-q}$$

- $a$: first layer spacing
- $q$: expansion ratio
- $N$: Number of layers ($n+1$)

Grid level 2 being finer than grid level 1: $a_2 = a_1 / \sqrt[3]{3}$, $N_2 = N_1 \cdot \sqrt[3]{3}$
## Grid Family

- **Final grid family**

<table>
<thead>
<tr>
<th>Grid</th>
<th>Coarse</th>
<th>Medium</th>
<th>Fine</th>
</tr>
</thead>
<tbody>
<tr>
<td># cells on blunt TE</td>
<td>8</td>
<td>12</td>
<td>18</td>
</tr>
<tr>
<td>Surface point</td>
<td>$130 \cdot 10^3$</td>
<td>$271 \cdot 10^3$</td>
<td>$566 \cdot 10^3$</td>
</tr>
<tr>
<td>Max. # of wall-normal layers</td>
<td>30</td>
<td>42</td>
<td>60</td>
</tr>
<tr>
<td>Expansion ratio</td>
<td>1.3009</td>
<td>1.2</td>
<td>1.135</td>
</tr>
<tr>
<td># points in nearfield</td>
<td>$3.47 \cdot 10^6$</td>
<td>$9.94 \cdot 10^6$</td>
<td>$28.69 \cdot 10^6$</td>
</tr>
<tr>
<td># of tetra cells</td>
<td>$5.31 \cdot 10^6$</td>
<td>$14.31 \cdot 10^6$</td>
<td>$38.58 \cdot 10^6$</td>
</tr>
<tr>
<td>Total # of points</td>
<td>$4.07 \cdot 10^6$</td>
<td>$11.70 \cdot 10^6$</td>
<td>$34.08 \cdot 10^6$</td>
</tr>
</tbody>
</table>
Grid Family

Wing TE discretization with 8, 12 & 18 cells
Grid Family

- Near-field discretization with 30, 42 & 60 layers
- Approximately self-similar wall-tangential discretization
- Grid-independent wall-normal total layer thickness
Adjoint-based Grid Improvements

- Identification of regions with high influence of artificial dissipation on specific cost function (C-drag/C-my)
  - Variable 4 (V4) used here as sensor from TAU adjoint solver
- Manual, interactive modification and addition of Solar sources
Adjoint-based Grid Improvements

- Identified problematic regions with remedy
  - Fuselage: spacing x0.5
  - Wing- and HTP-fuselage junction: reduce chord-wise anisotropy, increase spacing x1.5
  - Inner wing wake: spacing x0.5
  - HTP wake: spacing x0.75
  - Upstream of wing: extend upstream wing tri-sources; spacing x8, $r_1 x 2$, $r_2 x 2$
  - Wingtip vortex: add wingtip tri-source
Adjoint-based Grid Improvements

\[ \text{eta} = 20.09\% \quad \text{eta} = 99\% \]
Adjoint-based Grid Improvements

eta = 20.09%

eta = 99%
Workshop Summary

- Workshop summary and comparison between all delivered datasets; Solar/TAU: T, C, S (SST, SA, RSM)
- Asymptotic grid convergence
- SST and SA TAU results within scatter of all (SST and SA) structured results

![Graph showing CO2 vs Grid Fac for unstructured grids and structured grids.](Image courtesy: Tinoco et al.)
Post-Workshop Activities

- Wing-body separation bubble at trailing edge
  - Some participants predict one, others don't
  - Solar/TAU (all grids, all turbulence models) no separation

Reported Separation

<table>
<thead>
<tr>
<th>ID</th>
<th>Turb. Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>SST k-w</td>
</tr>
<tr>
<td>B</td>
<td>SA</td>
</tr>
<tr>
<td>E</td>
<td>SA</td>
</tr>
<tr>
<td>F</td>
<td>SA</td>
</tr>
<tr>
<td>H</td>
<td>SA</td>
</tr>
<tr>
<td>I</td>
<td>SA</td>
</tr>
<tr>
<td>J</td>
<td>SA</td>
</tr>
<tr>
<td>P</td>
<td>SA</td>
</tr>
<tr>
<td>R</td>
<td>SST k-w</td>
</tr>
<tr>
<td>U</td>
<td>SA</td>
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<td>2</td>
<td>SA</td>
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<tr>
<td>4</td>
<td>SA</td>
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</table>

No reported separation

<table>
<thead>
<tr>
<th>ID</th>
<th>Turb. Model</th>
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<tr>
<td>C</td>
<td>SA</td>
</tr>
<tr>
<td>D</td>
<td>EARSM</td>
</tr>
<tr>
<td>L</td>
<td>SA</td>
</tr>
<tr>
<td>M</td>
<td>SST k-w</td>
</tr>
<tr>
<td>N</td>
<td>SA</td>
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<tr>
<td>O</td>
<td>SST k-w</td>
</tr>
<tr>
<td>S</td>
<td>SSG/LRR</td>
</tr>
<tr>
<td>T</td>
<td>SST</td>
</tr>
</tbody>
</table>

Image courtesy: Tinoco et al.
Post-Workshop Activities

- Hints of insufficient wing-body junction discretization observed from the adjoint solution

cells with V4 > 5e-07

field cut at x = 1400"
Post-Workshop Activities

- Solver-side solution approach to junction near-field contraction via overset grid (chimera)
- C-H (C/90°) block initially constrained to wing/body TE region

![Cut-out from Solar grid](image1)

![New computational domain](image2)
Post-Workshop Activities

- Based on study of resulting BL profiles from initial hexa block, switch to complete C-H block around entire wing root and wake
  - Same first cell height and expansion ratio at overlap
  - Chimera grid composed of Solar medium grid (11.7 mio. points) + hexa (5.5 mio. Points)
Post-Workshop Activities

- Orientation for the following slides
  - View from the rear to the front, rotated by 10° around the z-axis

View direction on TE of wing-body junction

Clean wall surfaces
Post-Workshop Activities

Blue: initial Solar mesh

Red: additional hexa C-H block
Post-Workshop Activities

Surface grids
Post-Workshop Activities

Green: field cut through grids at \( x=1476'' \) (just upstream of TE)
Post-Workshop Activities

Region of interpolation between the two grids
Post-Workshop Activities

- Comparison between original Solar grid and hexa block of chimera grid, reveals the improved field discretization directly above the near-field layers

Original Solar grid

Hexa block of chimera grid
Post-Workshop Activities

- Solar & hexa chimera grid is relatively fine, when compared to other (medium) structured grids

Solar & hexa block grid  Boeing  ANSYS
Post-Workshop Activities

Through improved field discretization, the separation bubble is resolved for target-C-lift = 0.5 computations (case 1.1; aoa ≈ 2.3°)

Solution on original Solar grid (left) reveals the same location of the shock (isocurve of critical pressure coefficient in blue) as on the chimera grid (right)

Separation bubble (isosurface of x-velocity = -10 m/s in red) starts ahead of sonic line
Post-Workshop Activities

- Surface pressure and skin friction data compared at the innermost cut-plane of $y/2b=10.5\%$
- First experimental cut-plane at $y/2b=13.06\%$ outside of influence region of separation bubble
Post-Workshop Activities

- No difference in pressure rise over shock between the two solutions
- Separation visible (only) through skin friction coefficient

Case 1.1; Solar grid (red, continuous) compared to chimera grid solution (blue, dashed) at $y/2b=10.5\%$; pressure coefficient (left) and skin friction coefficient (right) for SA computations; upper wing data bold
Post-Workshop Activities

- No separation found with other turbulence models on Solar grid (SA, SST, RSM)

Case 1.1; Solar grid, SA (red, continuous), SST (green, dash-dot-dot) and RSM (black dash-dot) results at $y/2b=10.5\%$; skin friction coefficient; upper wing data bold
Post-Workshop Activities

- On chimera grid, separation is found for all tested turbulence models (SA, SARC, RSM)
- No influence on separation of rotational corrections for SA; RSM topologically similar, but separation is bigger

Case 1.1; Chimera grid solution for SA (blue, dashed), SARC (pink, dash-dot-dot) and RSM (gray, dash-dot) at $y/2b=10.5\%$; pressure coefficient (left) and skin friction coefficient (right); upper wing data bold
Post-Workshop Activities

- At the edge of the envelope (aoa = 4°), the inferior junction discretization of the standard Solar grid has (more) severe effects.
- Begin of separation moves upstream.

Case 1.2, aoa = 4°; Solar grid (red, continuous) compared to chimera grid solution (blue, dashed) at y/2b=10.5%; pressure coefficient (left) and skin friction coefficient (right); upper wing data bold.
Post-Workshop Activities

Massive separation bubble dominates inner wing flowfield in chimera grid solution

Case 1.2, aoa = 4°; Solar grid (left) compared to chimera grid solution (right); critical pressure coefficient (pink, dashed curve) and skin friction lines
Conclusions

- Grid family generation process developed for Solar, applicable to any advancing-layer/front method
  - Satisfactory grid convergence; behavior (second order) and gradient
  - Even without resolution of separation bubble at SOB (not resolved on any grid level)
- Performed successful adjoint-based grid assessment and improvement
- Grid deficiency for junction flow discretization solved via chimera grid technique
  - At Cl=0.5, separation onset seemingly triggered by shock destabilizing effect on junction boundary layer
  - At aoa=4°, substantial change in wing root flow topology