CREATE^{TM}-AV Kestrel Dual-Mesh Computations on the NASA Common Research Model

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Introduction

This work investigates the differences between Kestrel's fully unstructured and coupled unstructured-Cartesian simulations of a modern, transport aircraft

Outline:

1. Kestrel Description
2. The NASA Common Research Model
3. KCFD/SAMAir CRM Results
4. Effects of Subset Distance and AMR
5. Conclusions and Future Work

CREATE^{TM}-AV Kestrel

- DoD HPCMP initiated the Computational Research and Engineering Acquisition Tools and Environments (CREATE^{TM}) in FY2008
- The goal of all CREATE products is to give working-level engineers access to high-fidelity, physics-based codes
- CREATE Tools:
  - Enable virtual prototyping and early discovery of design defects during development
  - Allow for efficient evaluation of design changes during sustainment
- The CREATE program is developing dedicated software packages for ships, ground vehicles, antennas, meshing/geometry, and air vehicles
- Air vehicles is further split into rotorcraft (CREATE^{TM}-AV Helios) and fixed-wing applications (CREATE^{TM}-AV Kestrel)

Kestrel Architecture

- Kestrel's core functions are performed by components that are dedicated to a single task and unaware of other components present in the simulation
- The components are linked through a Python-based common scalable infrastructure (CSI) and share data via pointers
- Event based
  - Each component responds to events that are published by CSI
  - Components only subscribe to events that affect them
- This architecture enables an enormous amount of flexibility and facilitates:
  - Maintainable and extensible code, including from outside partners through a software development kit
  - The ability to efficiently run a variety of use-cases by excluding components that are not necessary

Dual-mesh Components

- KCFD
  - Kestrel's unstructured CFD solver
  - Supports mixed hex, prism, pyramid, and tet elements
- SAMAir
  - Kestrel v5 (2014) introduced an off-body Cartesian solver, SAMCart, based on technology pioneered by the Helios team
  - For Kestrel v7 (2016), the code was extensively re-worked and released as SAMAir
  - The name reflects the use of the Structured Adaptive Mesh Refinement Application Infrastructure (SAMRAI) from Lawrence Livermore National Laboratory and the code's NXAIR heritage
- PUNDIT
  - Parallel UNsteady Domain Information Transfer
  - Performs domain connectivity operations, including interpolation
  - Input-free, implicit hole-cutting

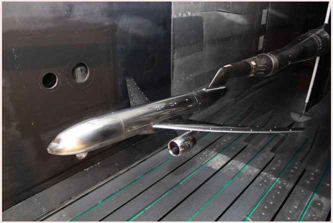
NASA Common Research Model

- Non-proprietary/non-sensitive geometry, representative of a modern transport aircraft
- The Wing/Body (WB) configuration has been studied in AIAA Drag Prediction Workshops (DPW) since DPW IV (2009)
- DPW VI (2016) included studies of configurations with engine nacelles; Wing/Body/Nacelle/Pylon (WBNP)
- Focus on comparison to other CFD codes rather than comparison to the wind tunnel results

CRM WB

NASA CRM website

CRM WBNP



DPW VI website

Problem Set-up

- Calculate the total drag coefficient at a fixed lift of $C_L = 0.5 \pm 0.0001$
- Each solution point started from initial, uniform flow solution
- Splart-Almaras turbulence model
- All other inputs left at default values
  - HLLE++ fluxes
  - Spatial accuracy 2^{nd}-order for KCFD, 3^{rd}-order for SAMAir
  - Global (time-accurate) time stepping at 2^{nd}-order temporal accuracy
- Solutions computed on the DPW VI meshes provided by NASA's GeoLab
  - "Merged" versions with prism boundary layers
  - WB cell count: 83,598,506 to 182,037,523
  - WBNP cell count: 120,990,279 to 266,916,327
- Focus on accuracy, not performance

Dual-mesh Workflow

1. Subset an existing, unstructured mesh
   - Kestrel provides this functionality with two tools: the Kestrel user interface (KUI) and Carpenter
   - User specifies a subset distance, but everything else is **automatic**, including tagging an "overset" boundary
2. Use KUI to define a Cartesian mesh
   - User supplies boundary extents with either min/max corners or as a number of reference lengths away from the body
   - Kestrel **automatically** calculates the number of refinement levels required to generate Cartesian cells that are similar in size to the unstructured cells at the overset boundary
3. Execute the Kestrel simulation
   - Domain connection is **automatic**; PUNDIT uses information from the unstructured and Cartesian meshes to assign hole, fringe, and orphan points
   - SAMAir logs the number of orphans and averages the solution when the total number is below a user-defined threshold
   - Single input adds geom. refinement to resolve excess orphans

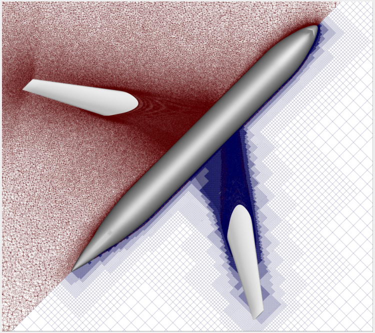
Mesh Adaptation in SAMAir

- Cells are tagged for refinement based on geometric or solution-based parameters
- For geometric refinement:
  - PUNDIT assigns a representative length scale to the unstructured cells close to the near-body overset surface
  - If any Cartesian cell width is significantly larger than this length scale, it is marked for refinement
  - This process continues until the Cartesian mesh size is comparable to the unstructured cells, or the maximum number of refinement levels is reached
- Solution refinement:
  - Tags cells based on local measures of density, entropy, vorticity magnitude, scaled Q-criterion, or shock sensor
- SAMRAI's routines then assemble regular blocks around the tagged regions

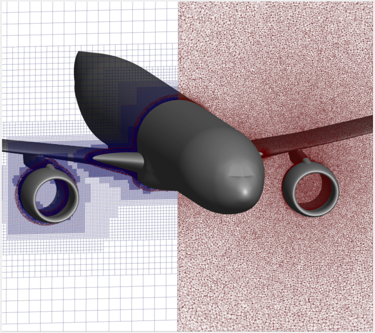
CRM Dual-mesh System

- SAMAir meshes subset at 5% MAC ($\approx$ 14")
  - WB DOF count: 56,530,970 to 158,613,041
  - WBNP DOF count: 67,286,091 to 130,395,586
  - 20%-50% reduction in DOF compared to single meshes
- No solution refinement; only geometric

WB "Coarse" Mesh



WBNP "Coarse" Mesh



Drag Coefficient Comparisons

Finite-Volume Codes:

- KCFD; 2^{nd}-order, cell-centered, unstructured
- KCFD/SAMAir; KCFD + 3^{rd}-order, node-centered, Cartesian
- OVERFLOW; 3^{rd}-order, node-centered, structured
  - *James Coder, University of Tennessee - Knoxville*
- FUN3D; 2^{nd}-order, node-centered, unstructured
  - *Eric Nielsen and William Jones, FUN3D Development Team*

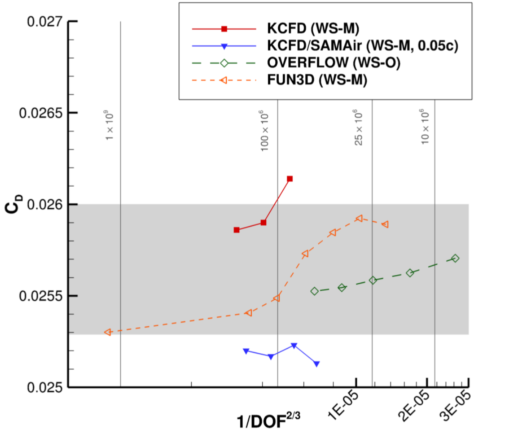
Meshes:

- WS-M; DPW VI mixed-element meshes (NASA GeoLab)
- WS-O; DPW VI overset mesh system (Boeing Long Beach)

WB Drag Coefficient

- DPW VI "Medium": $C_D = 0.02570 \pm 0.0026$
- Shaded region shows the range of solutions, excluding outliers
- SAMAir with 160×10^6 DOF is within one count of the 1×10^9 DOF FUN3D solution
- SAMAir C_D not sensitive to near-body refinement
- Default settings produce good solutions

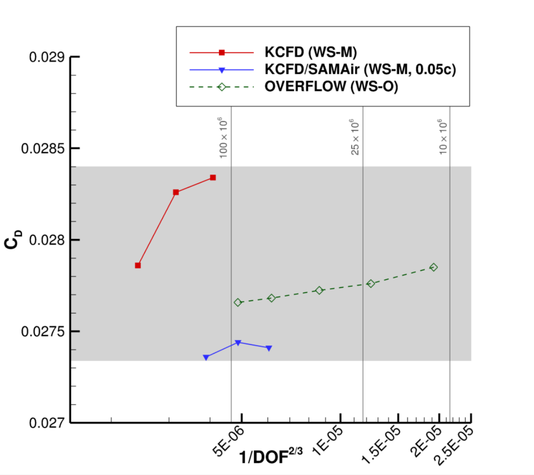
WB Drag Comparison



WBNP Drag Coefficient

- DPW VI "Medium": $C_D = 0.02803 \pm 0.0043$
- Larger spread in workshop results compared to the WB
- SAMAir within 2 counts of finest OVERFLOW solution
- SAMAir C_D not sensitive to near-body refinement
- Default settings produce good solutions

WBNP Drag Comparison



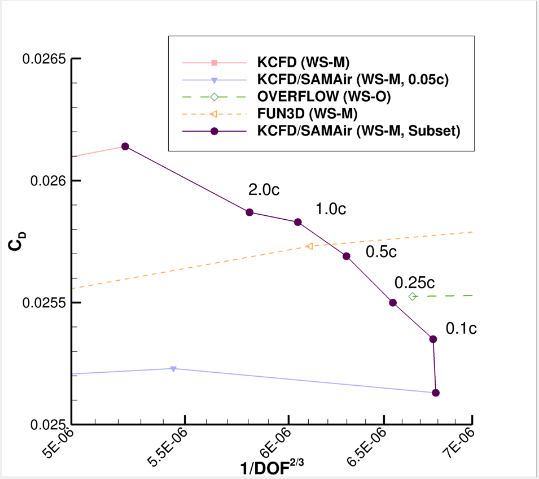
Drag Coefficient Summary

- SAMAir solutions compare well to the DPW VI workshop results
- Drag is slightly low compared to other workshop participants
- Default settings give good drag coefficients with “tiny” meshes
- Subsetting and wrapping the unstructured mesh with SAMAir has a large impact on drag, in the correct direction
- How does moving away from the baseline affect the solution?
    - Increase the subset distance
    - Activate solution refinement

Drag with Increasing Subset Distance

- Smooth transition between SAMAir and single-mesh KCFD solutions
- More investigation needed to identify "correct" distance
- Plots of pressure and skin-friction components of drag may be instructive

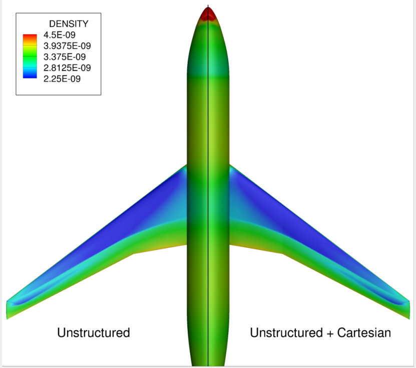
WB C_D with Subset



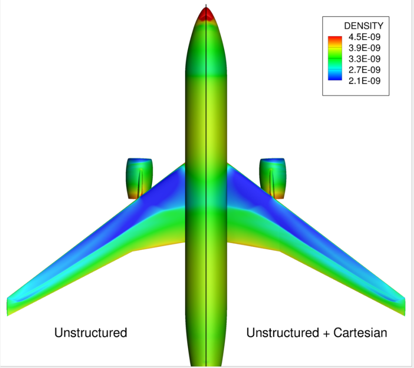
Single vs. Dual-mesh Density

- Subset plot shows the Cart. mesh makes a difference; where?
- Difficult to visually distinguish the two surface solutions

WB "Coarse"

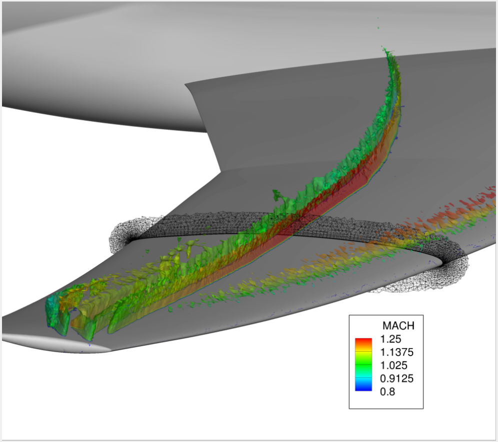


WBNP "Coarse"



Single vs. Dual-mesh Pressure Coeff.

Isosurface of $\Delta C_p = 0.02$

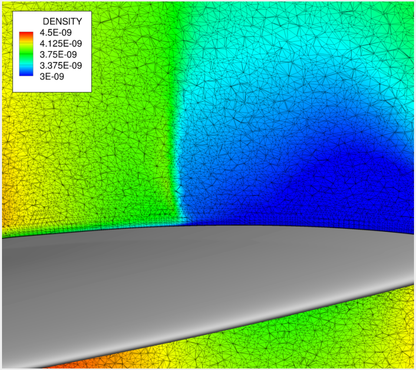


- KCFD and SAMAir computations use the same near-body mesh
- Differencing C_p between the two can give clues about where the solutions differ
- Largest difference is near the shock
- Use the shock sensor as the automatic mesh refinement (AMR) variable

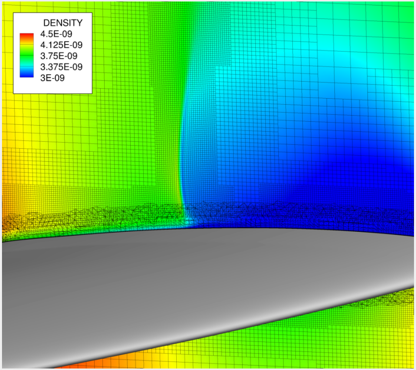
Shock Sensor AMR

- Sensor value: $\phi = \frac{\ell(\mathbf{u}\cdot\nabla p)}{ap}$

WB "Tiny" Baseline



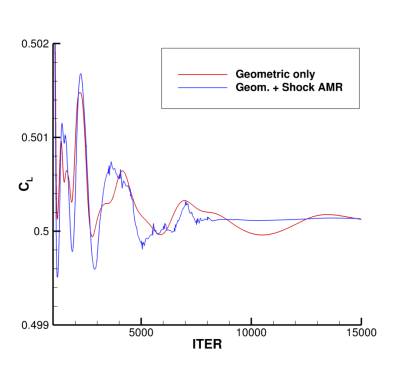
WB "Tiny" Adapted



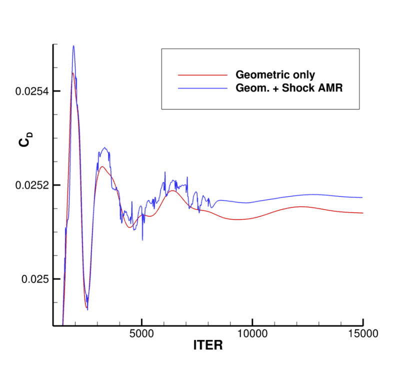
AMR Loads Convergence

- AMR every 500 iterations from iteration 500 to 8000
- Accelerates lift convergence
- Little effect on drag: $\Delta C_D \approx 5 \times 10^{-5}$

SAMAir Lift



SAMAir Drag



Kestrel

Closing Thoughts

Summary:

- KCFD/SAMAir dual-mesh simulations provide users good drag results with minimal effort
- Proper subset distance is an open question
- Shock-based AMR improves wall-clock time to an answer

Future work:

- Extract pressure coefficient profiles along the wing span
- Coarsen the workshop family of meshes
- Break out pressure and skin-friction contributions to total drag
- Investigate fifth-order SAMAir solutions
- Compare to high-order Streamwise Upwind/Petrov-Galerkin solutions from Kestrel's Conservative Field Finite-Element (COFFE) solver

Acknowledgements

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