HPCMP CREATE™-AV Kestrel Dual Mesh Computations on the ROBIN Fuselage

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Background

- **HPCMP CREATE™-AV**
  - Develops aircraft analysis software currently in use in Government, Industry, and Academia

- **CREATE™-AV KESTREL**
  - Multi-function code designed specifically for fixed wing aircraft analysis

- **KESTREL v5 features a dual mesh option**
  - KCFD computes the flow field close to the solid surfaces
    - Unstructured URANS solver
  - SAMKART computes the flow field away from the solid surfaces
    - Automatic grid setup and execution
    - Cartesian Euler solver (implicit or explicit time-integration)
    - GAMR adaptive mesh refinement
  - PUNDIT overset assembly

- **Why dual mesh?**
  - The Cartesian solver runs faster on a per node basis than the unstructured solver (i.e. for a given wall clock time you get a higher fidelity solution)
Kestrel v5 Credits

• **Kestrel Core Developers**
  – Scott Morton, Robert Nichols, Dave McDaniel, Tim Eymann, James Forsythe, Robert Starr, Steve Lamberson, Todd Tuckey, Patrick McNally, James Masters, Greg Denny, Travis Horine

• **Oversetting – PUNDIT, Off-body Cartesian System**
  – Jay Sitaraman, Andy Wissink

• **Integration, Inter-operability and Build Systems**
  – Stephen Adamec, Todd Tuckey, Brian Pittman, Jay Sitaraman

• **V&V, Quality Assurance & Support**
  – Theresa Shafer, Benjamin Hallissy, Chad Lillian, James Forsythe, David Hine, Jennifer Abras
METHODOLOGY
Dual Mesh Assembly Terminology

- Off-Body Mesh
- Near-Body Mesh
- Trim Distance

Off-Body Mesh Levels
(There are 6 shown in this grid)
Dual Mesh Construction

- User provides the trimmed near-body mesh
- User inputs parameters that define the off-body mesh
  - The Cartesian mesh is automatically constructed within KESTREL at runtime
  - The input parameters include at a minimum
    - Distance of the far field from the solid body
    - Number of grid levels
  - KESTREL will analyze the near-body fringe cell sizes and determine the finest cell size needed by the off-body mesh
  - Cartesian blocks are placed around the body in relation to the size of the near-body fringe
  - Remaining off-body grid levels are added
    - Each level is twice the size of the preceding level
  - PUNDIT performs the hole cutting
PUNDIT

- **Parallel UNsteady Domain Information Transfer features**
  - Implicit fringe determination
  - Implicit hole cutting
  - Minimum hole cutting using ray-tracing for solid bodies
  - Exact Inverse Map (EIM) donor search algorithm

- **Controls overset computations both between multiple unstructured meshes and the Cartesian mesh**
Adaptive Mesh Refinement (AMR)

- The off-body mesh density distribution is automatically adapted
  - Adaptation to the geometry
  - Adaptation to flow features

- GAMR (Guided Adaptive Mesh Refinement) is employed
  - Applies a combination of scaled q-criterion feature-based adaptation and Richardson extrapolation error-based refinement
  - Automatically scaled, hence no guessing of scalar-values to adapt to

- The user can limit how far from the body the adaptation is applied
Adaptive Mesh Refinement (AMR)

- In case of ROBIN, the flow-AMR is expected to target the separated region
Adaptive Mesh Refinement (AMR)

- Off-body, GAMR adapt for other features – C-17 Engine exhaust shear layer

(Kestrel v5, Dr. Tim Eymann, Eglin AFB)
Adaptive Mesh Refinement (AMR)

- Off-body, GAMR adapt for other features – Supersonic Ogive @ 10 degrees

(Kestrel v5, Dr. Tim Eymann, Eglin AFB)
Adaptive Mesh Refinement (AMR)
RESULTS
ROBIN Wind Tunnel Test

- Mach number of 0.1 (about 34 m/s)
- Reynolds number (based on the fuselage length) of 1.6M
- Standard sea level conditions
- Angle of attack = 0°
- 41 pressure taps along the centerline of the fuselage
- Mount shroud is constructed using an extruded NACA0018 airfoil section

Unstructured Grids

- Unstructured grid generation accomplished using Rhinoceros CAD software and TetrUSS grid generation software
- Boundary layer merging and near-body trim applied

<table>
<thead>
<tr>
<th>Boundary Layer Cells</th>
<th># of Cells</th>
<th># of Nodes</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid 2</td>
<td>Prisms</td>
<td>14.0M</td>
<td>4.1M</td>
</tr>
<tr>
<td>Grid 5</td>
<td>Prisms</td>
<td>15.5M</td>
<td>5.5M</td>
</tr>
</tbody>
</table>

- Single mesh case
- 0.05” cell size, for dual mesh use only
Explicit vs. Implicit Off-Body Solvers

- Near-body solver employs same settings for all cases
- Three off-body temporal schemes are available
  - Explicit Runge-Kutta (Third-order)
  - Alternating Direction Implicit (Second-order)
  - Symmetric Successive Over-relaxation (Second-order)
- Each method exhibits different characteristics
  - Explicit solver
    - Runs the fastest but converges the slowest (maximum stable time step = 5e-8 s)
  - Implicit SSOR
    - Runs the slowest but converges the fastest (time step = 1e-5 s)
  - Implicit ADI
    - Runs slower but converges faster than the explicit solver (time step = 1e-5 s)
- Implicit within individual blocks for off-body
Velocity Contour Comparison

- **Near-body grid trim distance of 0.5”**
- **Differences are seen between all solvers**
  - Explicit scheme
    - Pylon shedding likely seen because of the very small time step
    - Aft separated flow is minimal
  - Implicit SSOR scheme
    - Produces more aft separated flow
  - Implicit ADI scheme
    - Produces more aft separated flow
    - Solution quality more sensitive to time step size
Centerline Pressure Comparison

- Closer analysis confirms that the predictions in attached regions are about the same
- The aft separation region shows greater differences
  - The explicit solution is not fully converged
  - The implicit solvers produce similar results
Computational Metrics

- Implicit (SSOR) cases were run on HPCMP Pershing, explicit case run on HPCMP Riptide, all cases run on 256 processors
- Explicit solver runs the fastest, but takes two orders of magnitude more iterations to converge
  - Results in a longer wall clock time to complete the case
- Run time increases as trim distance increases
  - Near-body solver runs slower than the off-body solver

<table>
<thead>
<tr>
<th>Case Run</th>
<th>Grid (Trim)</th>
<th>Degrees of Freedom</th>
<th>Approximate Iterations to Converge</th>
<th>Time/proc/it/DoF [nanosec]</th>
<th>Estimated Run Time on 256 procs [days]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual Mesh Explicit</td>
<td>Grid-5 (0.5)</td>
<td>18.5M (cells near) 31.0M (nodes off)</td>
<td>~200K</td>
<td>1.97</td>
<td>5.74</td>
</tr>
<tr>
<td>Dual Mesh Implicit</td>
<td>Grid-5 (0.3)</td>
<td>14.6M (cells near) 46.2M (cells off)</td>
<td>~6K</td>
<td>9.49</td>
<td>1.02</td>
</tr>
<tr>
<td>Dual Mesh Implicit</td>
<td>Grid-5 (0.35)</td>
<td>15.4M (cells near) 45.5M (nodes off)</td>
<td>~6K</td>
<td>9.88</td>
<td>1.07</td>
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<tr>
<td>Dual Mesh Implicit</td>
<td>Grid-5 (0.5)</td>
<td>18.5M (cells near) 42.5M (nodes off)</td>
<td>~6K</td>
<td>10.09</td>
<td>1.09</td>
</tr>
<tr>
<td>Dual Mesh Implicit</td>
<td>Grid-5 (1.0)</td>
<td>29.3M (cells near) 35.2M (nodes off)</td>
<td>~6K</td>
<td>12.26</td>
<td>1.41</td>
</tr>
</tbody>
</table>
Trim Distance Study

• Trim distances of 0.3”, 0.5”, and 1.0” are studied here
  – Constant near-body mesh size of 0.05” for all trim distances
  – First level of the off-body mesh has the same constant cell size, but the placement varies
  – Differing solution methodology in each mesh will have a potential impact
  – All solutions are run using implicit SSOR in the off-body at a time step of 0.001 sec

• To achieve the fastest run time the near-body mesh should be trimmed as much as possible
  – Need to make sure that there is sufficient fringe area remaining
  – Need to make sure that the boundary layer computations are not impacted
Velocity Contour Comparison

- All plots represent instantaneous velocity
- Closest trim distance has no apparent impact on the attached solution
- Separation point appears to be the same for all grids
- Separated region in the off-body mesh does appear to be influenced by the trim distance
- Centerline pressure analysis confirms these observations
Centerline Pressure Comparison

- Attached regions show no difference between trim distances
- Separated flow is influenced by the trim distance
  - The closer trim distances more accurately follow the aft pressure contour
  - All miss aft peak (off-body is Euler)
Dual Mesh vs. Single Mesh

- Both cases run with the same kCFD inputs
- Attached regions are similar
- Separated region shows differences
  - These are attributed to the coarser grid used in the single mesh case
Dual Mesh vs. Single Mesh

- Attached regions show little difference
- Separated region shows difference in peak pressure
  - Similar differences in earlier CREATE-AV Helios comparisons (SciTech, 2014)
  - Off-body is Euler
Drag Coefficient Comparisons

- Drag coefficients show mixed results
  - The viscous components are more consistent
  - The pressure component differences are a function of the separated flow region

- CFD with and without the tunnel walls, current comparisons to without-wall free-air OVERFLOW computation

<table>
<thead>
<tr>
<th>Case</th>
<th>Pressure Drag</th>
<th>Viscous Drag</th>
<th>Total Drag</th>
<th>%Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td></td>
<td></td>
<td></td>
<td>0.145</td>
</tr>
<tr>
<td>OVERFLOW (tunnel)</td>
<td>0.090</td>
<td>0.055</td>
<td>0.145</td>
<td></td>
</tr>
<tr>
<td>OVERFLOW (free air)</td>
<td>0.058</td>
<td>0.056</td>
<td>0.114</td>
<td></td>
</tr>
<tr>
<td>Single Mesh</td>
<td>0.063</td>
<td>0.056</td>
<td>0.119</td>
<td>4.3</td>
</tr>
<tr>
<td>Dual Mesh Explicit</td>
<td>0.071</td>
<td>0.059</td>
<td>0.130</td>
<td>14.2</td>
</tr>
<tr>
<td>Dual Mesh SSOR</td>
<td>0.049</td>
<td>0.054</td>
<td>0.103</td>
<td>9.3</td>
</tr>
</tbody>
</table>

- Viscous off-body calculations – more at SciTech
Conclusions

- The dual mesh solver represents a significant leap in capability in the Kestrel code
  - The off-body Cartesian solver provides improvements in efficiency as well as flowfield preservation
- The implicit solver provides enhanced convergence characteristics over the explicit solver
  - Block implicit currently for off-body
- Problem setup can be tailored to provide the most efficient solution by eliminating as much of the near-body mesh as possible
  - Adjusting the regions where the different solvers are applied does have an impact on the separation predictions
- The predictions are insensitive to the methodology chosen in the attached regions
- The predictions are sensitive to the methodology in the separated regions
  - Off-body viscous
  - Additional convergence studies
Acknowledgments

• HPCMP CREATE™-AV Program

• Supercomputing resources provided by the HPCMP
  – Maui High Performance Computing Center (MHPCC)
  – Army Research Lab (ARL)

• NASTRAN ROBIN surface from Dr. Rajneesh Singh, ARL

• Wind Tunnel data and images and OVERFLOW results from reference 1
QUESTIONS?