A New Solution Adaption Capability for the OVERFLOW CFD Code

Pieter G. Buning

NASA Langley Research Center, Hampton, VA

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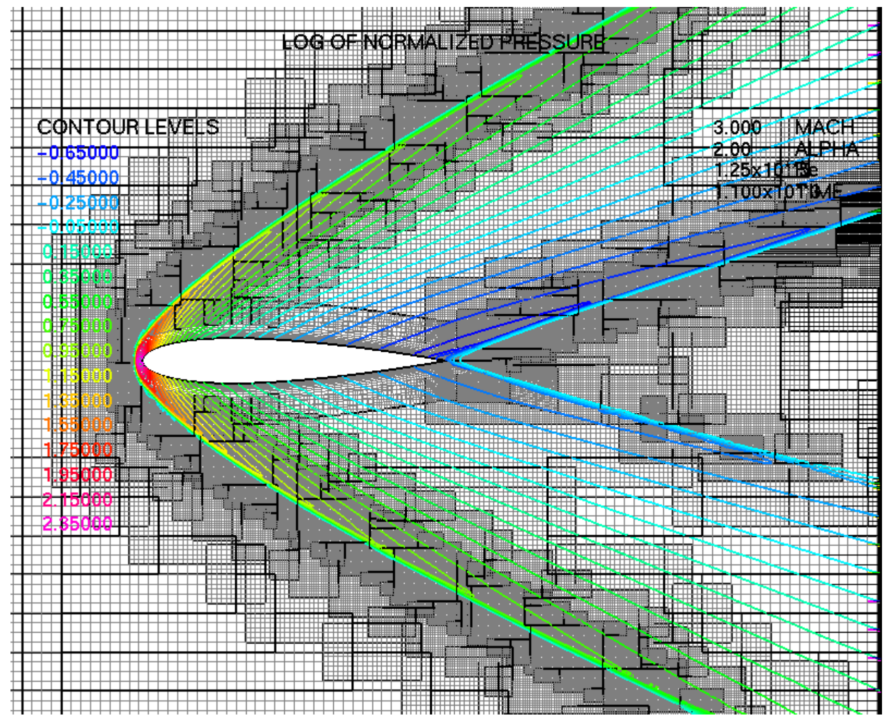
Goals

- Add a solution-adaptive grid capability for off-body (Cartesian) grids
- Make it an integral part of the OVERFLOW off-body grid generation
- Based on adaptive grid capability in OVERFLOW-D*, but able to create finer grid levels than “Level 1”
- Efficient enough for time-accurate moving grids!



* see Meakin, AIAA-95-1722 and AIAA-97-1858

Outline

- (Goals)
- Approach
- Sensor function and marking
- Grid generation and connectivity
- Interpolation onto new grid system
- Sample results
- Conclusions, issues, and future work

Approach

- Use as much of the current off-body grid generation mechanics as possible
- Where we have refinement grids, either
  - Blank out coarser-level grids, or
  - Make all grids abutting (with added overset boundaries)
- Use feature-based adaption for now
  - Easier to implement than adjoint, certainly for unsteady problems
  - Appropriate for vortex-dominated problems like rotorcraft

Approach

Terminology:

- Grids are either “near-body” (user-supplied) or “off-body” (Cartesian, automatically generated)
- “Level 1” off-body grids are the finest off-body grids (before adaption), with a user-specified grid spacing
- Level 2, 3, etc., are coarser by factors of 2
- Refinement grids are labelled Level -1, -2, etc., and are finer by factors of 2

Further,

- Near-body grids are always surrounded by Level 1 grids
- Geometry cuts holes in Level 1 and finer off-body grids
- Neighboring off-body grids differ by only one level

Approach

Controls:

- NREFINE – maximum number of refinement levels
- ETYPE – sensor function (undivided 2nd difference, vorticity, undivided vorticity...)
- EREFINE – sensor value above which we mark for refinement
- ECOARSEN – sensor value below which we mark for coarsening

We would prefer to control:

- Accuracy (via error estimate)
- Cost (number of grid points)

Sensor Function and Marking

- Undivided 2nd difference of (elements of) Q=(ρ, ρu, ρv, ρw, ρe_0)
  - 2nd difference of q times Δx^2; or
  - Difference between q_i and average of (q_{i-1}, q_{i+1}); or
  - Interpolation error between current grid and 2x coarser grid; or
  - Truncation error estimate
- Actually computed as

  (normalized and squared;

  take max over Q variables)

$$\max_{i=j,k,l}\left\{\left[\frac{q_i-\frac{1}{2}\left(q_{i-1}+q_{i+1}\right)}{q_{ref}}\right]^2\right\}$$

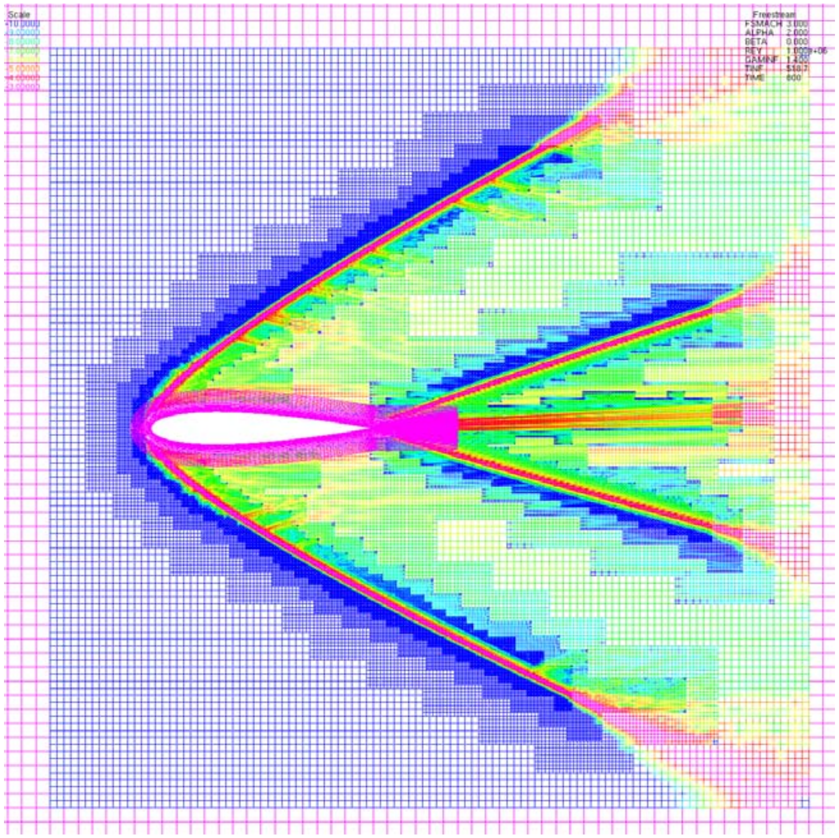
- This function
  - Is non-dimensional
  - Is independent of grid units
  - Gets smaller as the grid is refined (where Q is smooth)

Sensor Function and Marking

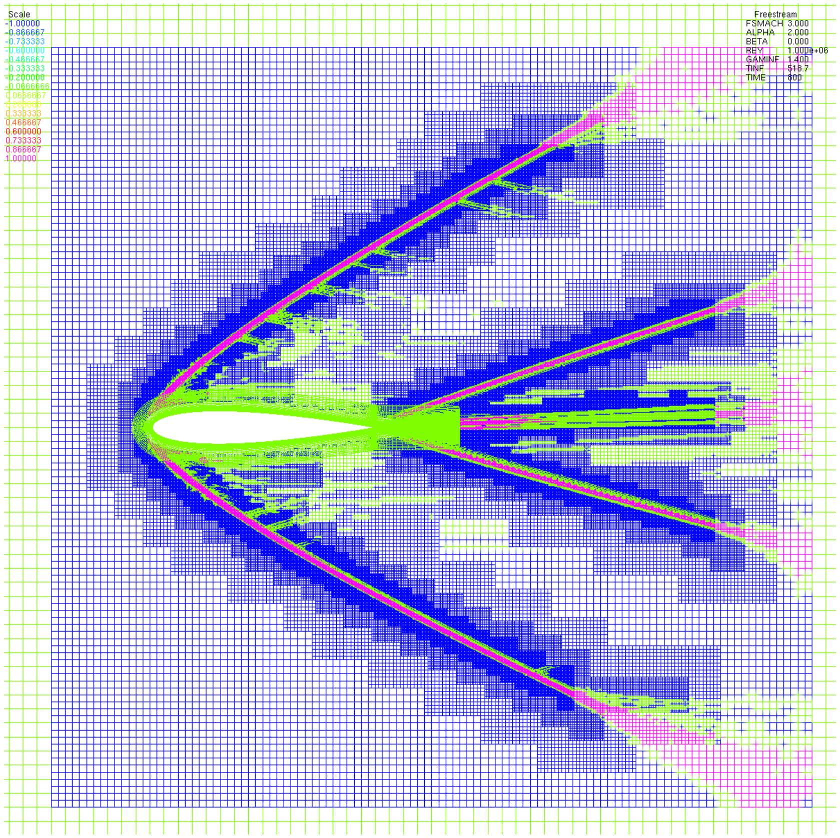
- At each grid point
  - If the sensor function value exceeds a refinement tolerance, mark for grid refinement;
  - If it falls below a coarsening tolerance, mark for grid coarsening
- Within an 8x8x8 grid cube, or “box”
  - If any point votes for refinement, the box is marked for refinement;
  - If all points vote for coarsening, the box is marked for coarsening
- Regions can only coarsen or refine by one level at a time
- Only level 2 and finer grids are marked

Sensor Function and Marking

Sensor function
(blue-10^{-10}; magenta-10^{-3})



Marker function
(blue-coarsen; green-maintain; magenta-refine)

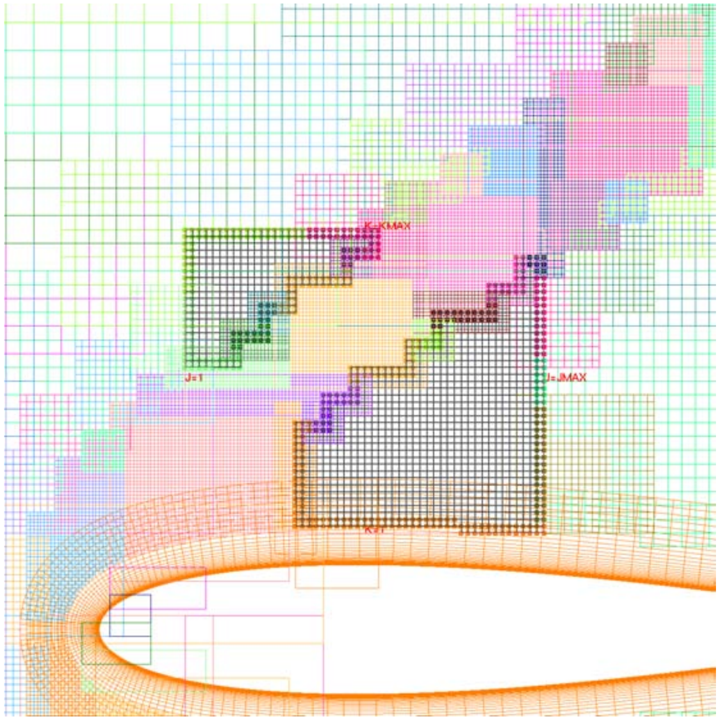


Grid Generation

- Start from finest level
- For each grid level (up through level 1):
    1. Mark regions from previous adapt cycle refinement boxes
    2. Unmark regions from current adapt cycle coarsen boxes
    3. Mark regions from current adapt cycle refinement boxes
    4. Mark near-body grid proximity boxes (level 1 only)
    5. Mark regions from user-specified boxes
- For grid level 2 and up:
    1. Fill buffer around clusters of previous-level grids
    2. Clusters become rectangular
    3. Merge neighboring clusters

Grid Connectivity

- Hole cutting
  - All refinement grids get cut by geometry (just like level 1)
- Blanking for refinement
  - Next-finer grid level explicitly blanks out regions in current level
- Connectivity
  - Refinement grids can have
    - Hole boundary points from geometry cuts
    - Hole boundary points from finer refinement grids
    - Outer boundary points



Sample level (-1) grid blanking and interpolation stencils

Solution Interpolation onto Adapted Grids

Goals:

- Process must be MPI-parallel, and include (re)load-balancing
- Near-body grids (and auto splitting) do not change, so involve no interpolation (but may move to different MPI groups)
- Interpolation must be performed in-core

Process:

- Create new off-body grid system
- Create a new distribution of near-body and off-body grids
- MPI groups exchange near-body grids and solutions (no new splitting)
  - This is parallelized to the extent that independent groups can exchange grids independently
- Off-body grid solution interpolation:
  - All MPI groups loop through old off-body grids, coarse-to-fine
  - Use bounding box to find which new grids touch this old grid
  - Owner uses non-blocking MPI sends to relevant new group(s)
  - New groups use blocking MPI receives, then interpolate onto new grid(s)

Solution Interpolation onto Adapted Grids

Original OVERFLOW-D method wrote old solutions to disk, read back in to interpolate onto new grids

+Avoided the need for having old and new solutions in memory at the same time

+Not a limitation for steady-state (adapting less than 10 times)

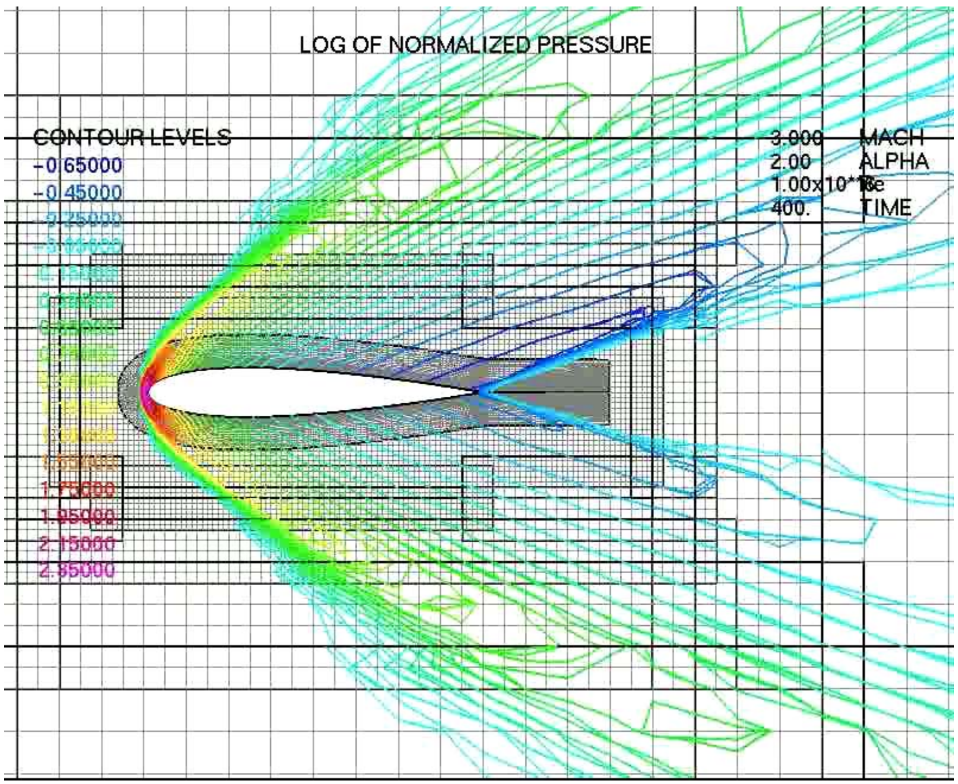
+Not as much of a limit for “regular” problems, where less than 30% of the total grid points are in the off-body grids

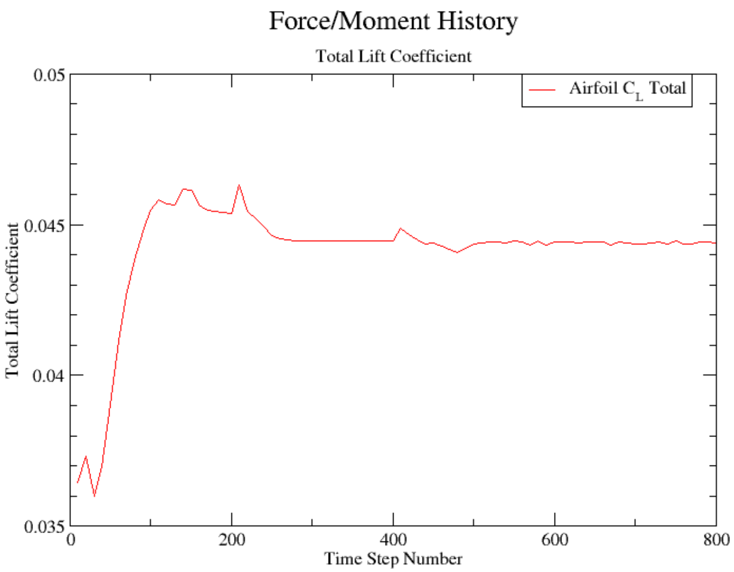
–Big problem for rotorcraft problems, where more than 90% of the points are in the off-body grids, ***and*** problem is unsteady

–For a sample UH-60 test case, adaption took 50% of the total time when using disk, compared to 3% when using memory

Sample Results – Supersonic Airfoil

- Steady flow, easy adaption
- Converge first, then adapt every 10 steps for 100 steps
- Nice adaption behavior, though lift chatters and residual hangs up (even after adaption is turned off)

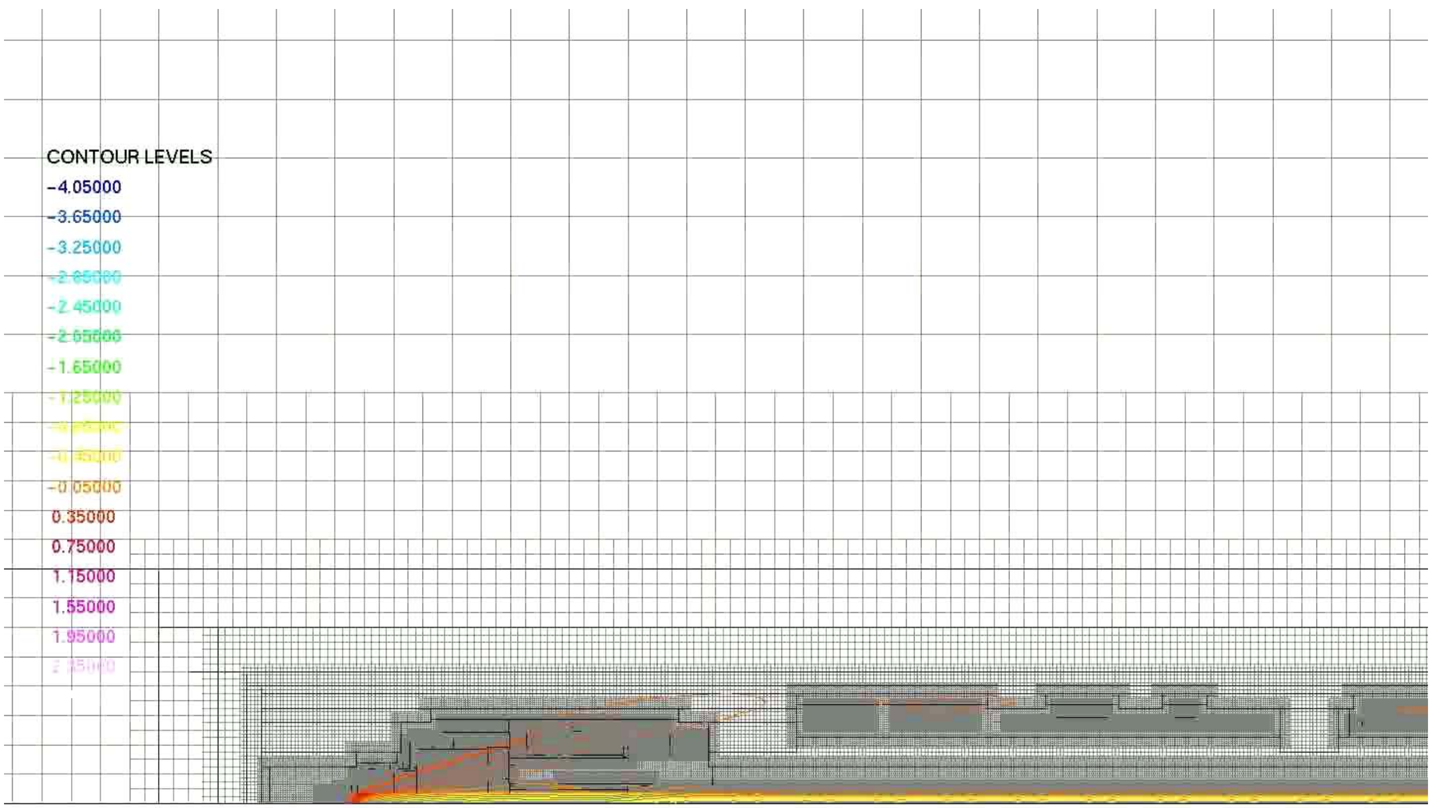




Sample Results – 2D Jet in Supersonic Cross-Flow

Sonic H_2 jet (pressure ratio 100) into Mach 4 N_2 free-stream

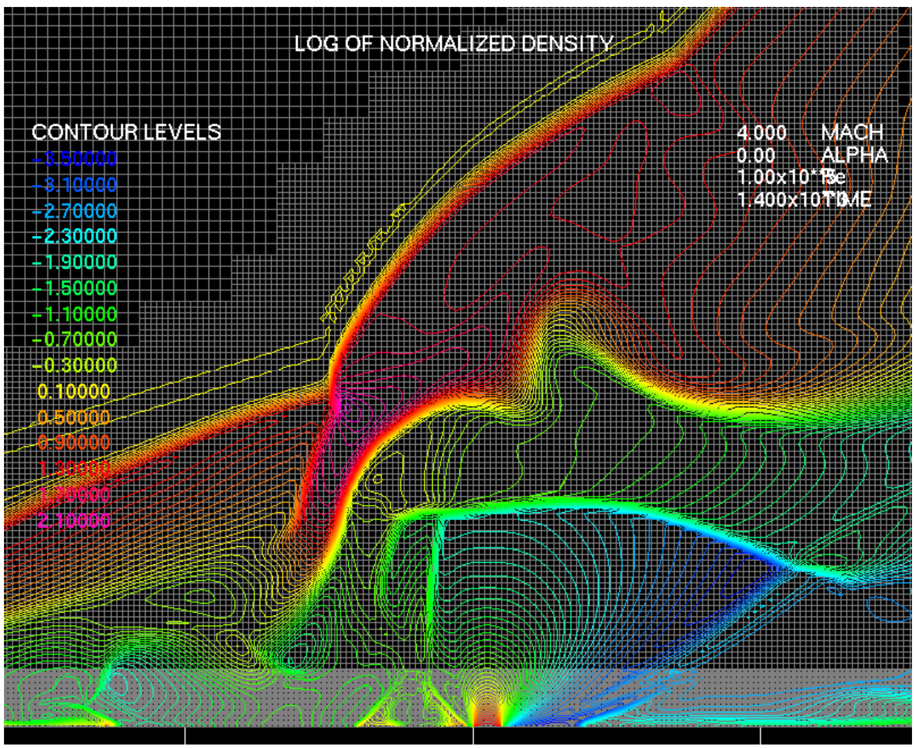
- Developing shock structure and contact surface
- Again, lots to adapt to
- Wall grid has small normal extent, stream-wise spacing to match finest expected off-body adaption



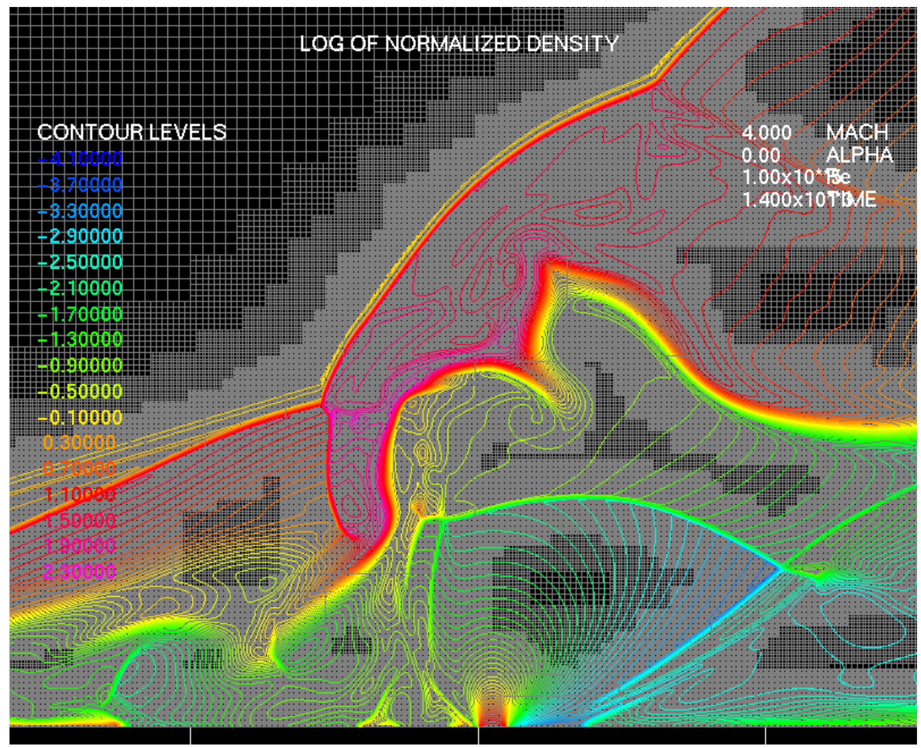
Sample Results – 2D Jet in Supersonic Cross-Flow

Two different levels of refinement:

- NREFINE=0 or 2 (minimum spacing of $D_{jet}/5$ or $D_{jet}/20$)
- Results look fairly similar, but added detail with finer adaption



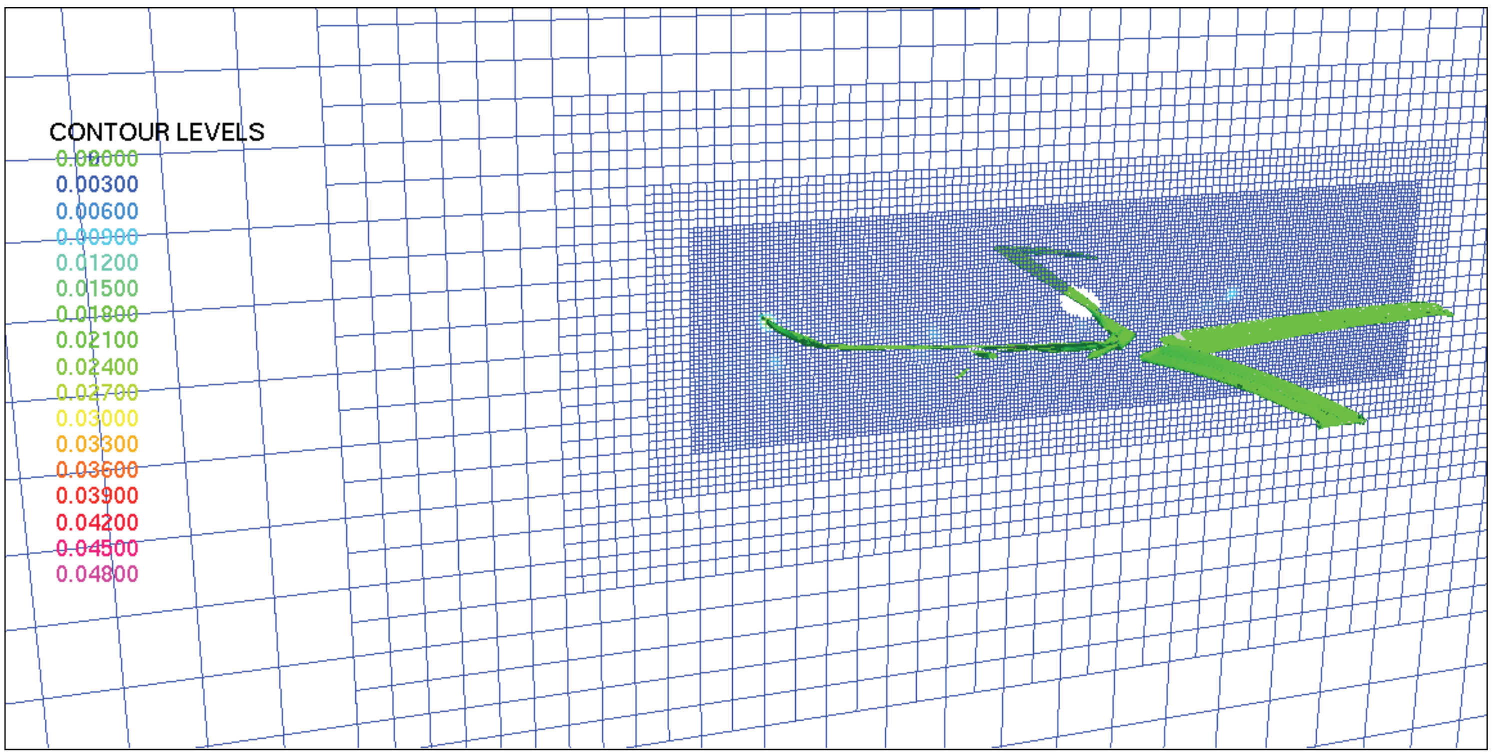
136 grids, 245K points



944 grids, 1269K points

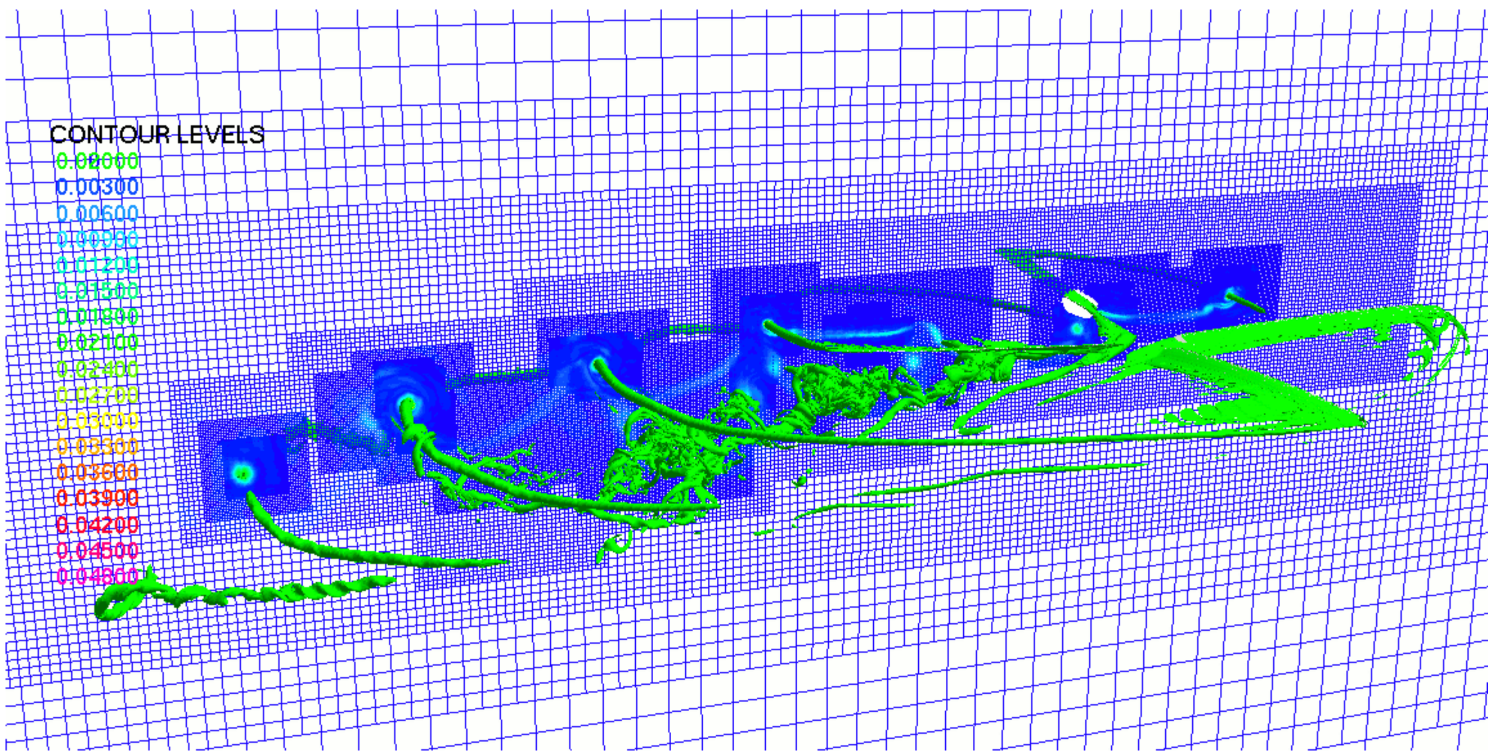
Sample Results – Helicopter Rotor

- Coarse-grid UH-60 test case from Mark Potsdam (Army AFDD)
  - Main blade grid is 125x82x33 (101 points on airfoil, 33 points in surface-normal direction, 82 span-wise stations)
  - Finest (level 1) off-body spacing is 20% of blade chord



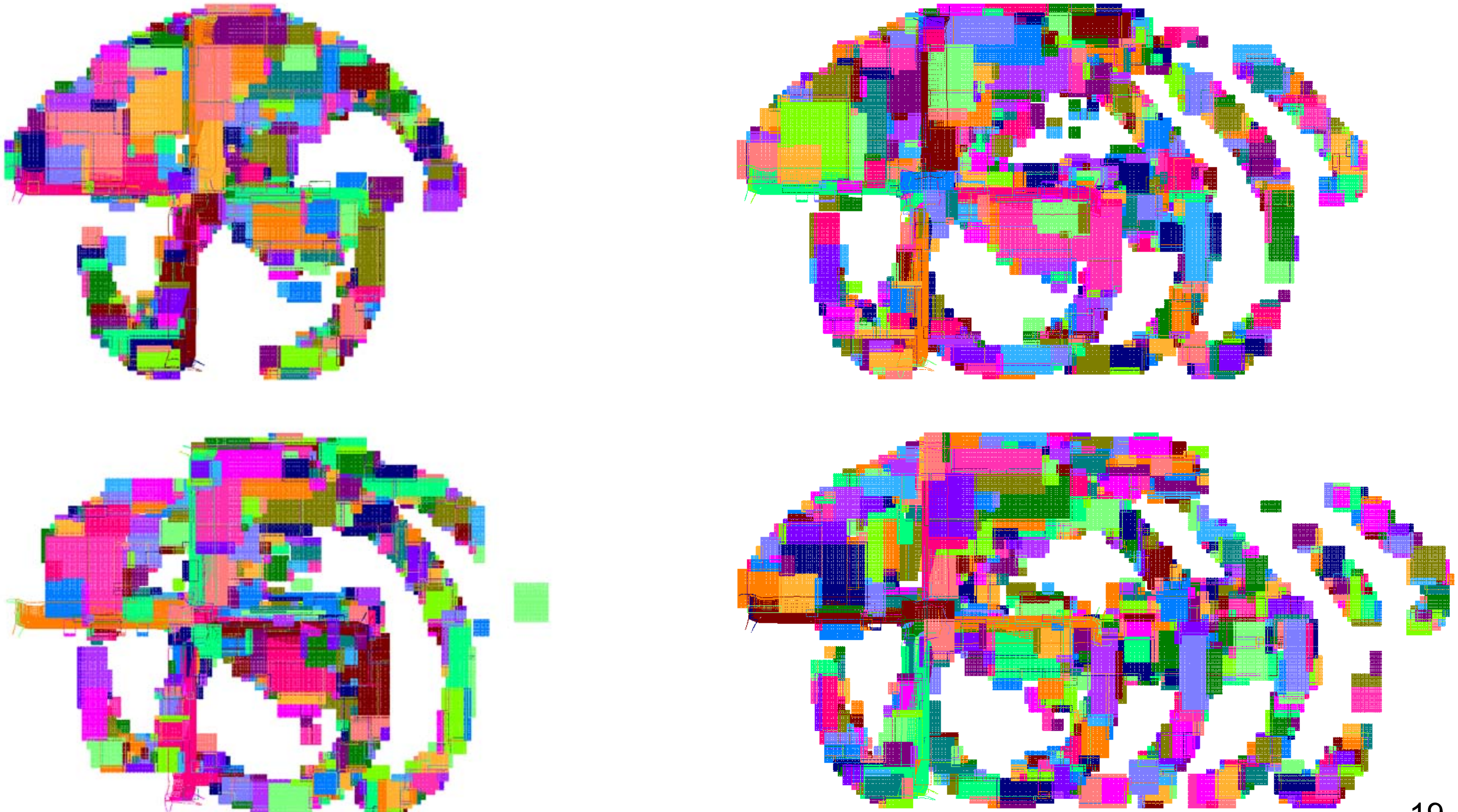
Sample Results – Helicopter Rotor

- Adapted grid system after one revolution
  - Two levels of refinement
  - Adaption performed every 10 steps (2 deg rotation)
  - Much better resolution of tip vortices
  - Grid size increases from 5M points to 67M points



Sample Results – Helicopter Rotor

- Development of level (-2) grids at 90, 180, 270, 360 deg rotation



Sample Results – Helicopter Rotor

- Ending with 1871 grids, 67M points
- Average 68 sec/step (20 sub-iterations/step), using 128 processors
  - 81% flow solver
  - 9% idle
  - 6% Chimera communication
  - 2% overset grid connectivity
  - 2% grid adaption
- Breakdown of adaption process
  - 80% off-body solution interpolation
  - 15% off-body grid generation
  - 0.5% sensor function calculation

Grid Statistics

- 2D jet in supersonic cross-flow

Grid type	# grids	% points	% blanked
Near-body	1	5	0
Level (-2)	162	50	1
Level (-1)	86	26	10
Level 1	33	12	11
Level 2	40	6	0
…	…	…	…
total	342	100	4

- UH-60 rotor

Grid type	# grids	% points	% blanked
Near-body	12	3	0
Level (-2)	1153	66	2
Level (-1)	505	23	24
Level 1	79	6	28
Level 2	99	2	0
…	…	…	…
total	1871	100	9

Conclusions

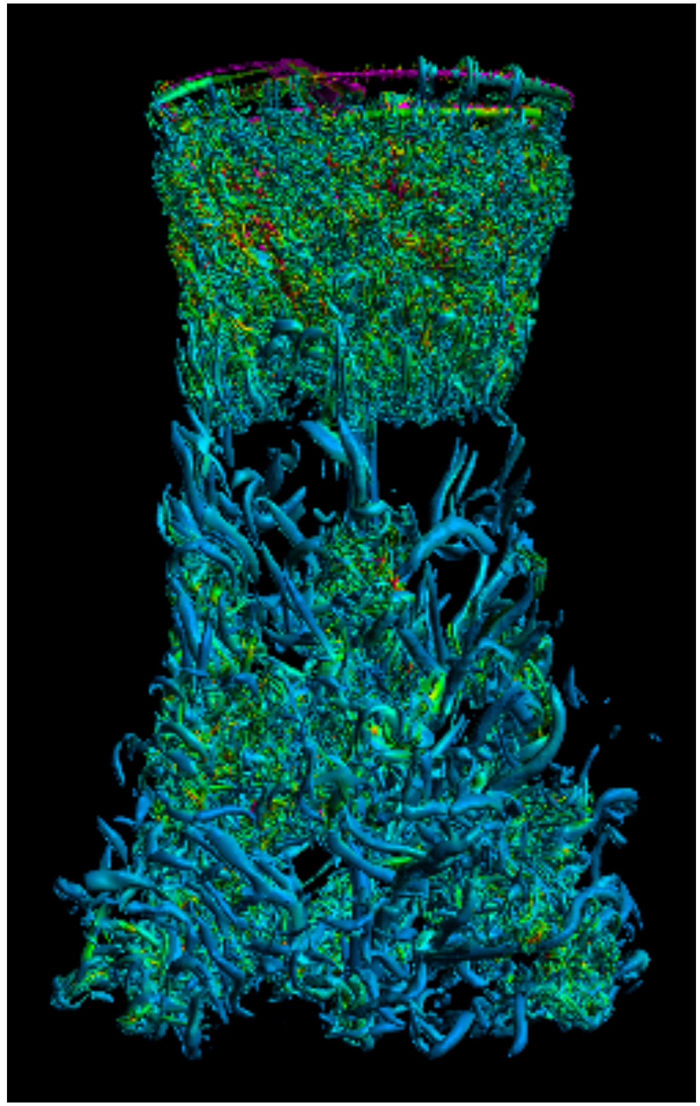
- Solution adaption process has been implemented in OVERFLOW
  - Allows off-body refinement grids that are finer than Level 1
  - Grid adaption is an integral part of the code
  - Adaption is efficient enough for time-accurate solutions
  - Grid blanking for refinement grids is significant but not overwhelming
  - Adaption process is both MPI- and OpenMP-parallel

Issues

- How to control the number of grid points?
  - Limit for run time and memory usage
- How often to adapt?
  - Make sure adapted region covers moving features
- Picking near-body grid resolution
  - Very fine means lots of points
  - Too coarse means we lose the benefit of adaption
  - We need adaption here too!

Issues

- Physics or numerical artifacts?
  - Effect of time-step and sub-iteration count on time accuracy when refining grids



Future Work

- Near-body grid adaption
  - Needed to maintain similar resolution of features, and similar spacing in overlap regions
  - One issue is maintaining smooth geometry definition
- Methods to control number of points
  - c.f. M.J. Aftosmis and M.J. Berger, “Multilevel Error Estimation and Adaptive h-Refinement for Cartesian Meshes with Embedded Boundaries,” AIAA-2002-0863, Jan. 2002
- Look at other sensor functions (e.g., vorticity, adjoint, …)
  - c.f. S.J. Kamkar, A.M. Wissink, A. Jameson, and V. Sankaran, “Feature-Driven Cartesian Adaptive Mesh Refinement in the Helios Code,” AIAA-2010-0171, Jan. 2010
  - c.f. M. Nemec and M.J. Aftosmis, “Adjoint-Based Adaptive Mesh Refinement for Complex Geometries,” AIAA-2008-0725, Jan. 2008