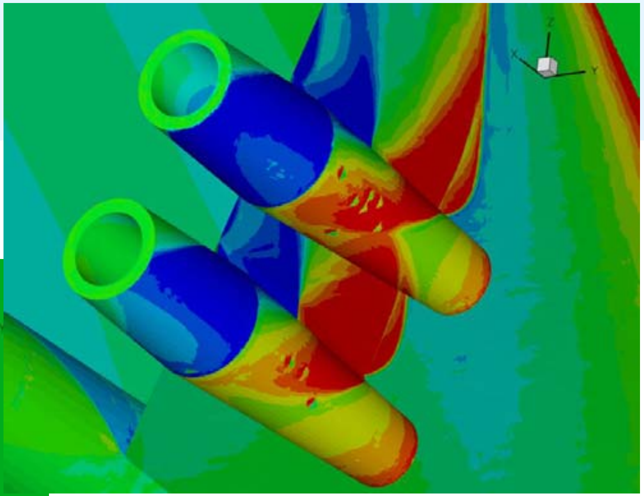
Output-Adaptive Tetrahedral Cut-Cell Validation for Sonic Boom Propagation

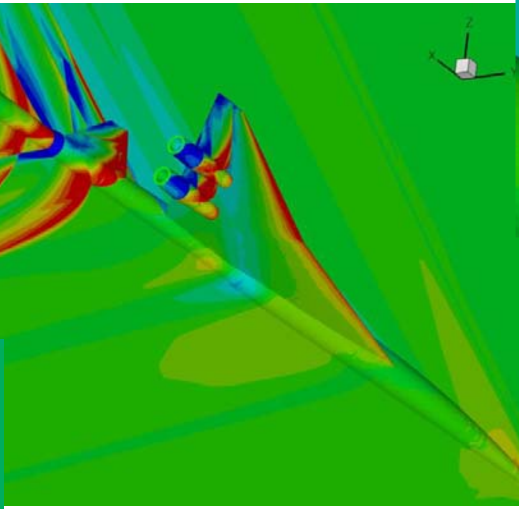


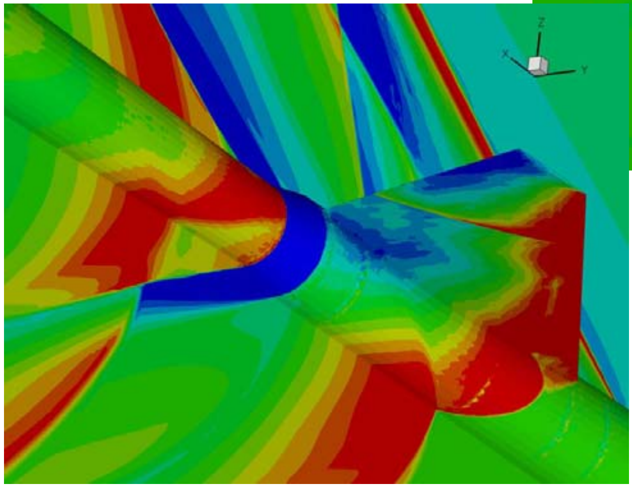
Mike Park and Eric Nielsen

Fundamental Aeronautics 2008 Annual Meeting

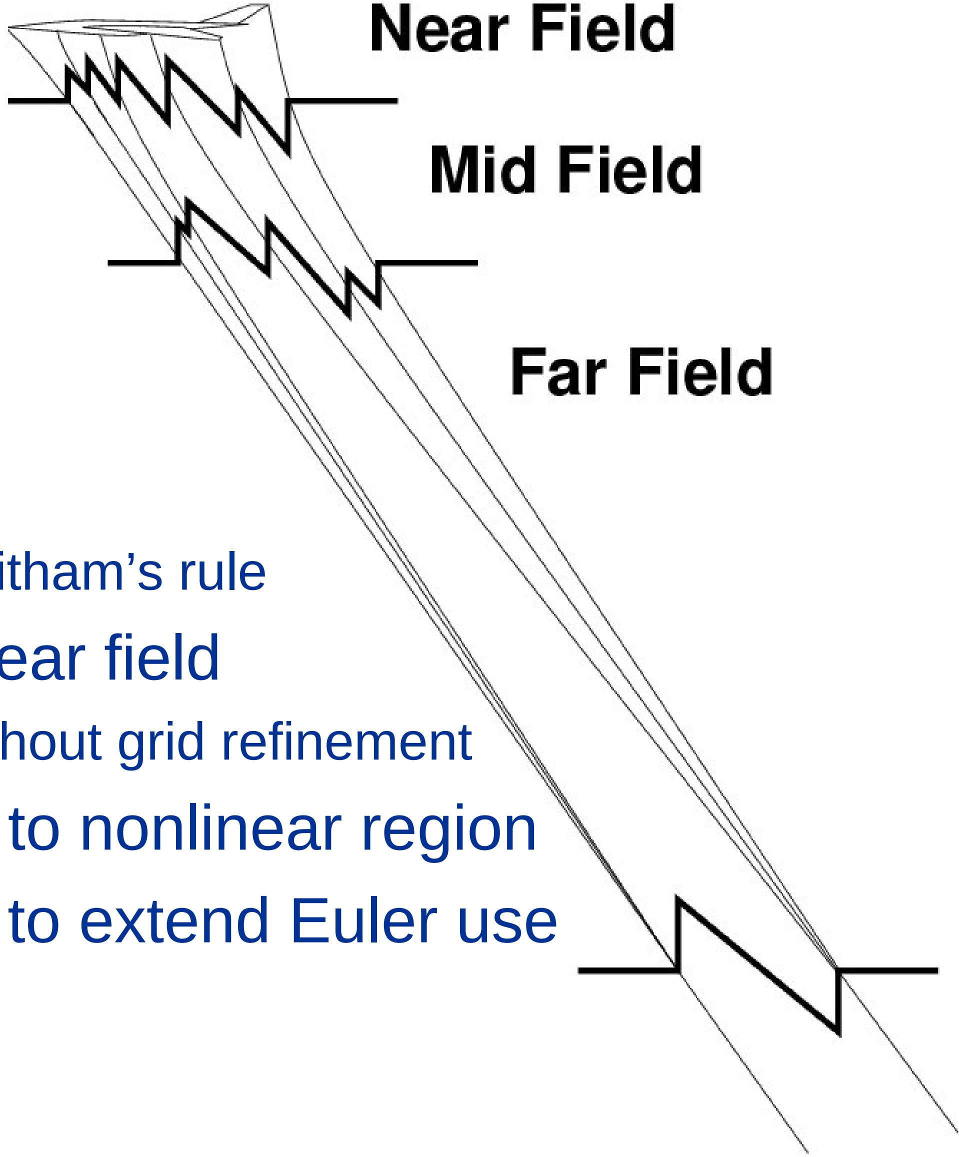
Atlanta, GA

Oct 6, 2008





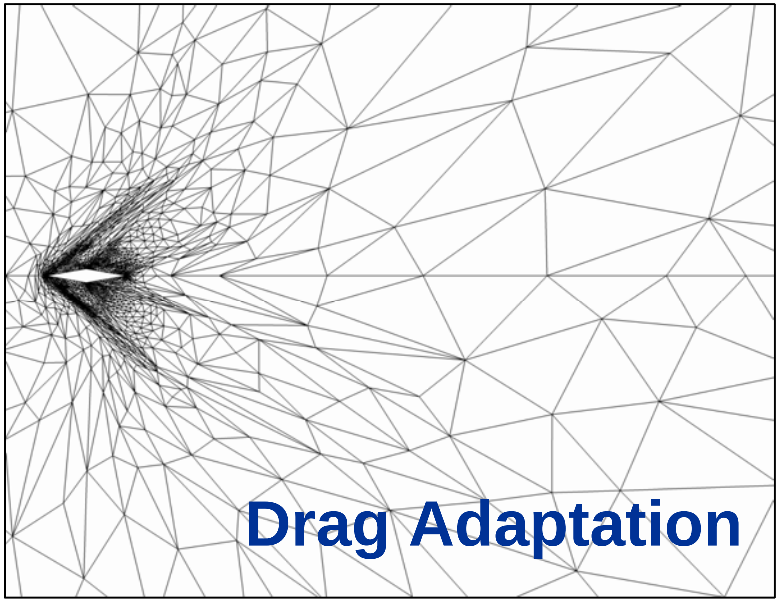
Sonic Boom Prediction



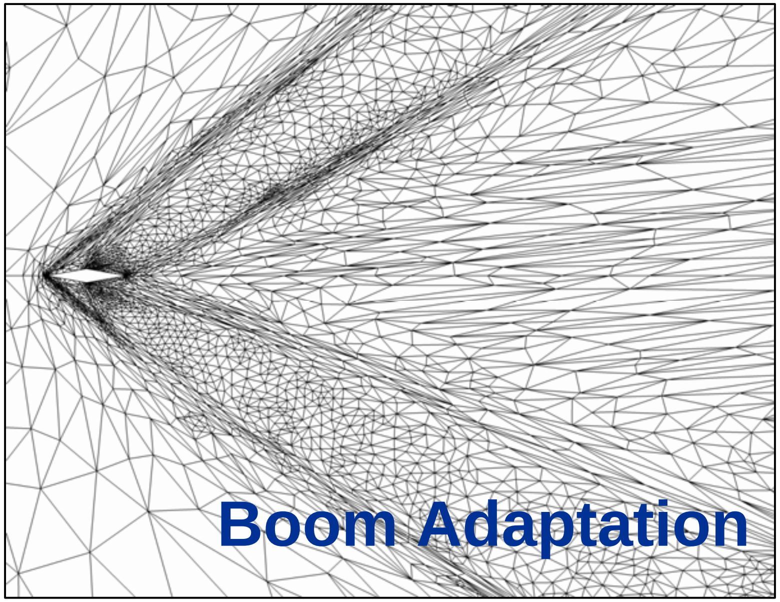
- Near field
  - Highly nonlinear
- Mid field
  - Shocks coalesce
- Far field
  - Geometrical Acoustics, Whitham’s rule
- Euler equations used in near field
  - Signals quickly degrade without grid refinement
- Far field methods applied to nonlinear region
- Goal of output adaptation to extend Euler use
  - Ensure accuracy

Output-Based Adaptation

- Mathematically rigorous approach involving the adjoint solution that reduces dependence on initial grid quality
- Uniformly reducing discretization error is not ideal from engineering standpoint, some errors are more important to outputs (i.e., drag, boom)



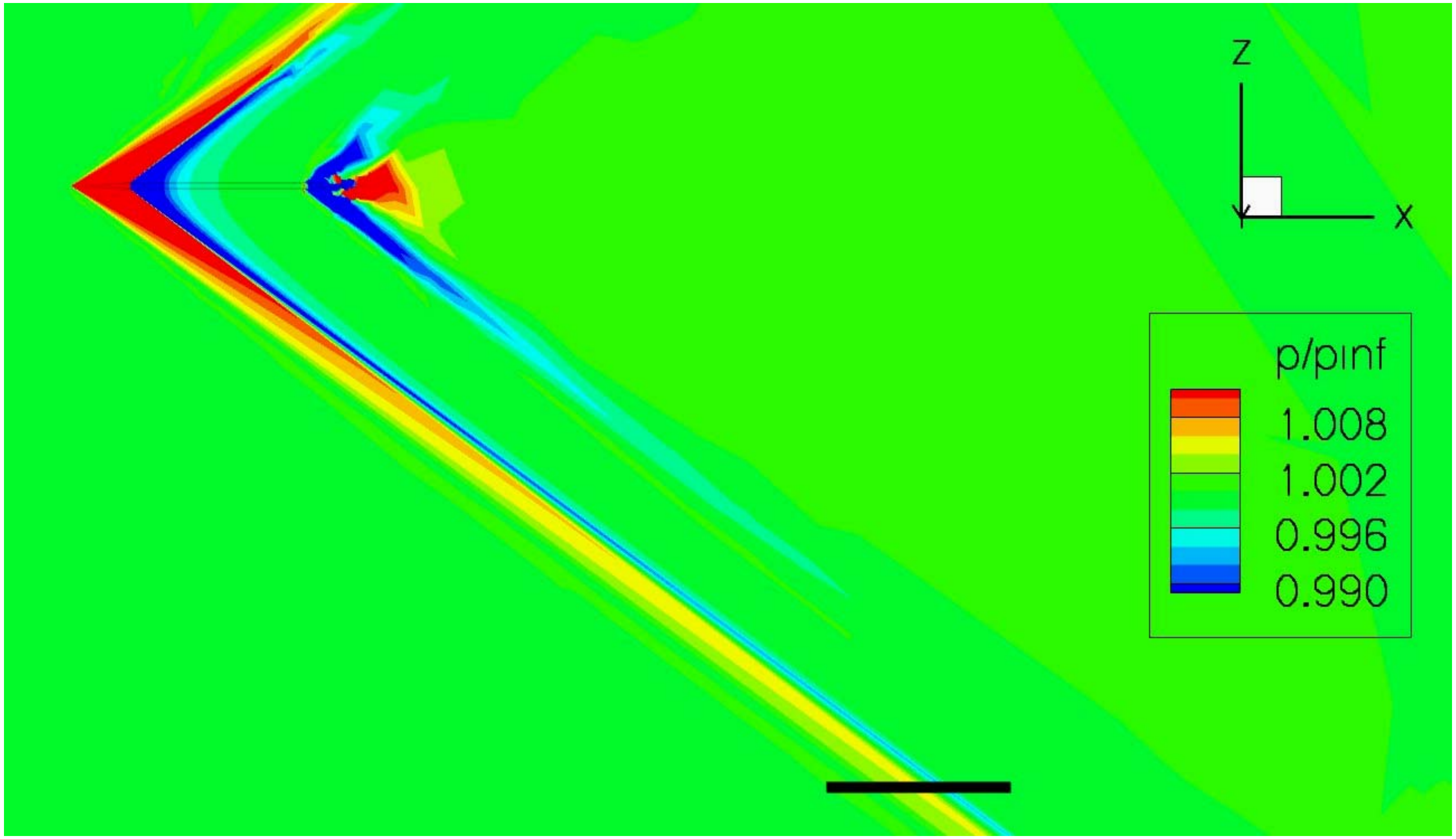
Drag Adaptation



Boom Adaptation

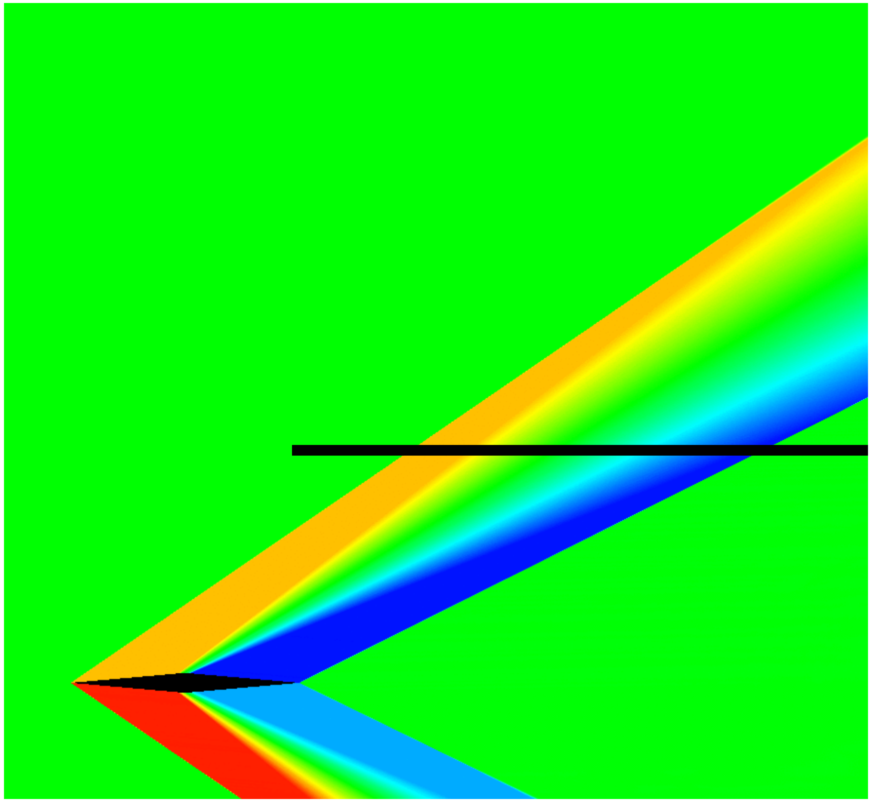
Output Function: “Sensor”

- Integral of pressure deviation squared on a cylinder
- Trimmed to model span and location of wind tunnel data (avoids resolution of sting closure)

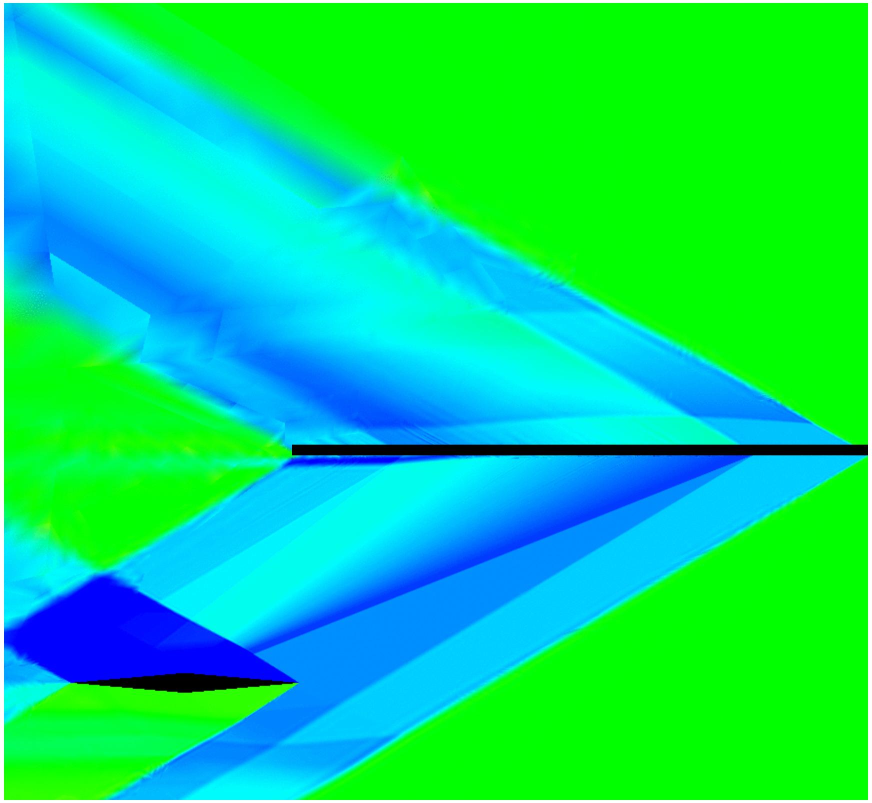


Output Adaptation for Sonic Boom

- Surface pressure integral
- Adaptation is targeted to improve this integral



Flow Solution



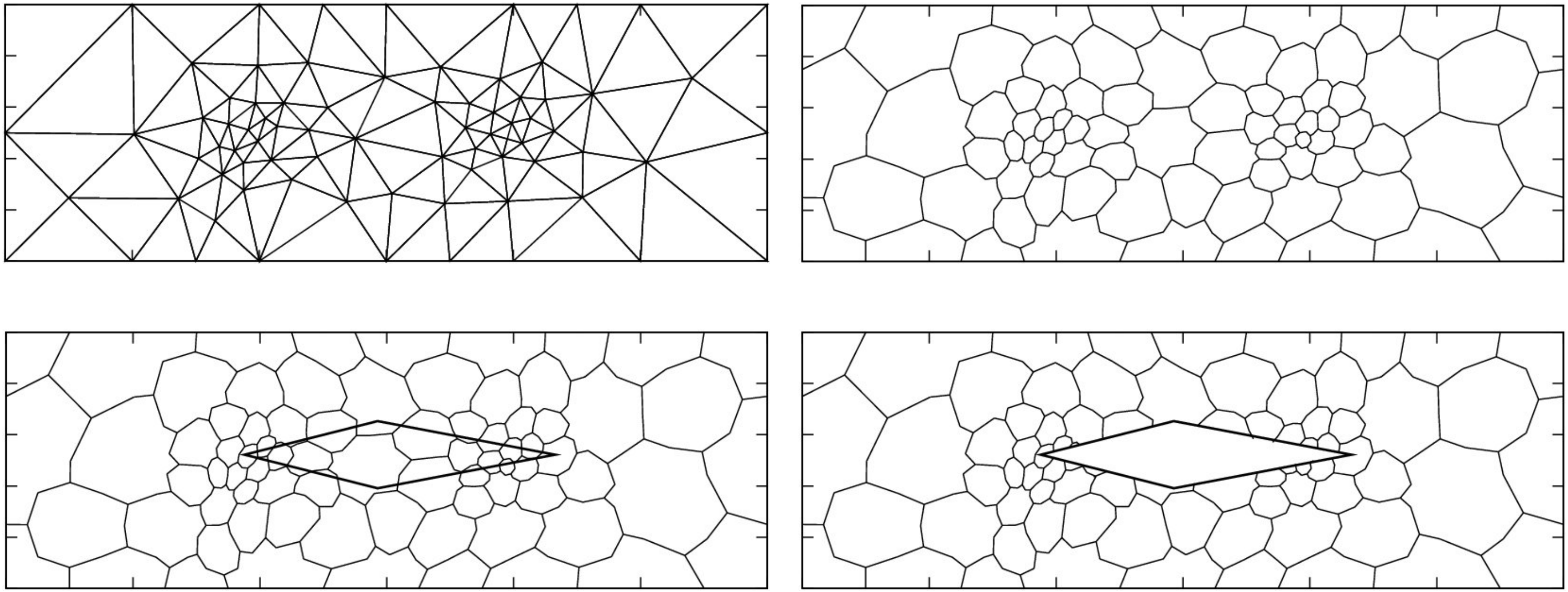
Adjoint Solution

Recent Progress FUN3D

- Output-adaptive tetrahedral cut-cell scheme
  - Permits truly automated anisotropic adaptation
    - Anisotropic body-fitted adaptation on curved boundaries limited application of output adaptation
  - No *a priori* knowledge of shock locations
  - Reduces grid generation task to a geometry surface grid
  - Similar to the CART3D Cartesian cut-cell scheme
- Heuristic reconstruction limiter
  - Standard limiters can cause flow and adjoint solver instabilities
  - Smooth convergence for flow and adjoint solvers
  - Jeff White (Hypersonic FAP)
- http://fun3d.larc.nasa.gov

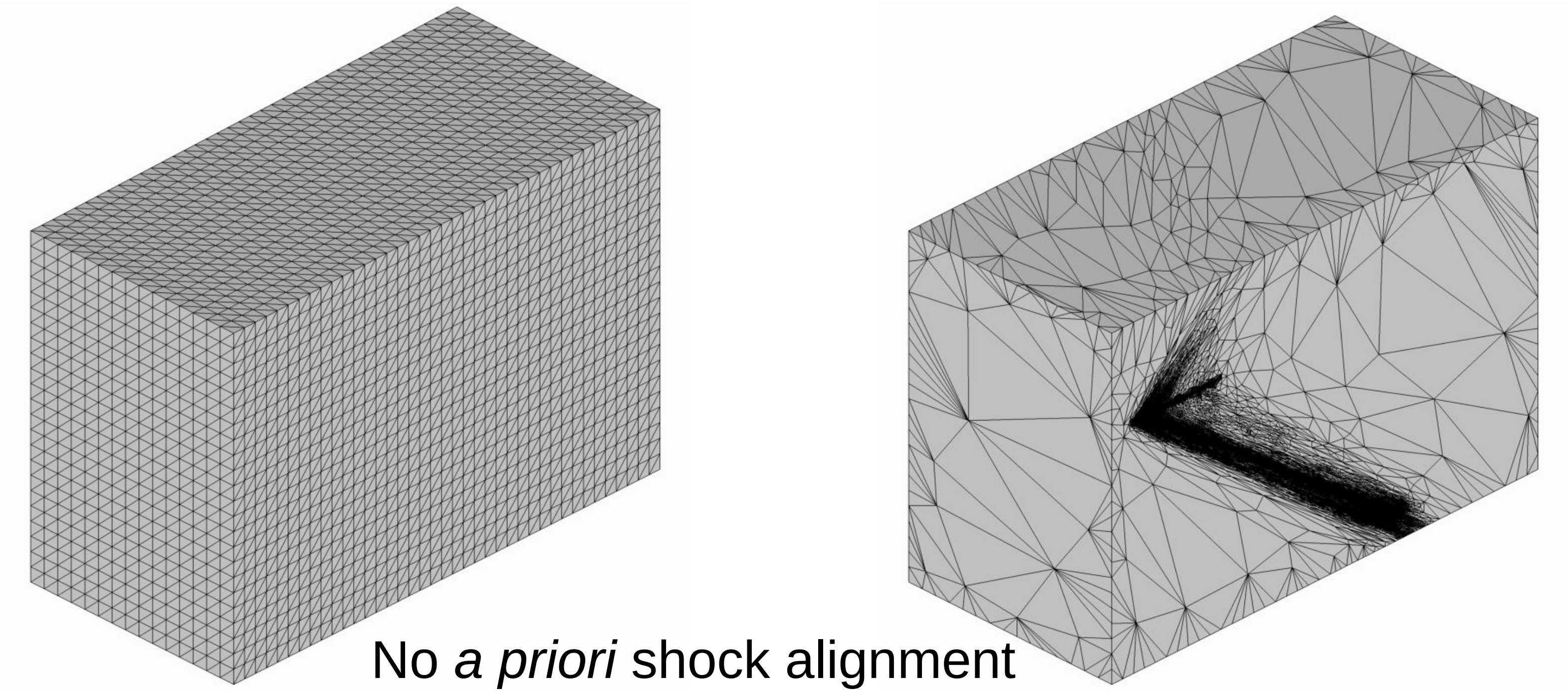
Cut-Cell Method

- Background volume grid
- Surface grid of geometry
  - Boolean subtracted from median dual background grid



Background Grid

- Coarse structured grid subdivided into tetrahedra
- Adapted to reduce the uncertainty in a pressure integral at the “sensor” location
  - Desired grid size is specified by adjoint error estimate
  - Desired anisotropy is specified by Mach Hessian



No *a priori* shock alignment

Validation Cases

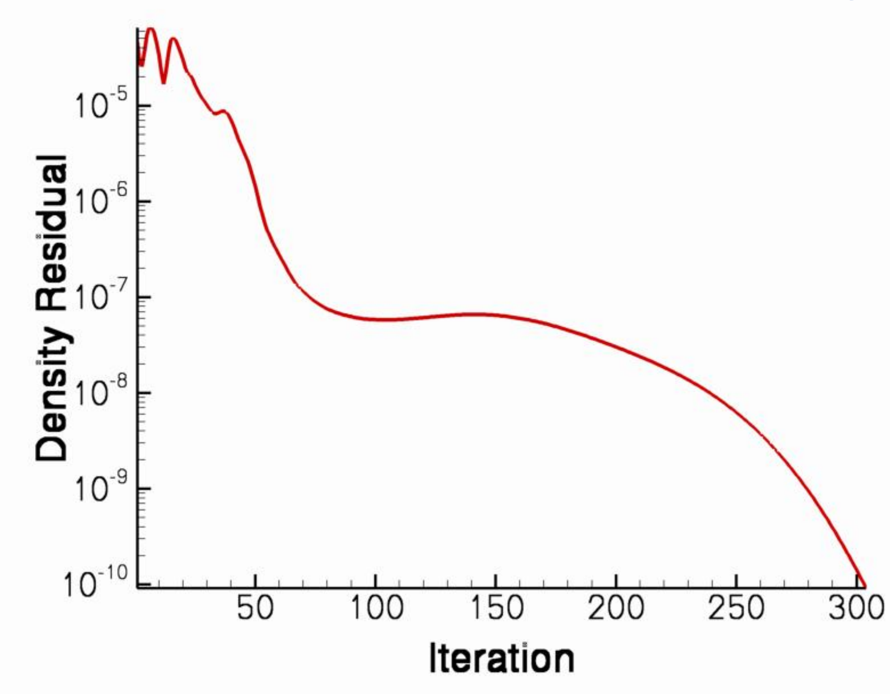
- Axi-symmetric geometries
  - 6.48 Degree Cone-Cylinder
    - NASA TM X-2219 (1971) Model I
  - Parabolic Body of Revolution
    - NASA TN D-3106 (1965) Model 4: r($x^{1/2}$)
  - Quartic Body of Revolution
    - NASA TN D-3106 (1965) Model 5: r($x^{1/4}$)
- Wing-Bodies
  - 69 Degree Swept Delta Wing Body
    - NASA TN D-7160 (1973) Model 4
  - Ames Low Boom Wing Tail with 4 Nacelles
    - NASA CP-1999-209699 (1999) LBWT-4

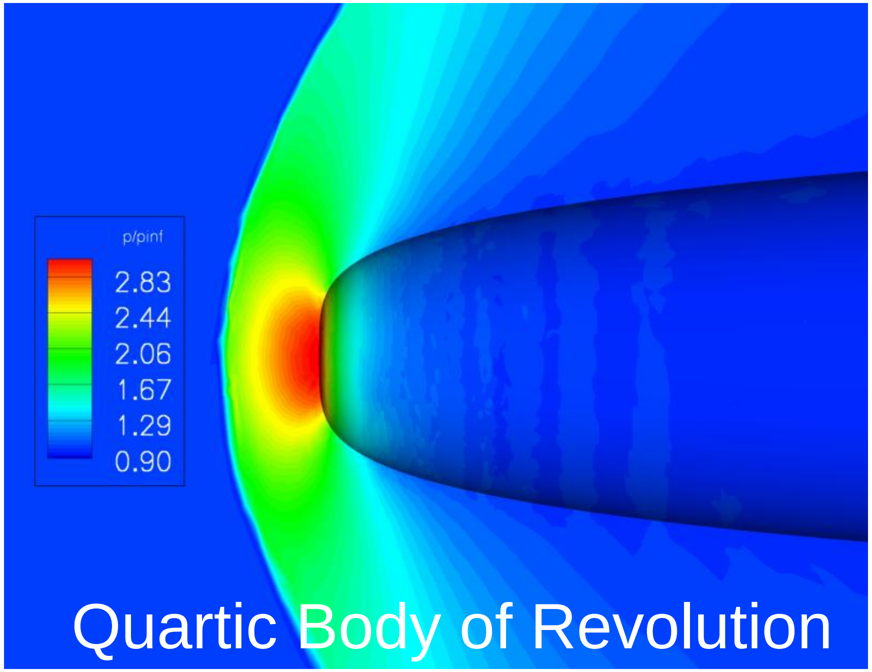
Axi-Symmetric Body Geometries

- Octave (MATLAB) script to convert r(x) to a triangulation of a body of revolution
    - Uniform circumfrential spacing (2-4 degrees)
    - Equally distribute slope errors or aspect ratio
    - 75 thousand triangles (25 thousand for Cone-Cylinder)
- Cylindrical sting (3 body lengths) closed with aft pointing cone (1 body length)

Axi-Symmetric Bodies

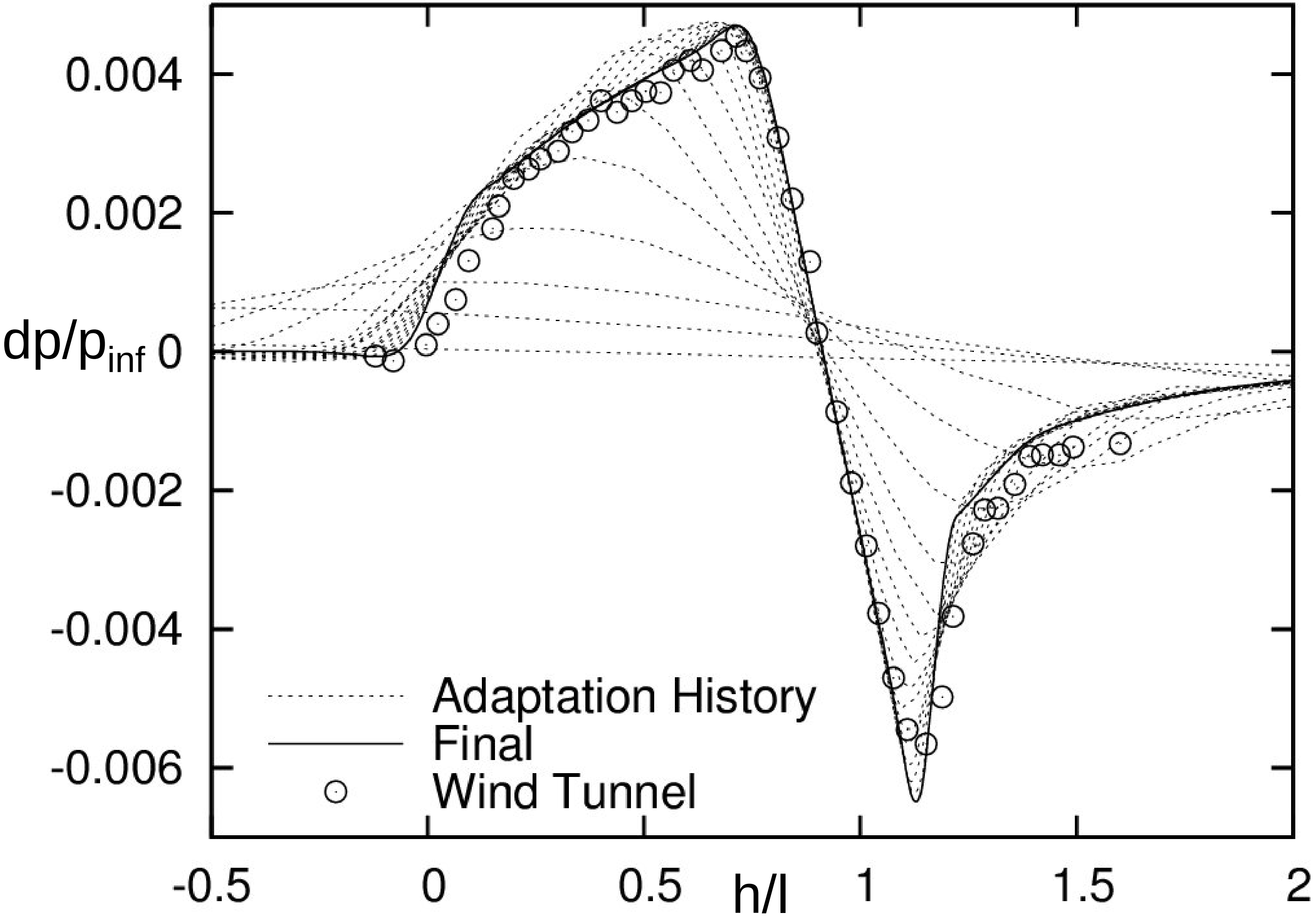
- Longest propagation distances (10 body length)
  - Ensure sufficient iterative convergence
- Quartic Body has a significant shock stand-off distance required a less aggressive CFL schedule for initial transients during impulsive start



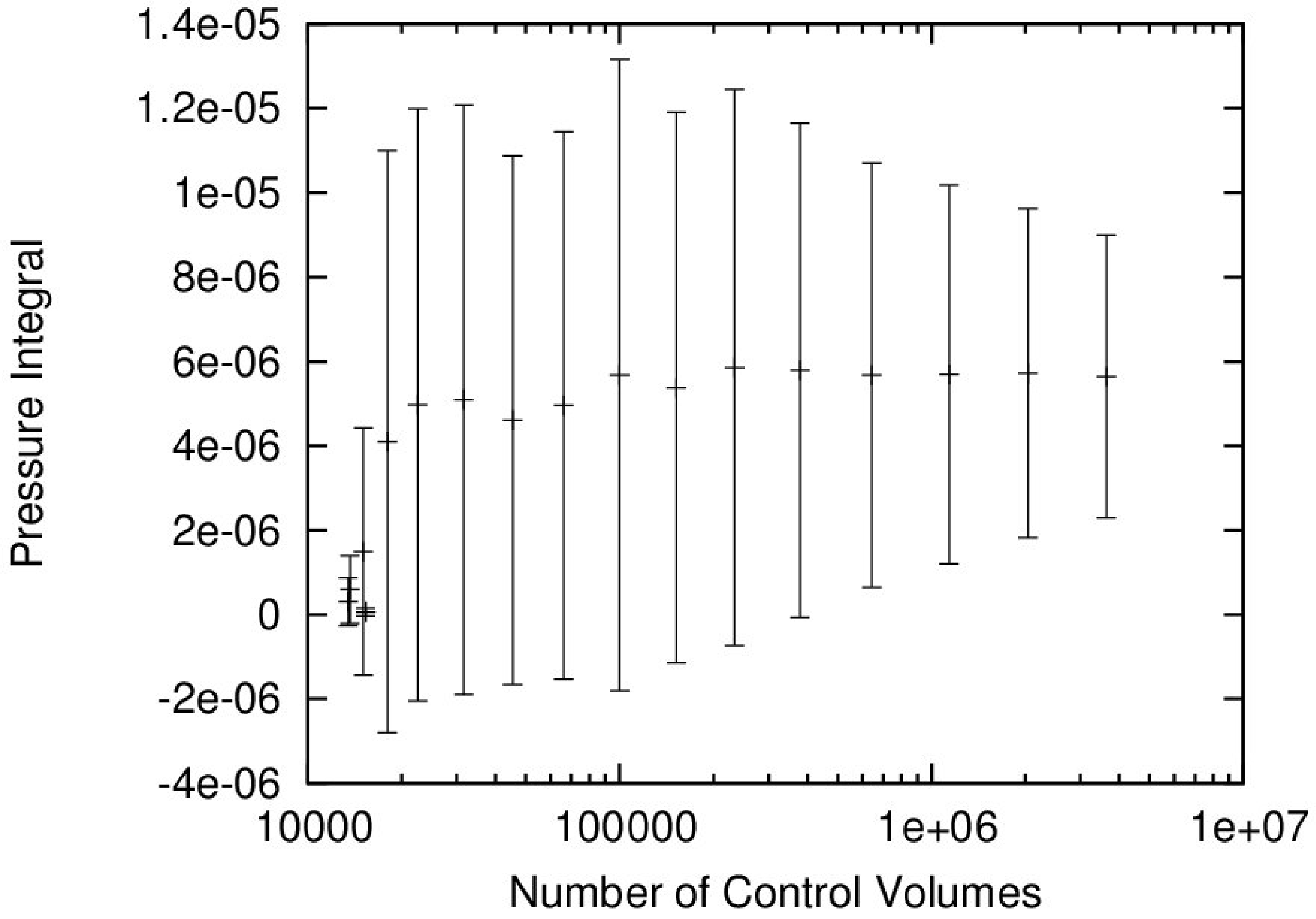


Quartic Body of Revolution

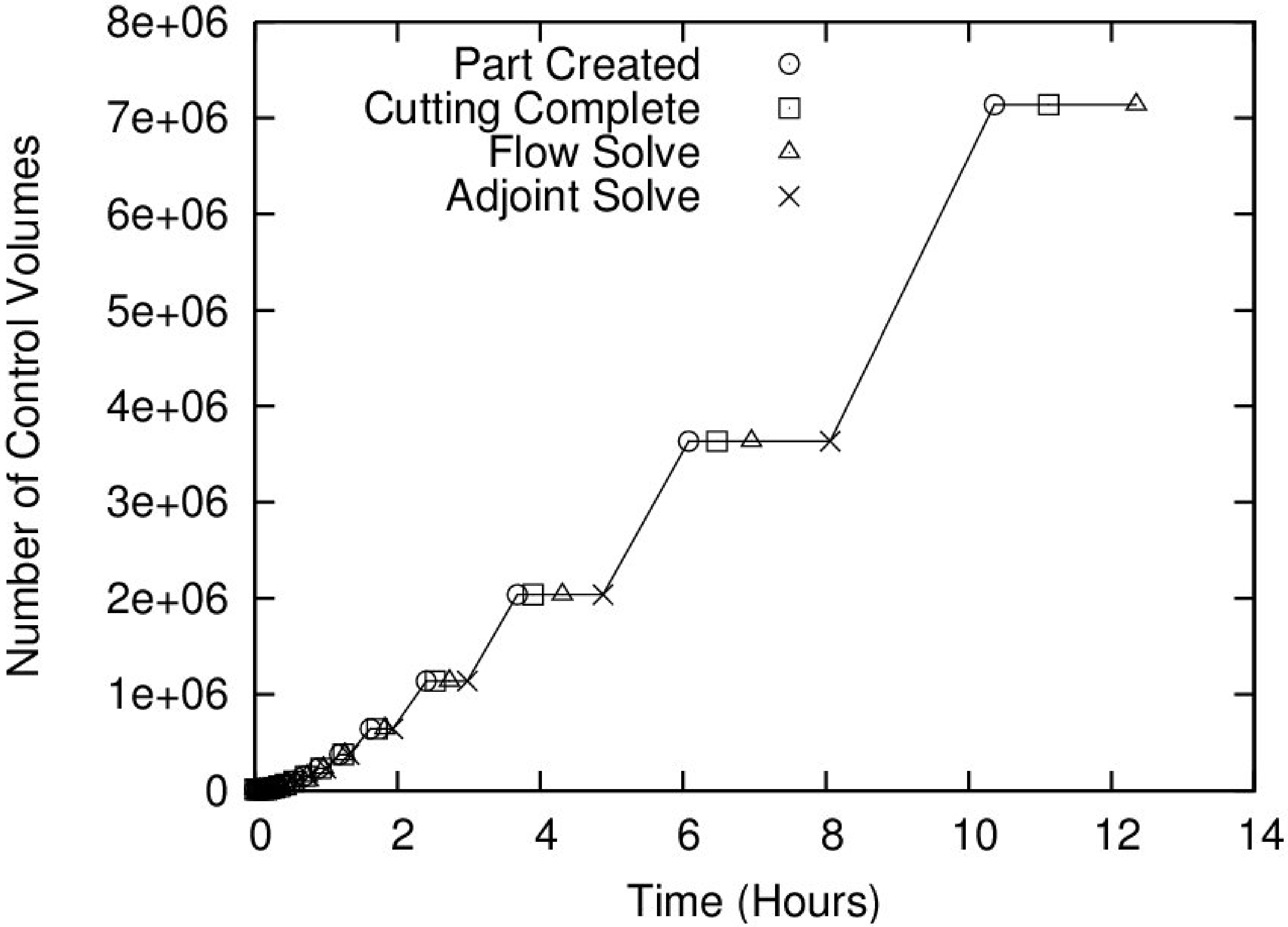
6.48 Degree Cone Cylinder, 1.68 Mach, h/l=10



6.48 Degree Cone Cylinder, 1.68 Mach, h/l=10

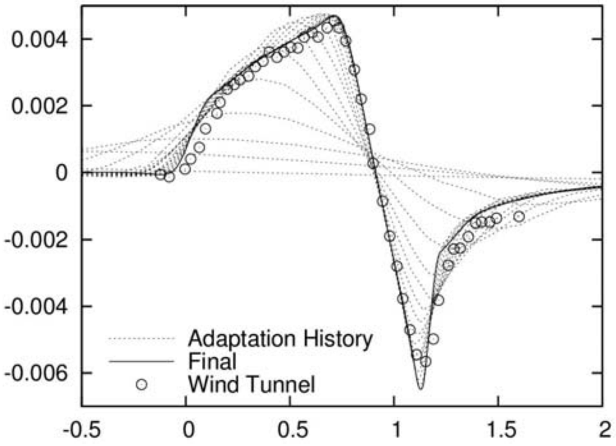


6.48 Degree Cone Cylinder, 1.68 Mach, h/l=10

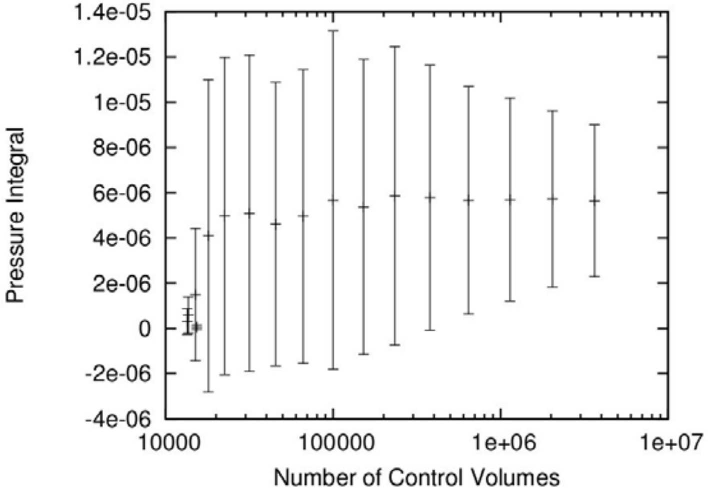


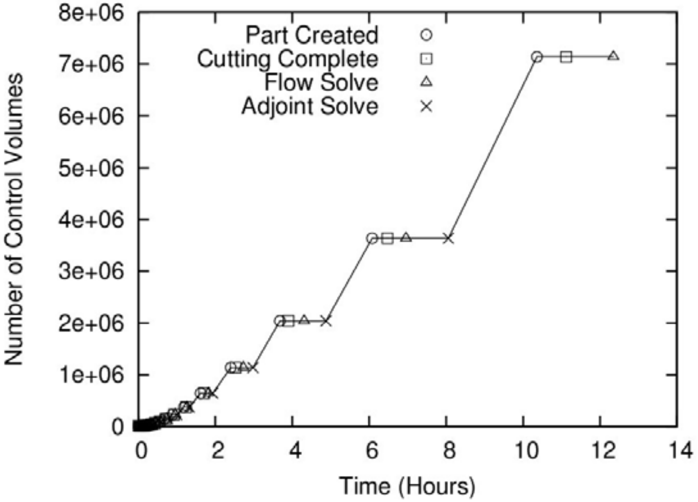
24 x 3

Designer Trades Accuracy for Resources



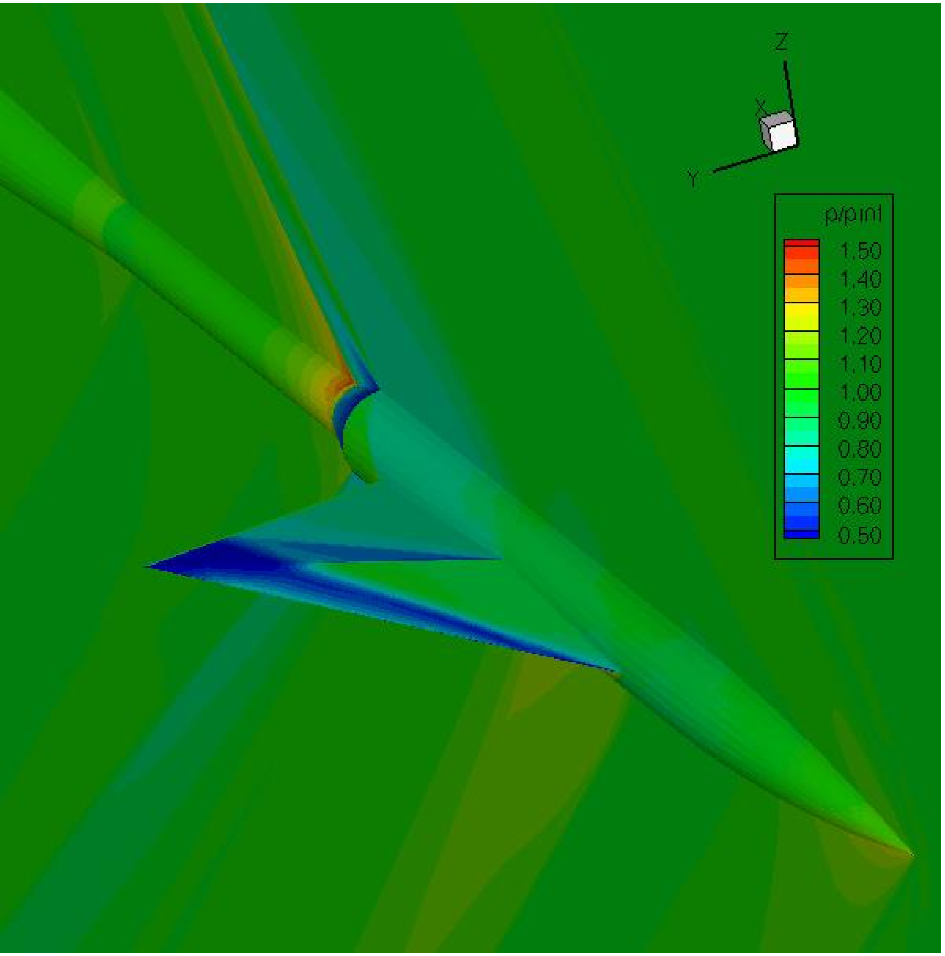
Signal with Accuracy Estimates ↔ Resources

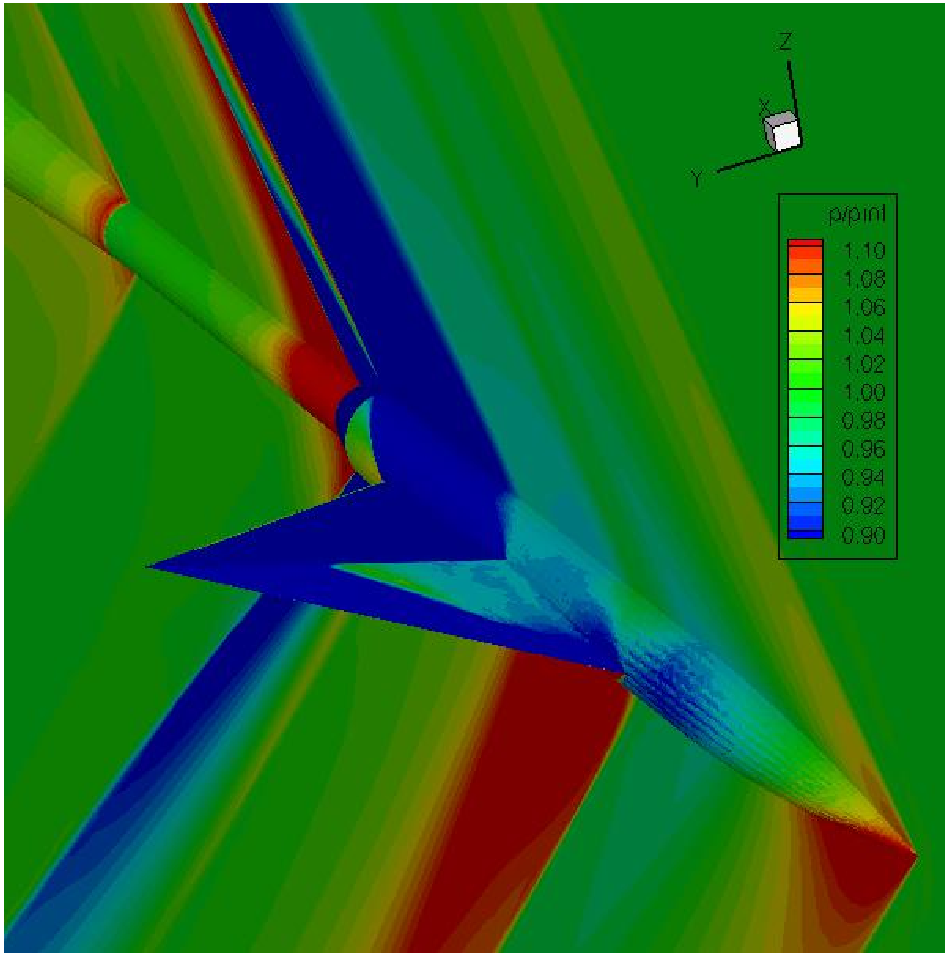




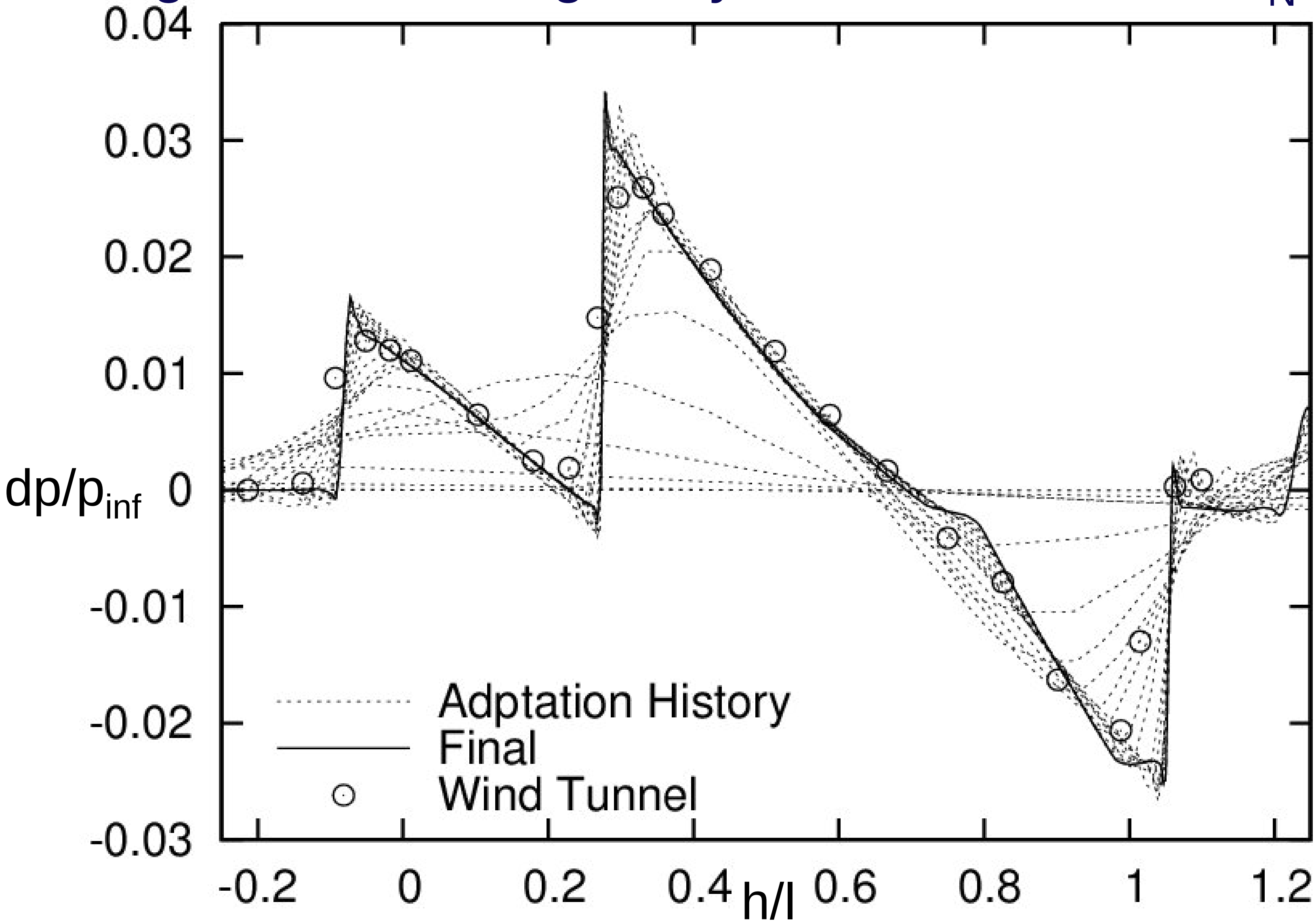
69 Degree Delta Wing Body, 1.68 Mach, 0.15 C_N

- Vortex and circumferential geometry discontinuties

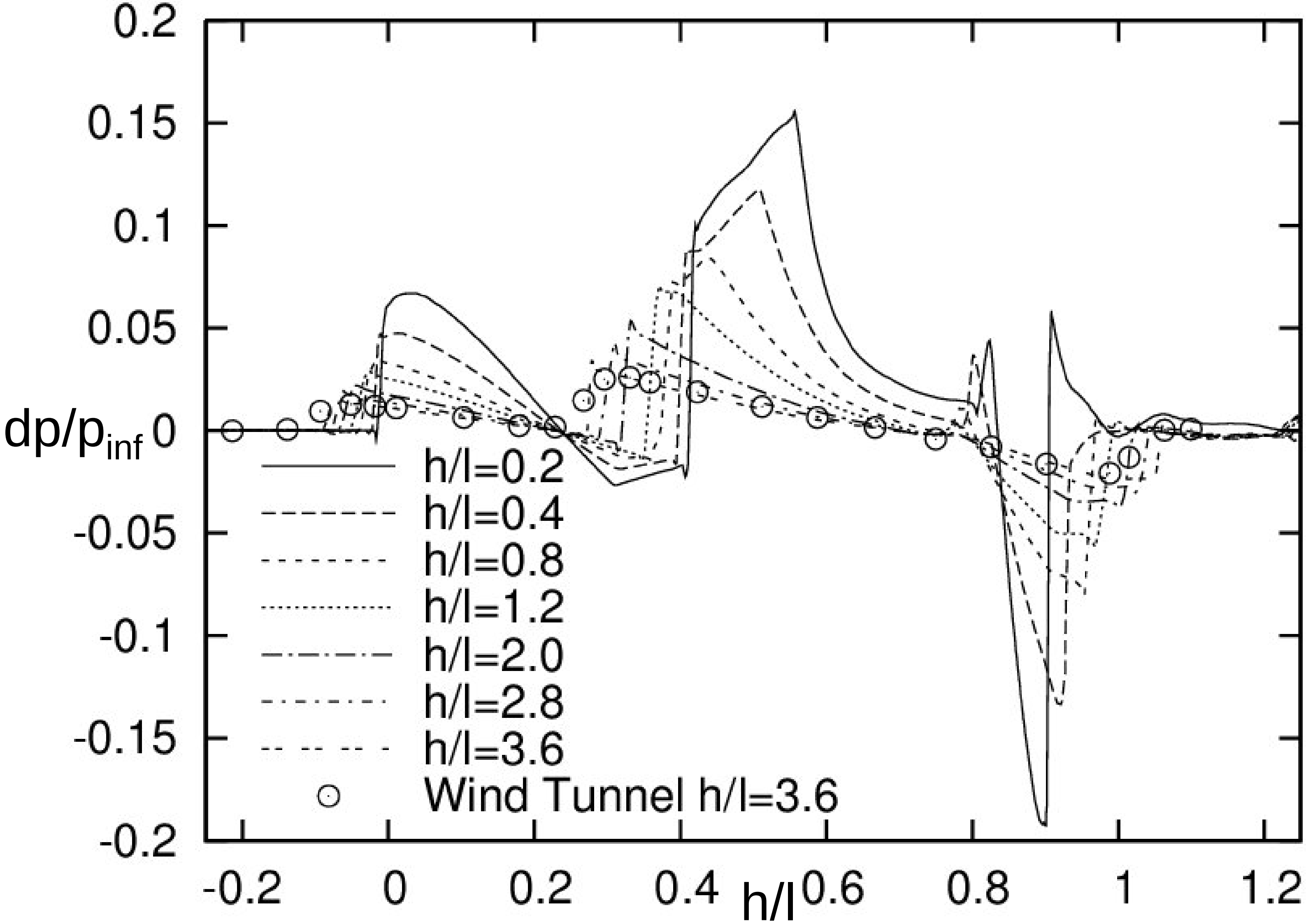




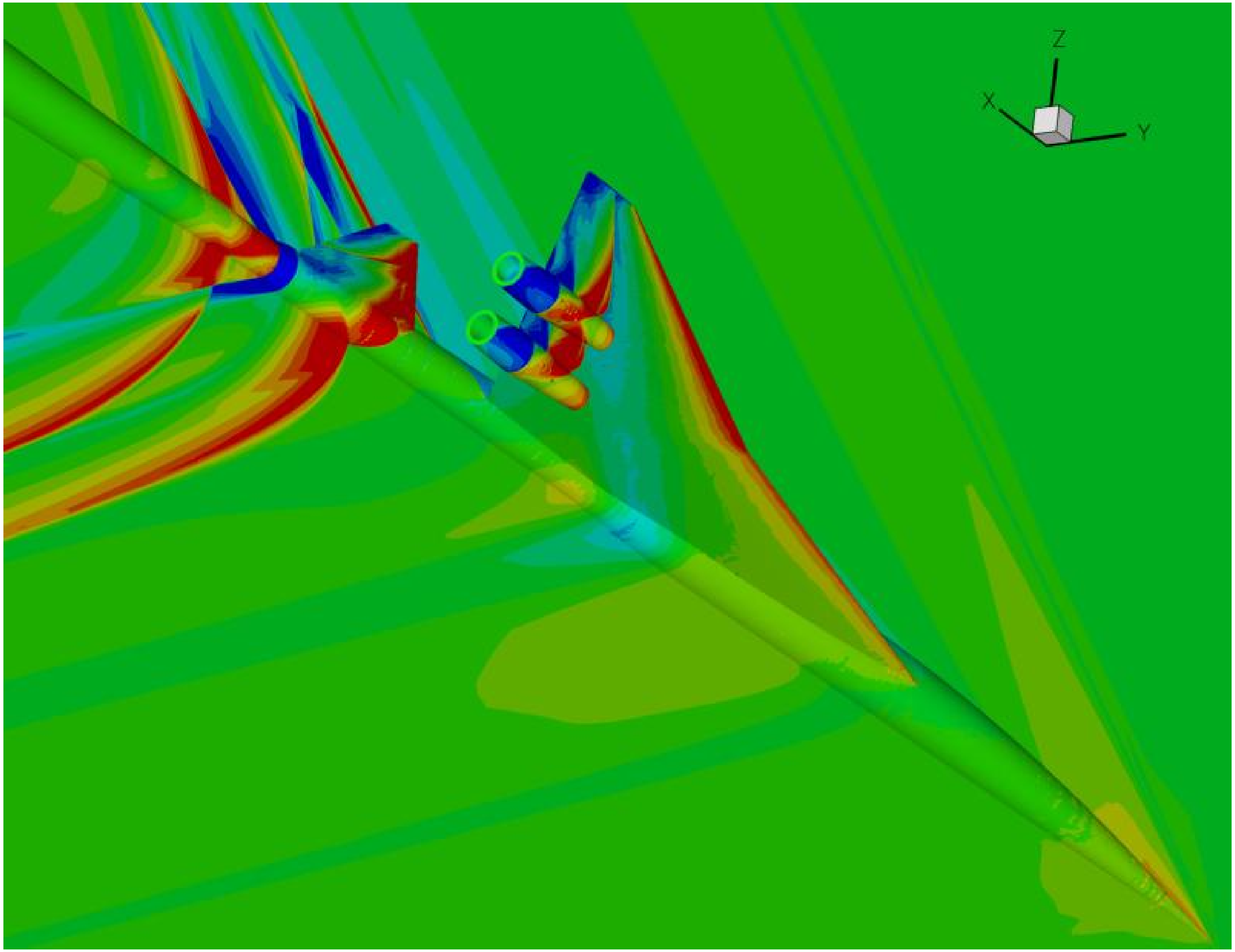
69 Degree Delta Wing Body, 1.68 Mach, 0.15 C_N



69 Degree Delta Wing Body 1.68 Mach 0.15 C_N

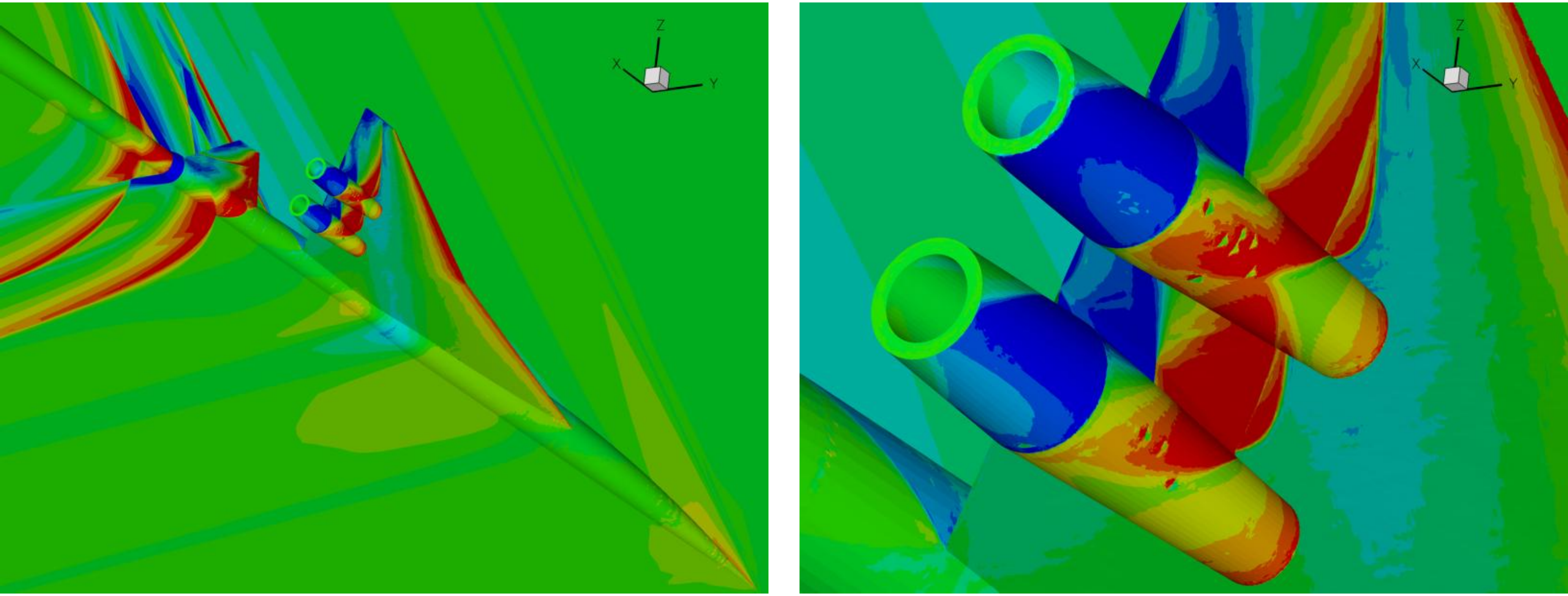


Ames Low Boom Wing Tail, 2.0 Mach, 2.0 AoA



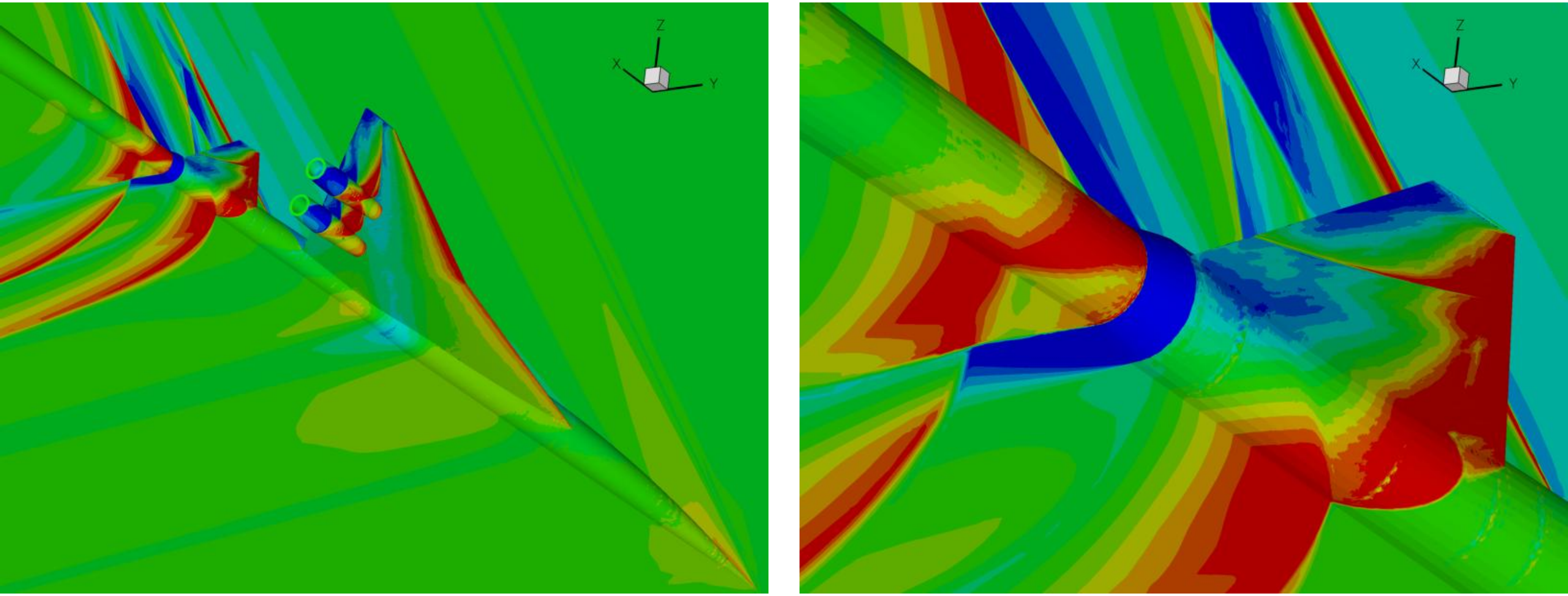
Ames Low Boom Wing Tail, 2.0 Mach, 2.0 AoA

- LBWT has aft-facing surface normal modeled with a transpiration boundary condition to prevent unphysical expansion
- Unintended geometry discontinuities are resolved



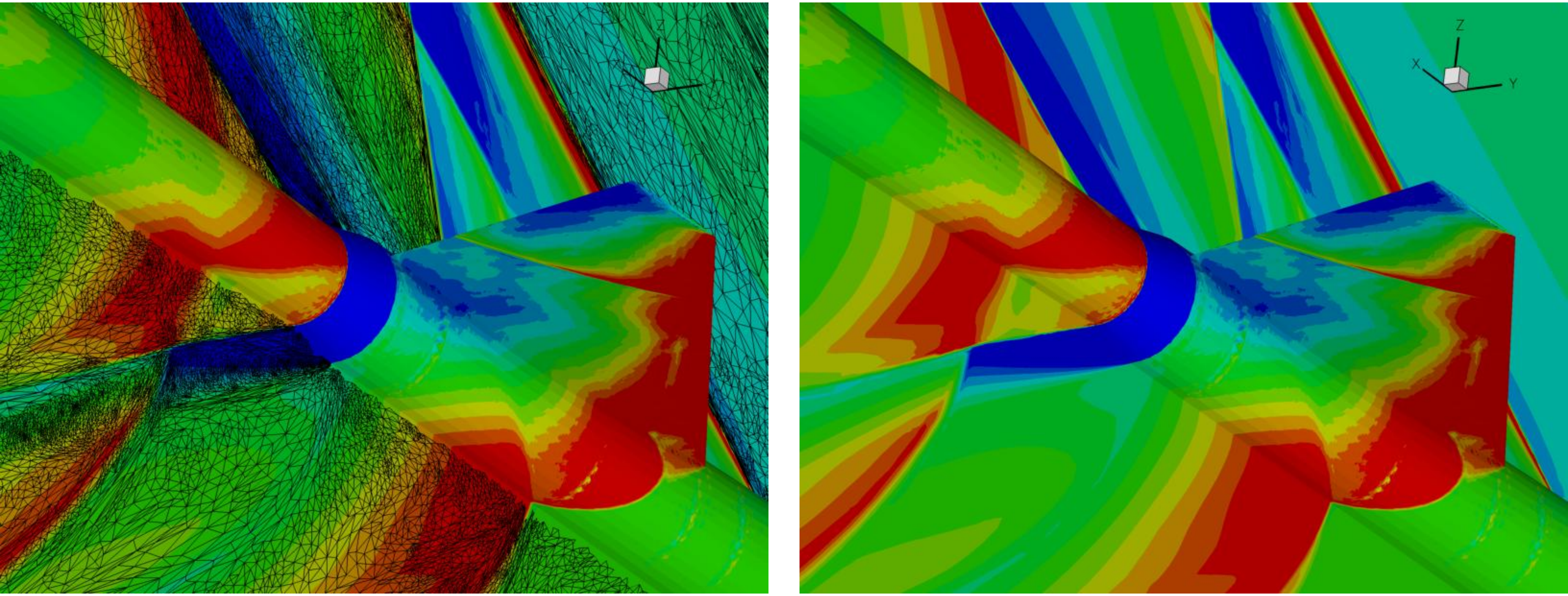
Ames Low Boom Wing Tail, 2.0 Mach, 2.0 AoA

- Tail, fuselage, and sting have complex shock-shock interaction with wings and nacelles



Ames Low Boom Wing Tail, 2.0 Mach, 2.0 AoA

- Adaptation aligns grid to complex shock-shock interaction topologies



Simulation Inputs

- Surface triangulation to resolve geometry
- Dimensions of background grid
- Position of sensor surface
- Mach and angle of attack
- CFL number schedule
- Iterative convergence criteria (max residual reduction or iteration)
- Number of processors

Case Statistics

Case	Total time	Adaptations	Final flow solve	Final size
6.48 Cone-Cylinder	12 hr	18	74 min	7.1 million CV
Parabolic BoR	14 hr	22	38 min	1.5 million CV
Quartic BoR	14 hr	27	31 min	1.1 million CV
69 Degree Delta Wing	12 hr	21	90 min	6.7 million CV
LBWT	12 hr	19	30 min	6.9 million CV

Summary

- Adjoint provides output sensitivities
  - Automated output-based adaptation
  - Enables design
- Robust output adaptation cut-cell approach predicts wind tunnel measurements
  - Tetrahedral background grids
  - Automated after geometry surface triangulation
  - No *a priori* shock knowledge used for initial grid generation
  - Five cases performed in 2 work days
  - Iterative convergence is important for long propagation distances, complicated by detached bow shocks
- More info: http://fun3d.larc.nasa.gov