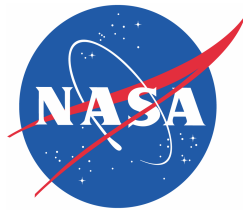


Recent FUN3D-Related Research and Applications

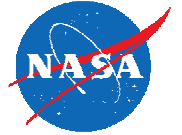


Eric J. Nielsen
Computational AeroSciences Branch

Informal Status Update for Boeing-Seattle
August 25, 2010

<http://fun3d.larc.nasa.gov>

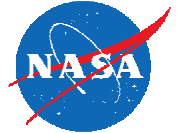
Introduction



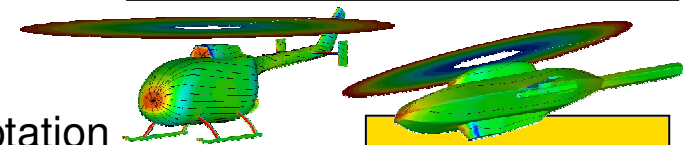
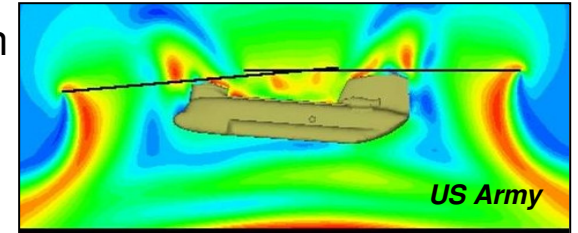
- Very informal overview of recent work provided here
- Solicited various people for 1 or 2 high-level slides describing their work since last NASA/Boeing TIM (November 2009)
- More detailed discussions to follow at November 2010 TIM?
- I am not intimately familiar with a lot of this work, but can try to answer questions as we go...

FUN3D Core Capabilities

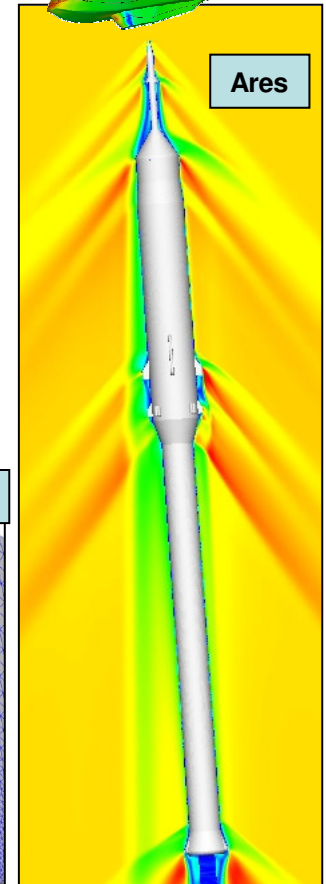
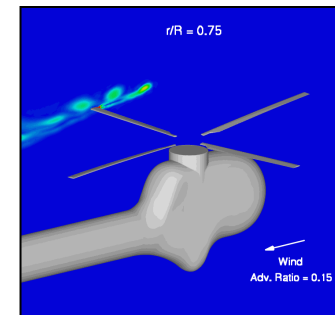
<http://fun3d.larc.nasa.gov>



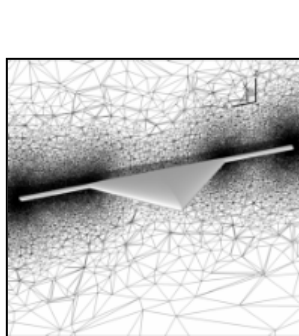
- Solves 2D/3D steady and unsteady Euler and RANS equations on node-based mixed element grids for compressible and incompressible flows
- Supports numerous internal/external efforts across speed range
- General dynamic mesh capability: any combination of rigid/overset/morphing grids, including 6-DOF effects
- Aeroelastic modeling w/ mode shapes, full FEM, CC, etc
- Constrained/multipoint adjoint-based design and mesh adaptation
- Modern software practices including 24/7 testing
- Linear scaling through thousands of cores
- Capabilities fully integrated, very responsive support team, online documentation, training videos, tutorials, etc



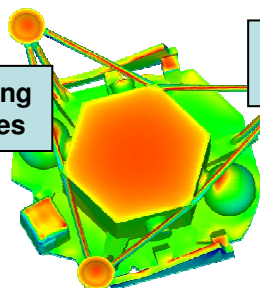
Rotorcraft



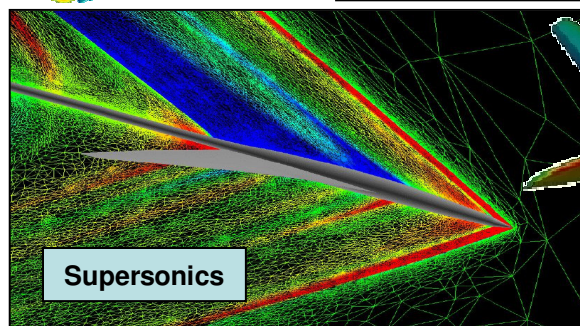
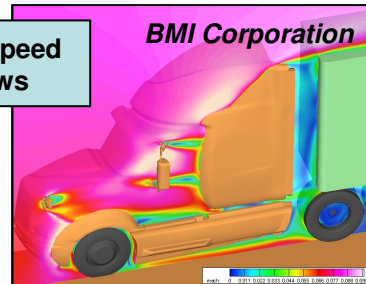
Ares



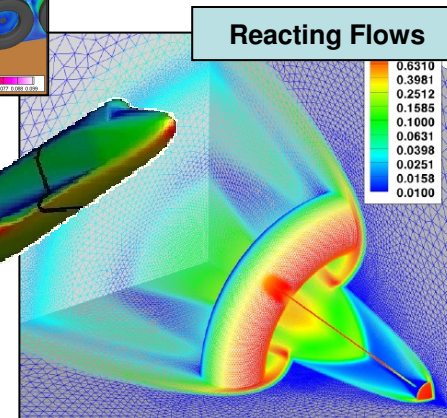
Morphing Vehicles



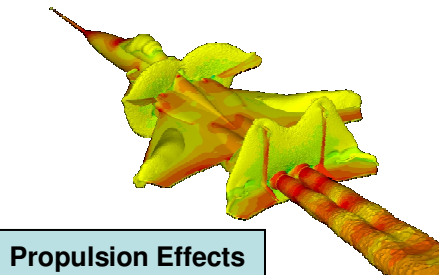
Low-Speed Flows



Supersonics

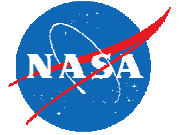


Reacting Flows

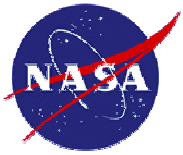


Propulsion Effects

Multigrid Efforts

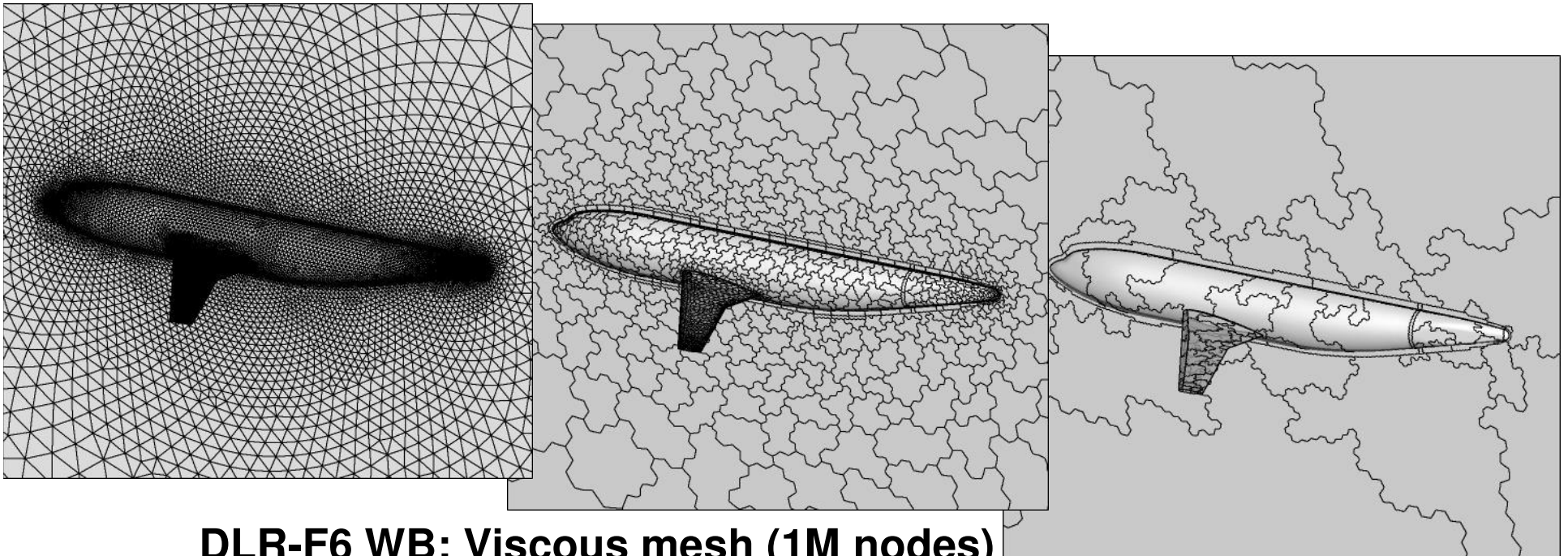


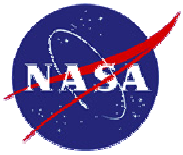
- Info provided by Jim Thomas and Hiro Nishikawa (NIA research associate on NRA)
- Working with Boris Diskin (NIA)



Agglomeration Multigrid Methods

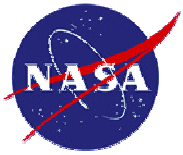
- **Agglomeration multigrid method follows pioneering work of Venkatakrishnan and Mavriplis with modifications**
 - Topology-preserving agglomerations
 - Consistent coarse-grid discretization
- **Both cell-centered and node-centered discretizations**





Agglomeration Multigrid Methods

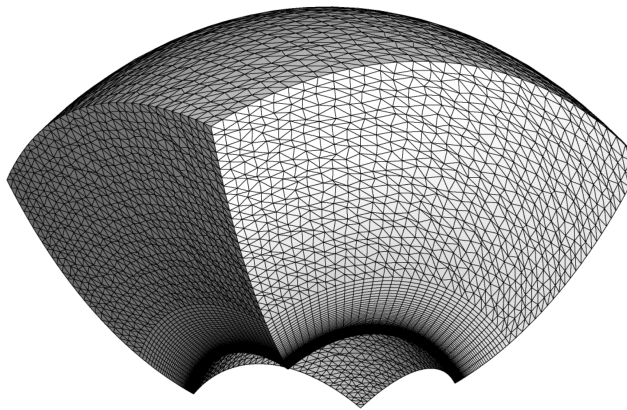
- **Diffusion on isotropic grids (AIAA-2009-4138/AIAA J)**
 - Showed grid dependence with inconsistent coarse grids
 - Applied quantitative multigrid analysis tools
 - Ideal Coarse Grid (ICG)
 - Ideal Relaxation (IR)
- **Diffusion on highly stretched grids (Computers & Fluids 2010)**
 - Developed IR operator for line relaxation
 - Showed limitations with tetrahedral grids both theoretically and practically
 - Grid-independent convergence with full coarsening and line relaxation with prismatic cells in highly stretched regions
- **Euler and RANS for complex geometries ongoing (AIAA paper Summer 2010)**



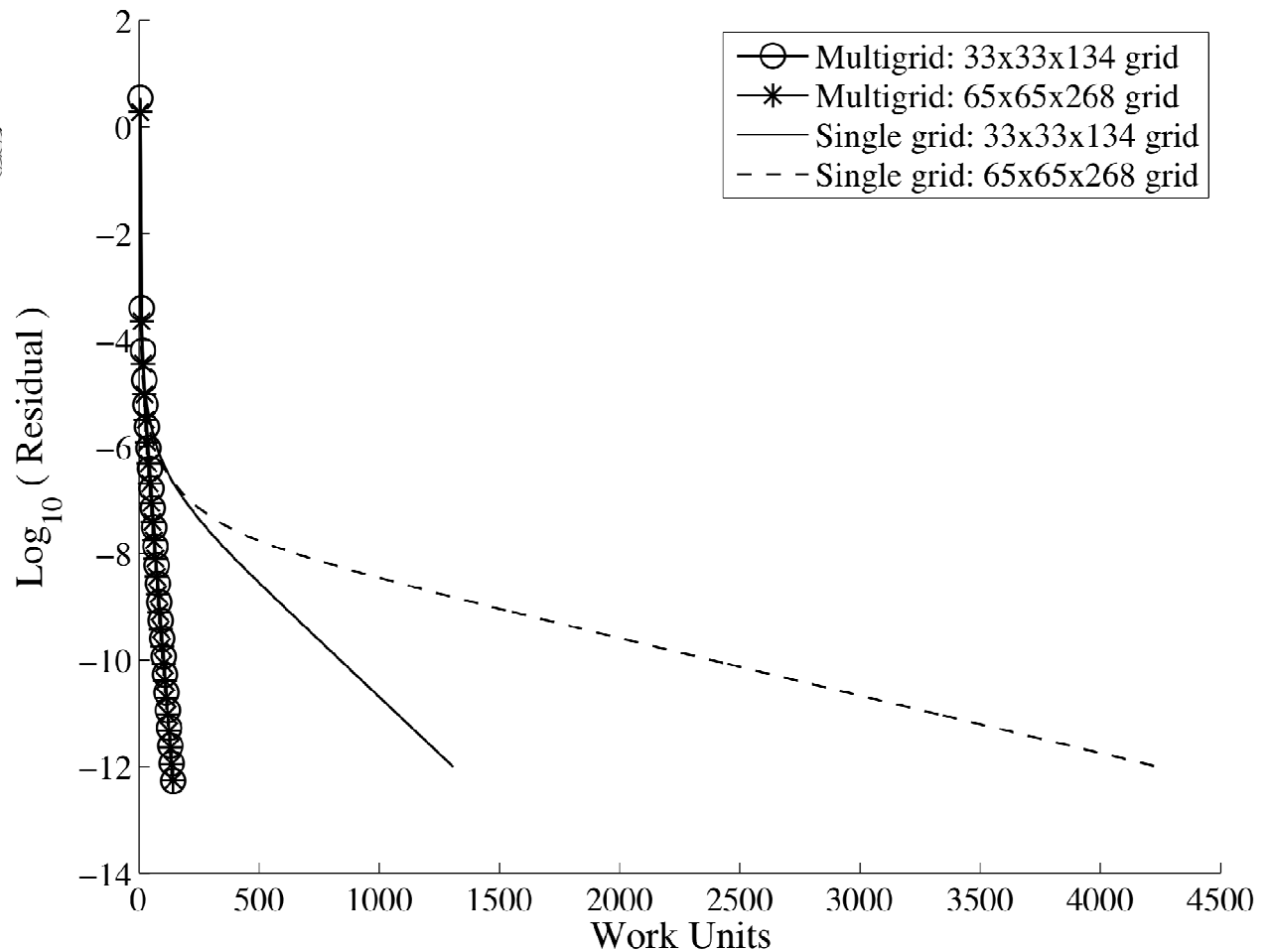
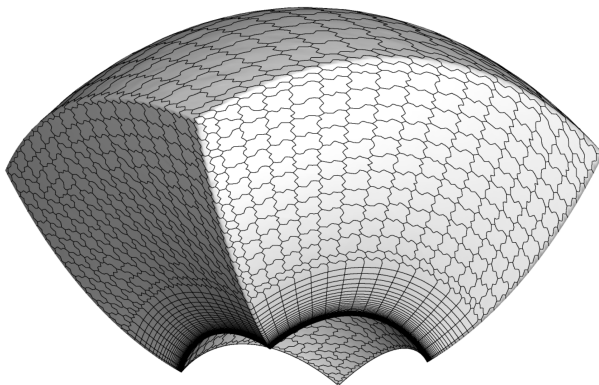
Grid-Independent Convergence

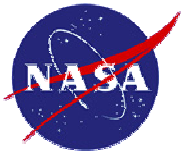
Diffusion ; $(A)_{\max}=1000$

Primal Mixed-Element Grid



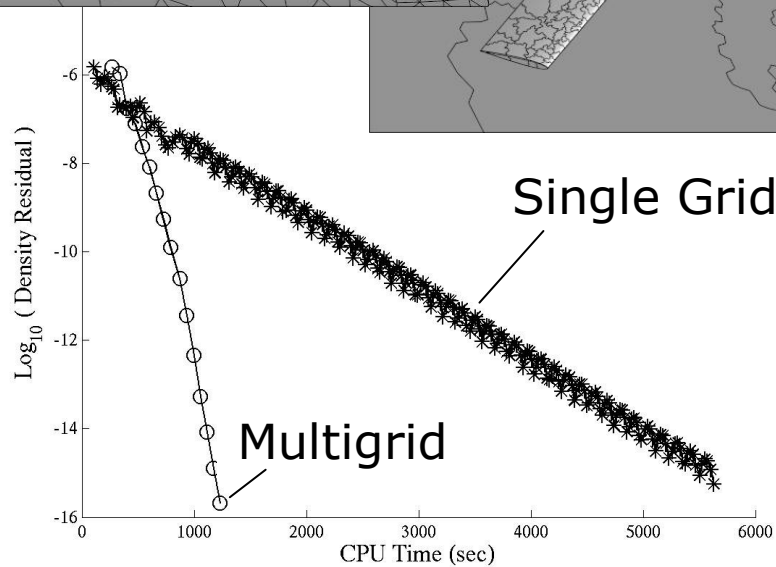
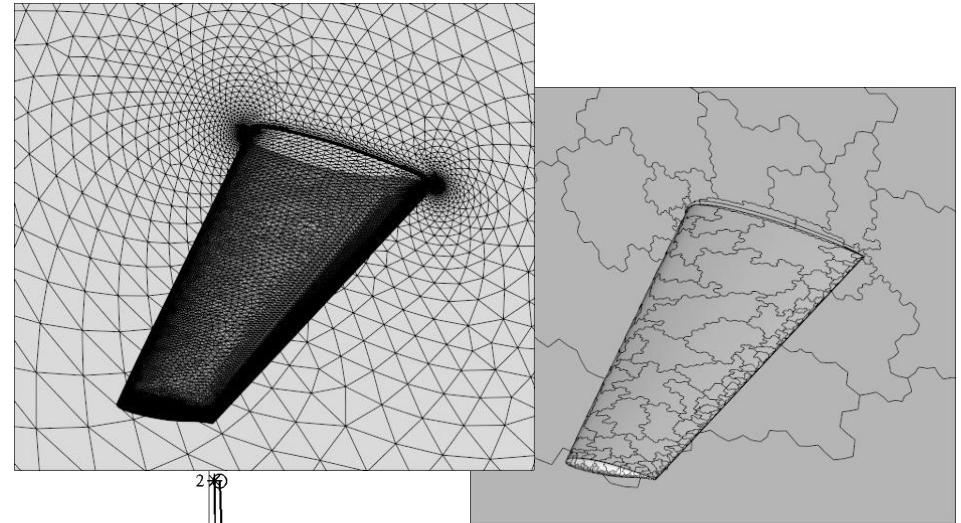
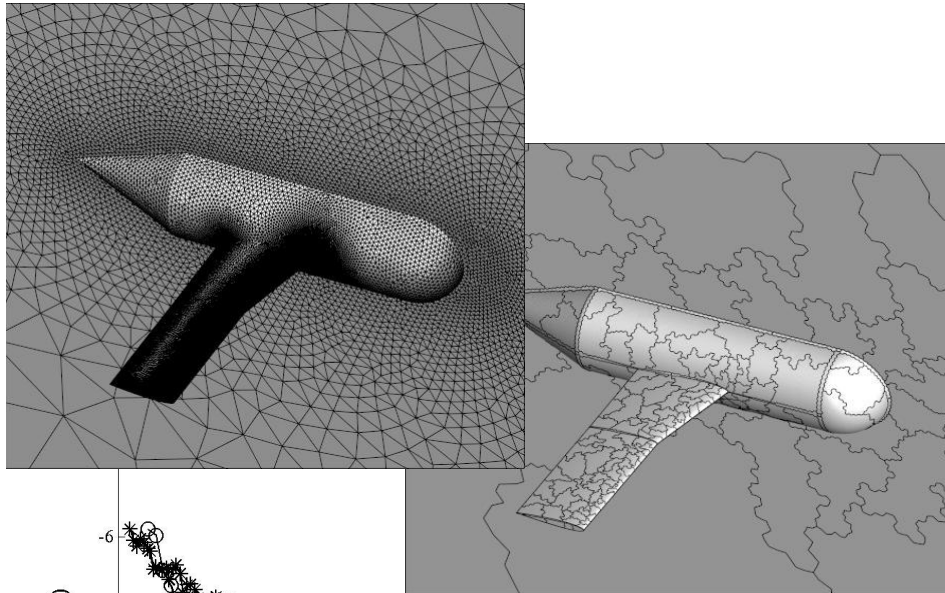
1st Agglomerate



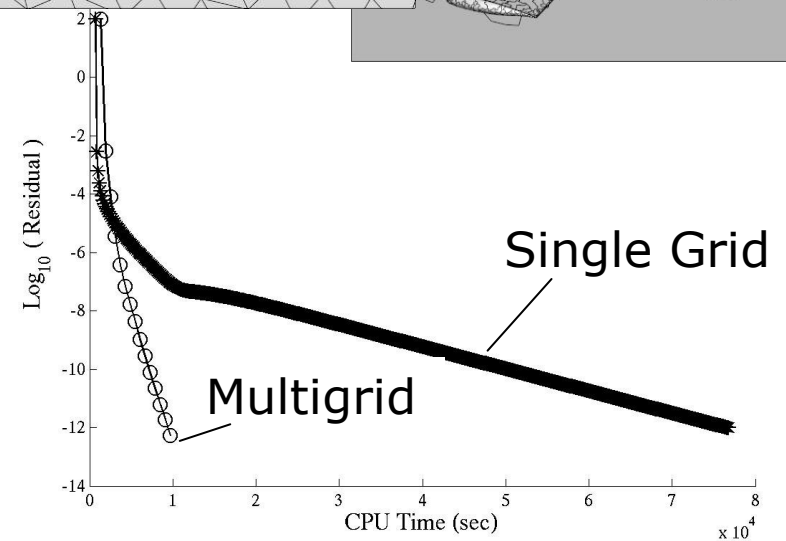


Agglomeration Multigrid

Towards grid-independent convergence for fully unstructured grids



Inviscid results (1M nodes): ~6 times faster, including the time to generate coarse grids.



DPW-W2(1.9M nodes);
Diffusion equation.

Agglomeration Multigrid

Key elements newly developed in this work

1. Consistent and robust viscous scheme on coarse grids

Face-tangent LSQ scheme is the only such scheme among those tested. Widely-used inconsistent schemes (edge-derivatives or Galerkin construction) fail or deteriorate MG convergence on fine grids.

3. Hierarchical agglomeration scheme

Independently agglomerate:

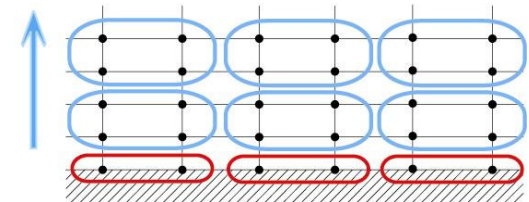
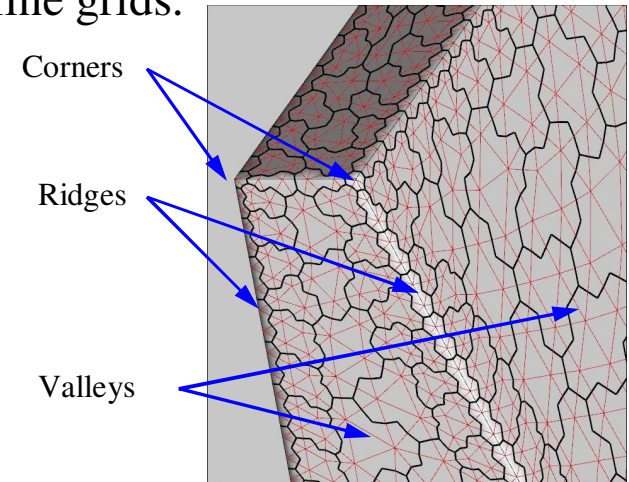
Corners – Ridges – Valleys – Interiors

It guarantees valid LSQ stencils on boundaries and also preserves geometries.

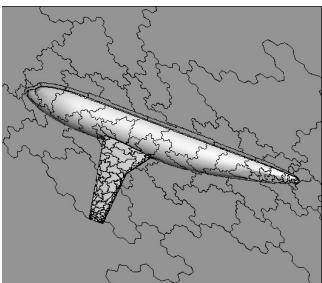
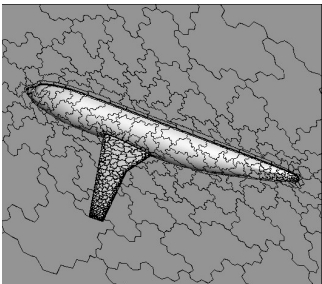
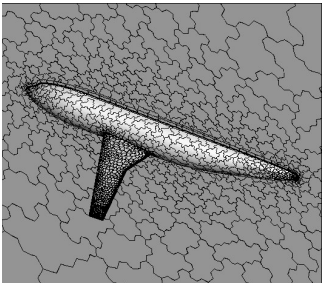
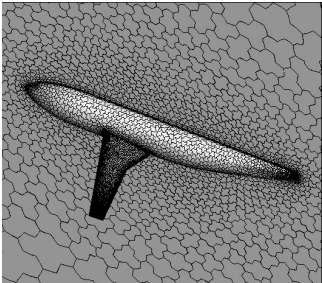
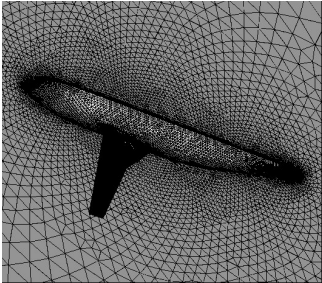
2. Full-coarsening + line-relaxation

The former preserves the stretching in the viscous layer

The latter is a standard technique to improve smoothing.

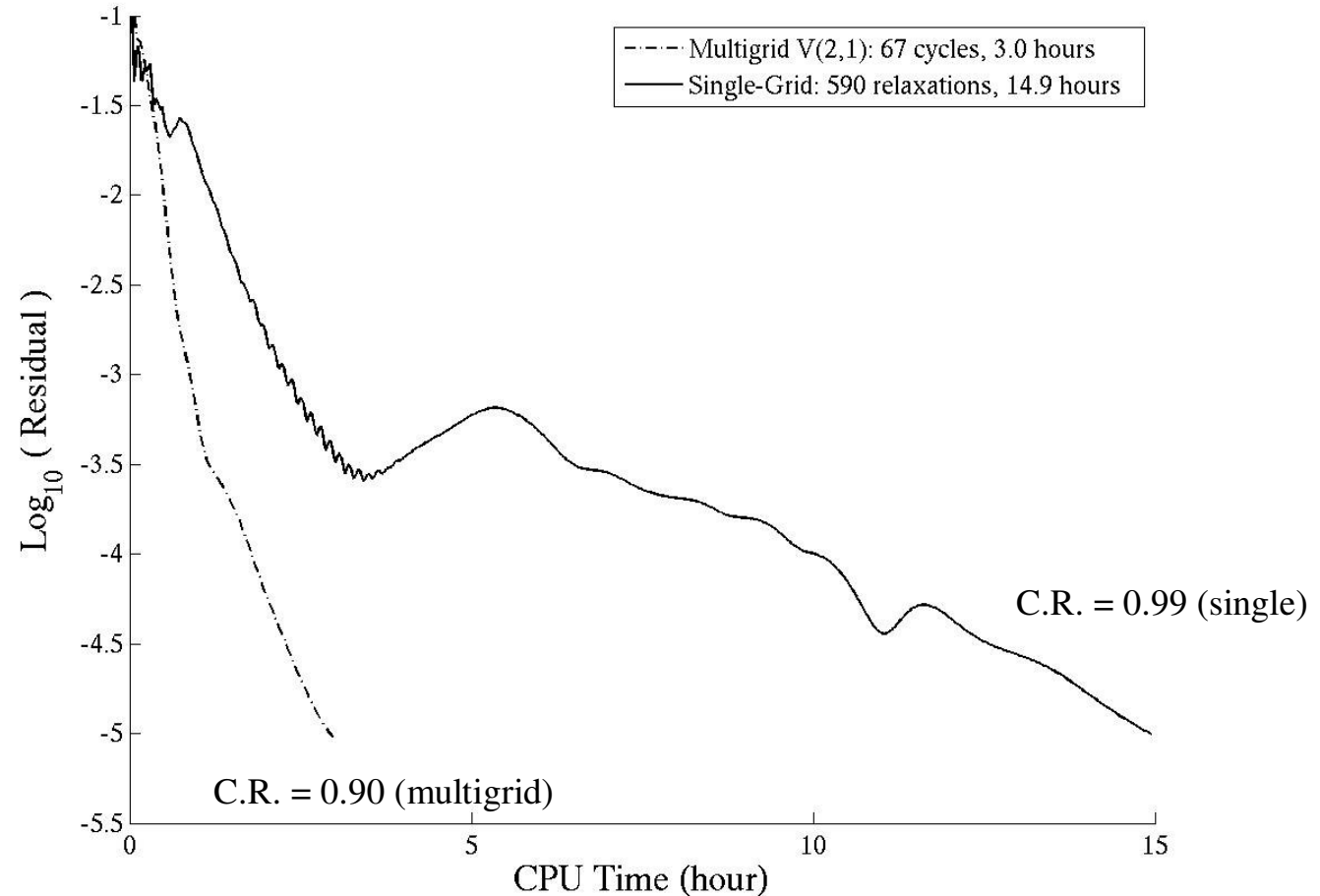


MG demonstrated for diffusion/Euler/RANS (AIAA-2010-4731)



RANS-SA: F6WB (1M nodes)

AOA=1 degree, Mach=0.3, CFL=200, Re=2.5M



5 times faster than the single-grid scheme.

Many fewer linear sweeps are needed in MG relaxation than in SG scheme:

$$[\text{MG V(2,1) with 5 sweeps}] = 1.5 \times [\text{SG with 15 sweeps}]$$

Current Effort for Multigrid

1. Parallelization of Multigrid Algorithm

Hierarchical agglomeration within each partition (no agglomeration across partition boundaries)
Straightforward in algorithm (currently operational with up to 4 processors.)

2. Optimization of Multigrid Algorithm

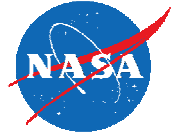
Explore smart Jacobian strategies:

- Frozen in a cycle, once at each level, etc, to reduce MG cost.

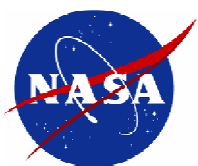
Seek optimal (or robust) cycle:

- V-cycle or W-, F-cycle? $V(2,1)$ or $V(3,3)$? Ultimately FMG.

High-Lift Workshop



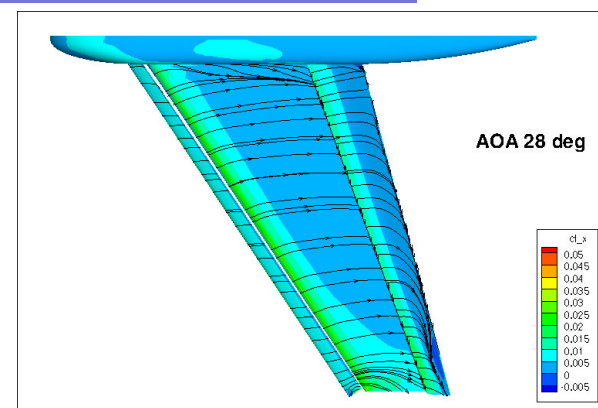
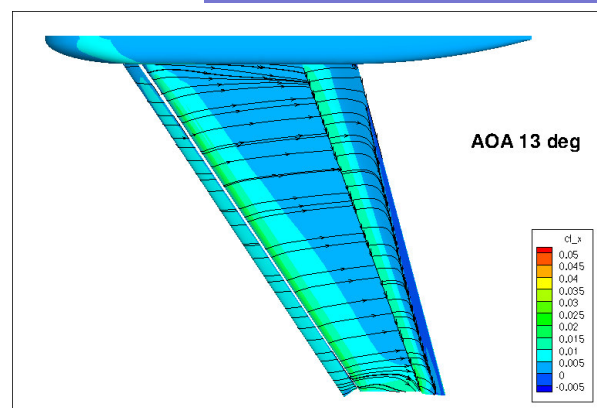
- Info provided by Beth Lee-Rausch and Chris Rumsey
- More to come in mesh adaptation section



1st High Lift Prediction Workshop



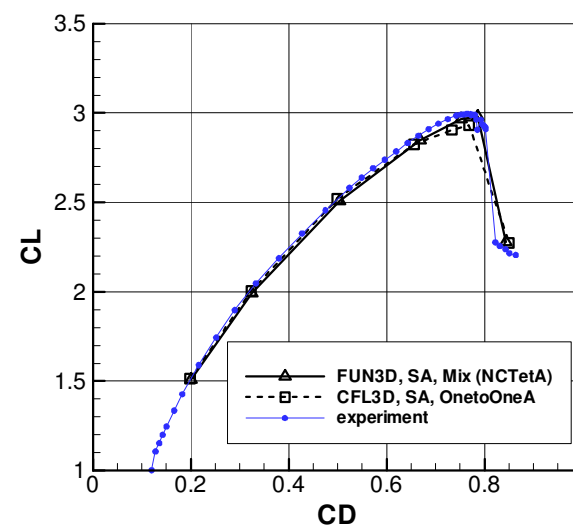
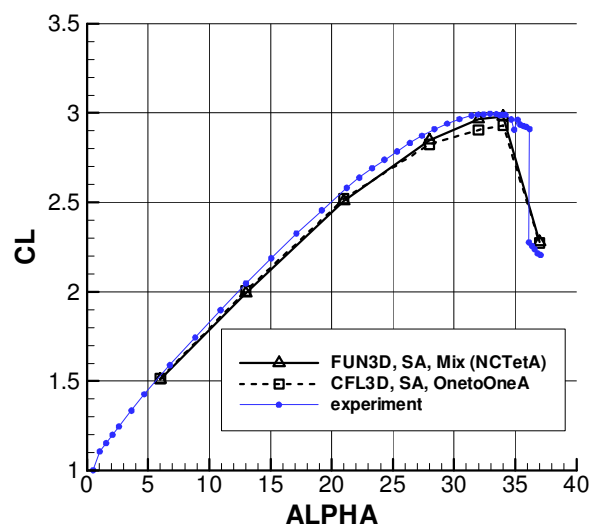
Trap Wing "Config 1" - Slat 30, Flap 25

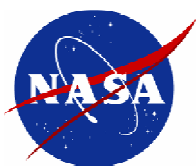


- Mach 0.20
- $Re_c = 4.3$ million

FUN3D vs CFL3D with SA Turbulence Model

- Unst. Grid
- 11M nodes
- Vgrid NC
- Mixed Elements

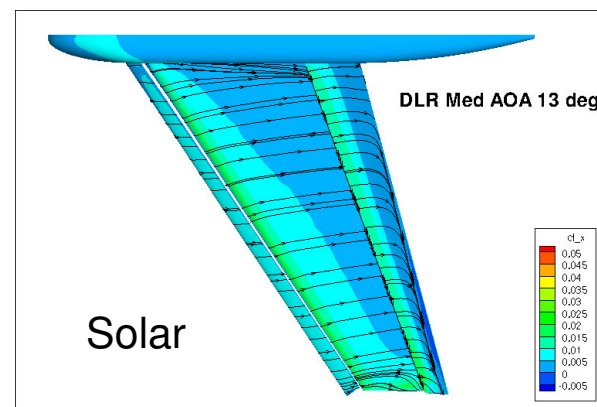
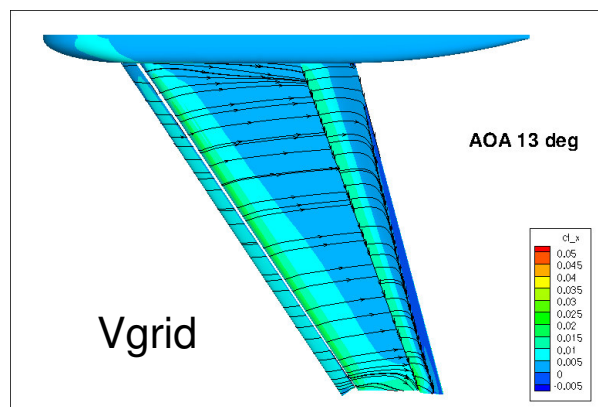




1st High Lift Prediction Workshop



Trap Wing "Config 1" - Slat 30, Flap 25

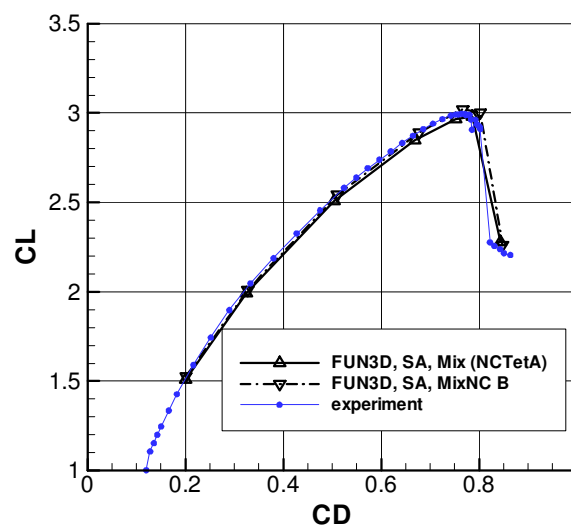
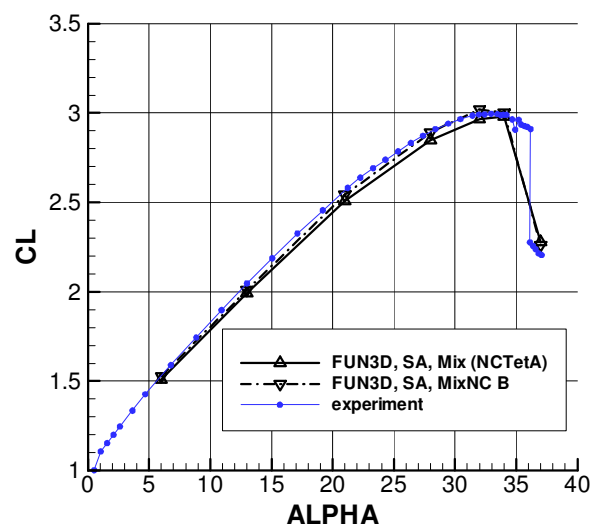


- Mach 0.20
- $Re_c = 4.3$ million

Vgrid vs Solar Grid with SA Turbulence Model

Unst. Grids

- Vgrid 11M nodes
- Solar 37M nodes
- Mixed Elements





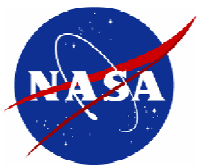
1st High Lift Prediction Workshop

- Grid convergence study
- SST lower lift than SA (likely flap separation) CFL3D results but other participants saw same effect
- Structured grid and unstructured grid results with same turbulence model compare well
- At higher alpha more difference between codes and more variation with grid refinement
- Flap study (medium grid)
- Grid density/topology matters at highest AOA
- One-to-one structured grid B seems to predict early stall (CFL3D results)
- SOLAR grid results improved correlation at high AOA
- Configuration 1 has more flap separation than configuration 8
- SST predicts more flap separation than SA
- FUN3D predicts wing separation at highest AOA for configuration 8 (not seen in CFL3D solutions)

DPW-4

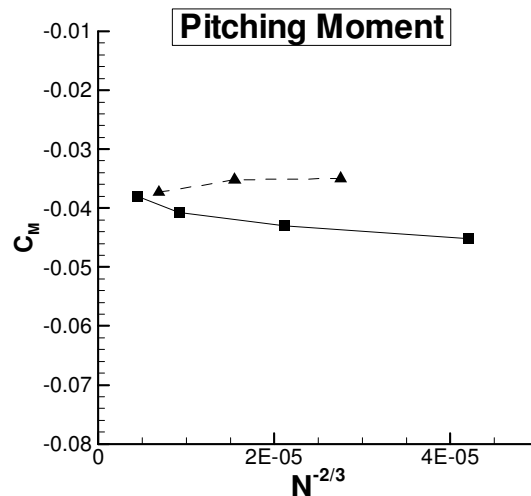
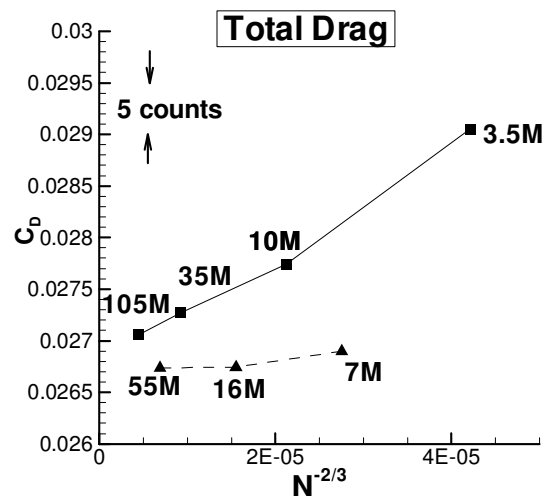
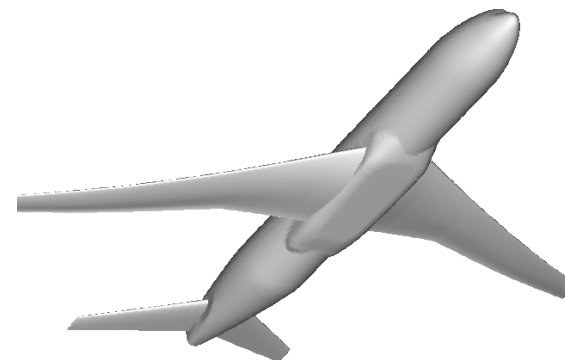
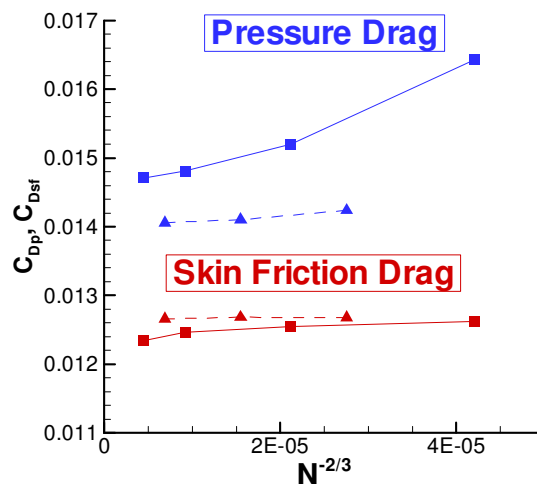
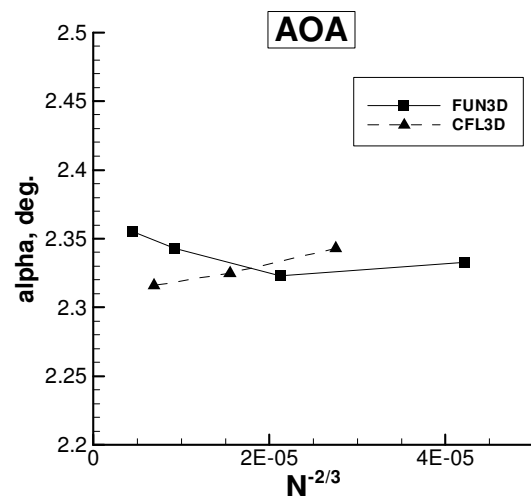


- Info provided by Beth Lee-Rausch and Chris Rumsey



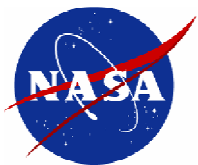
4th Drag Prediction Workshop (DPW-IV)

FUN3D and CFL3D Comparison

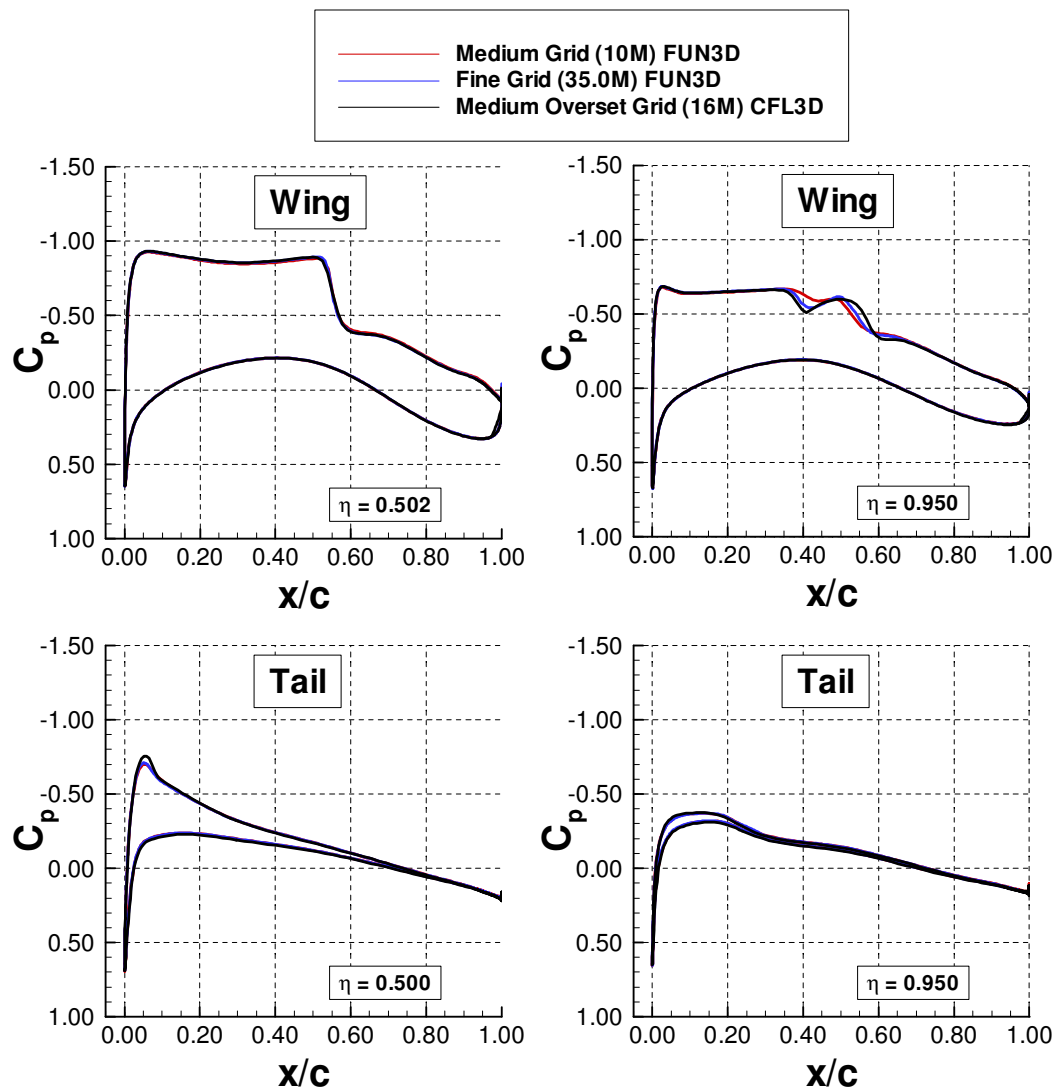


Grid Convergence Study

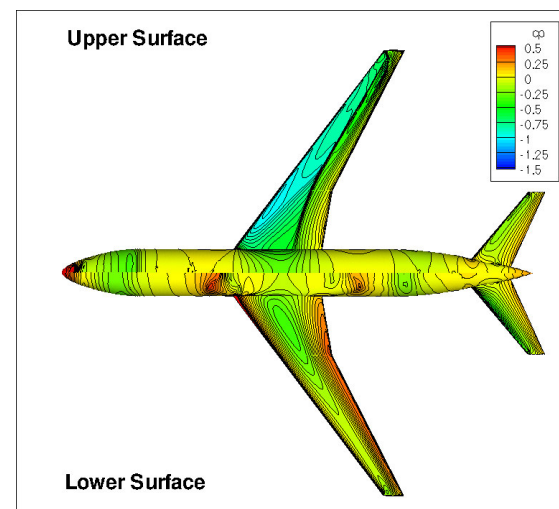
- Mach 0.85
- $CL = 0.500 \pm 0.001$
- $Re_c = 5 \times 10^6$, fully turbulent
- Tail Incidence angle, $i_H = 0^\circ$
- SA turbulence Model



4th Drag Prediction Workshop (DPW-IV)



Fine Grid Pressure



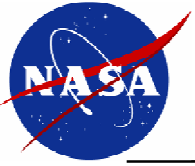
Grid Convergence Study

- Mach 0.85
- $CL = 0.500 \pm 0.001$
- $Re_c = 5 \times 10^6$, fully turbulent
- Tail Incidence angle, $i_H = 0^\circ$
- SA turbulence Model

Rotorcraft Efforts

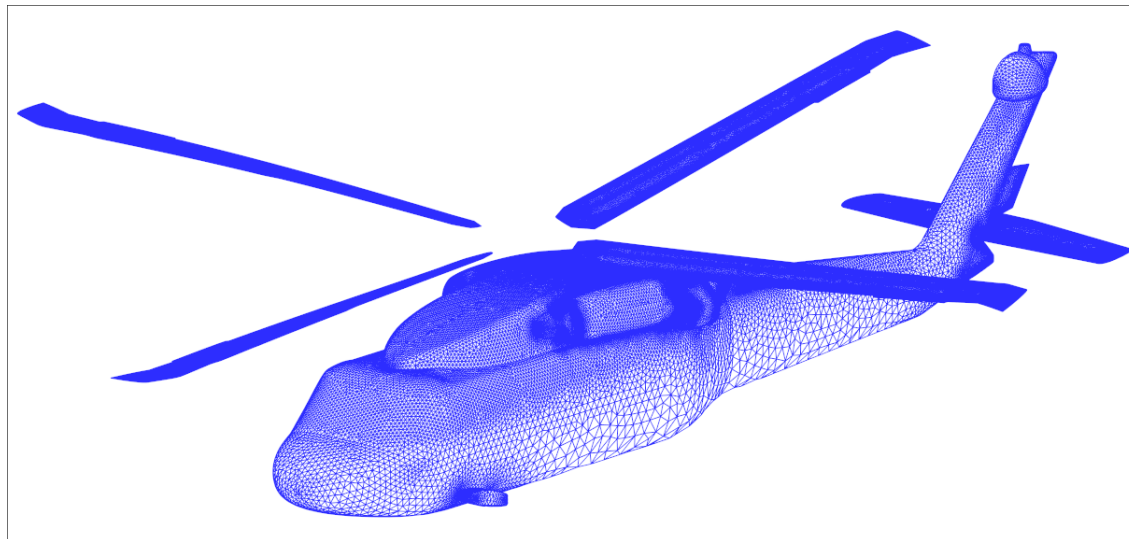


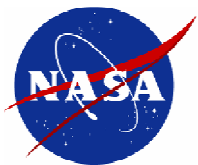
- Info provided by Bob Biedron



Rotorcraft Airloads

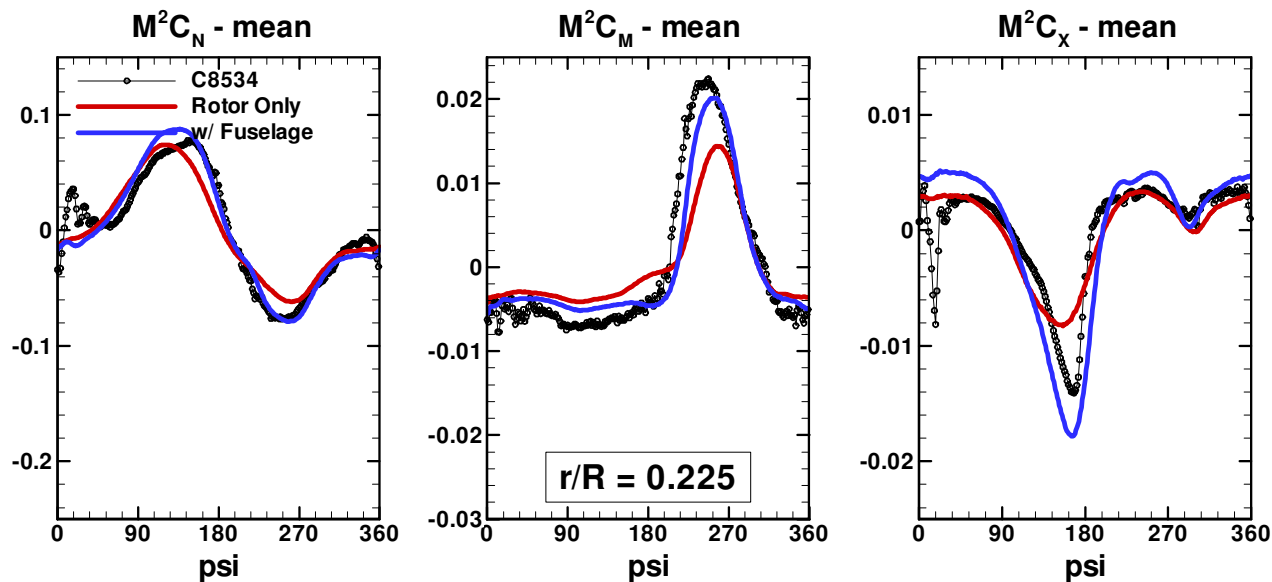
- Recent Work In Coupled CFD/CSD
 - Process has been automated via scripts
 - Mixed-element grids now accommodated
 - Transfer of software to Boeing Mesa (Hormoz Tadghighi)
- Application focus now primarily on UH60-A
 - Wide range of available flight-test data from high speed (C8534) to high thrust (C9020) for validation



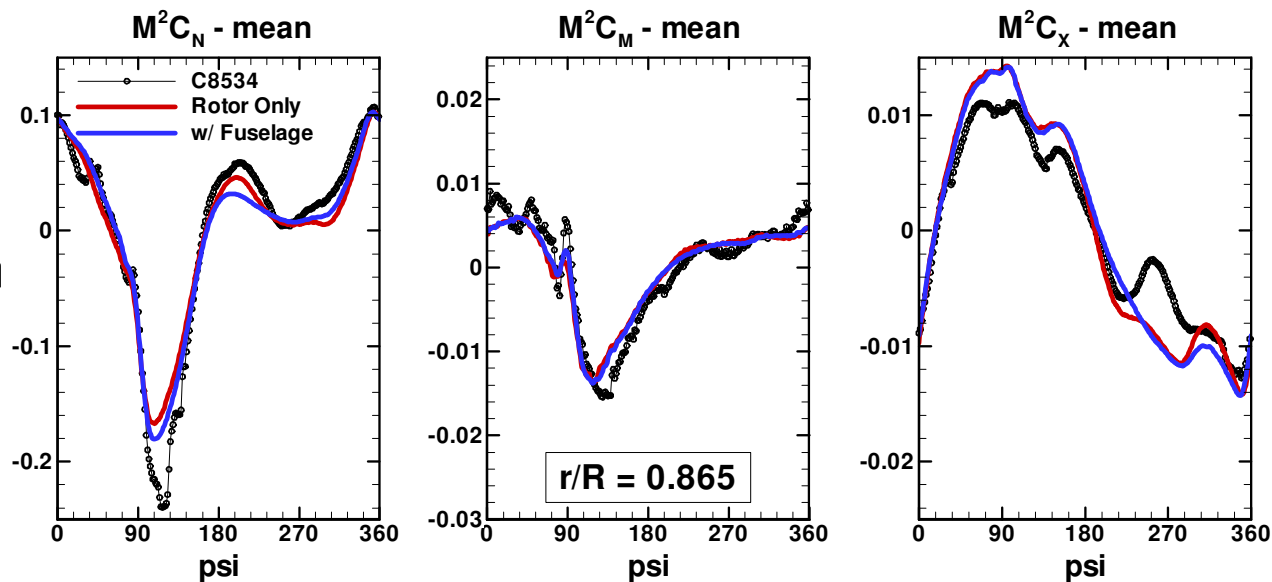


UH60A - High Speed Case - Effect of Fuselage

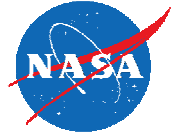
- Inboard Station



- Outboard Station



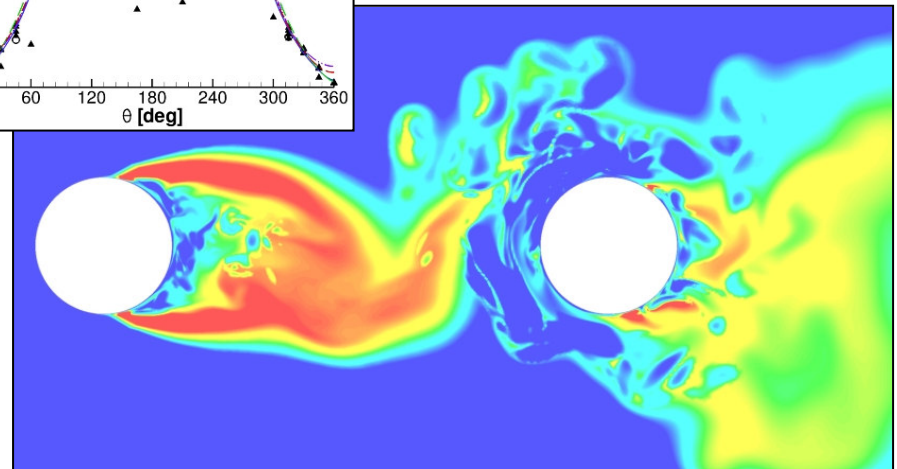
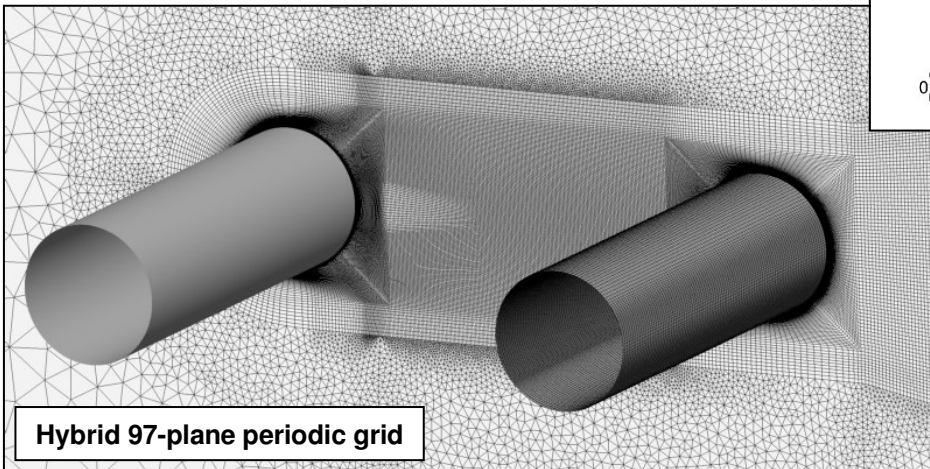
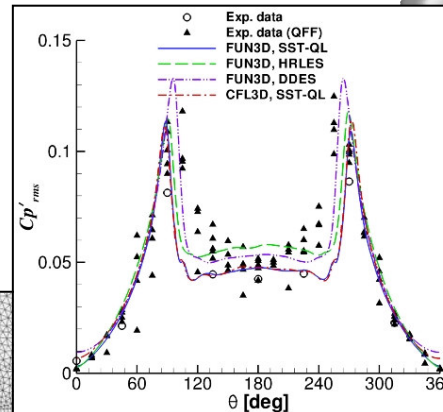
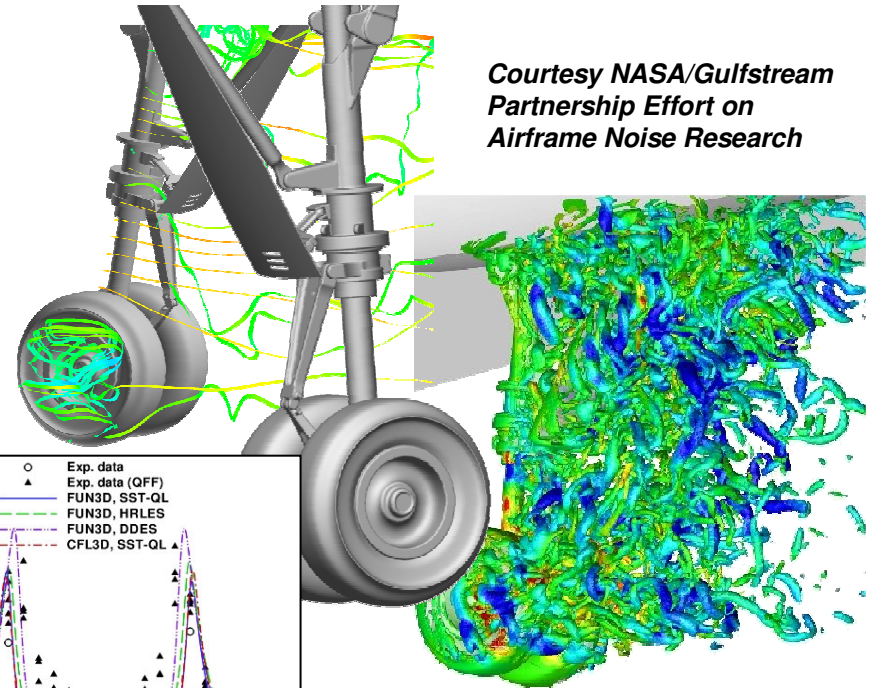
Airframe Noise: Landing Gear



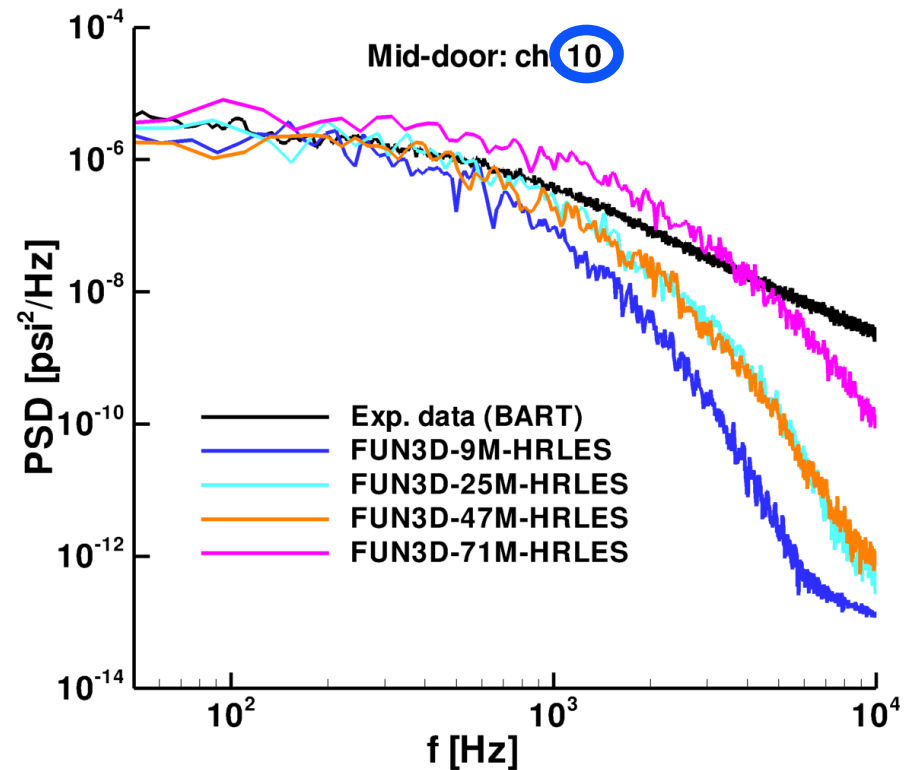
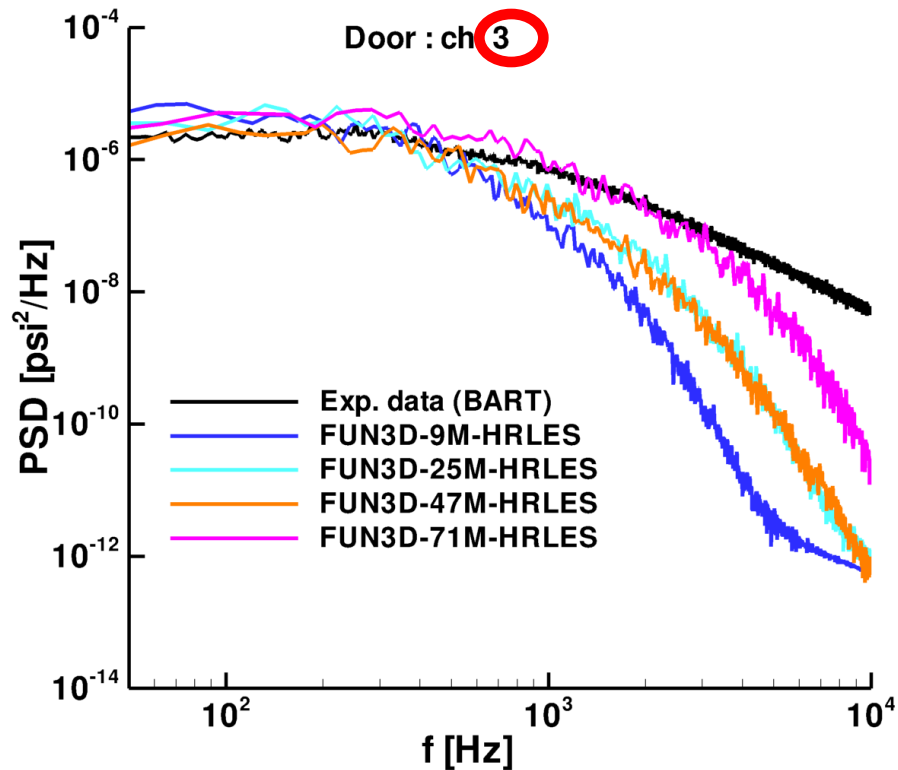
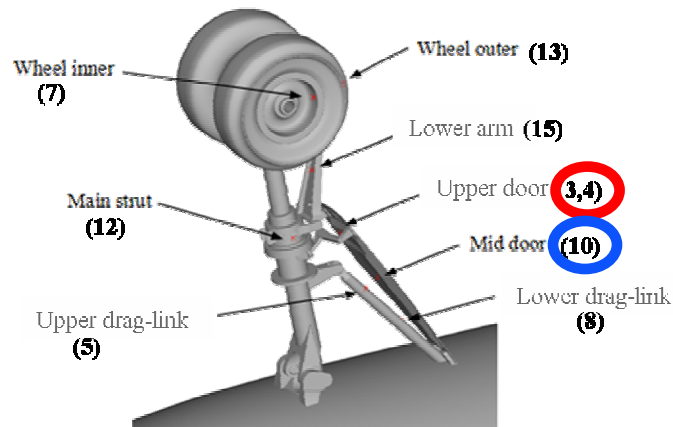
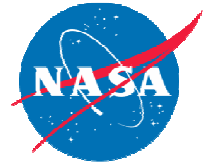
- Info provided by Veer Vatsa

Unsteady Flows / Aeroacoustics

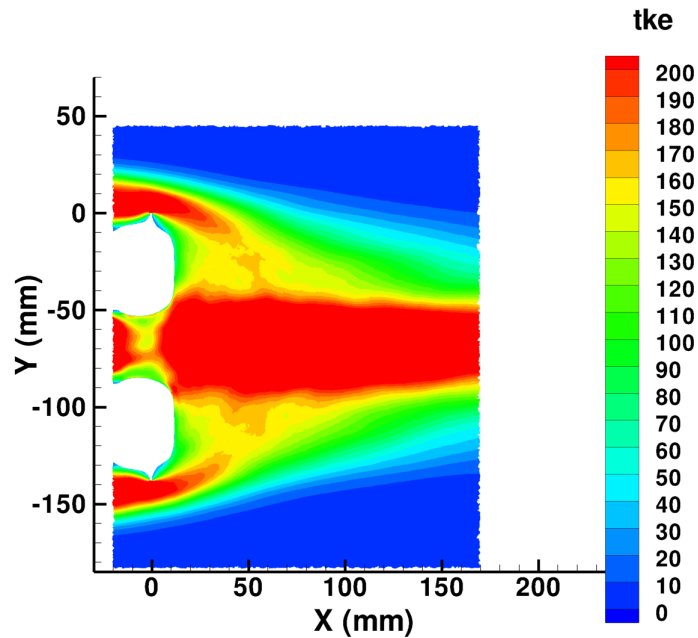
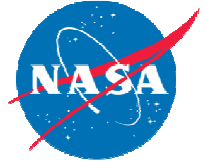
- Long-duration simulations (>100,000 physical timesteps) to establish time averages, perturbation pressures, shedding spectra, etc
- Single and tandem cylinders
 - Idealized problems comparing CFL3D and FUN3D
- FUN3D landing gear simulations
 - Grid sizes from 9M to 71M grid points (~400M elements)
 - Several months runtime on 1024 cores
 - Examining effects of grid density, discretization, and turbulence modeling strategies
 - Participated in 2010 BANC-I workshop in Stockholm
- Next step: FWH noise predictions
- POC: Vatsa, Lockard, Khorrami



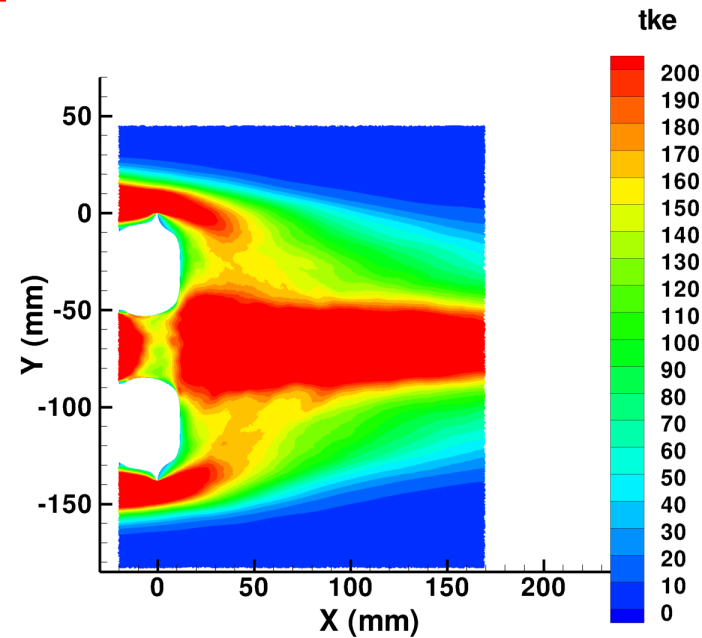
Power Spectral Density Comparisons



2-D Turbulence Kinetic Energy at wheel wake centerline

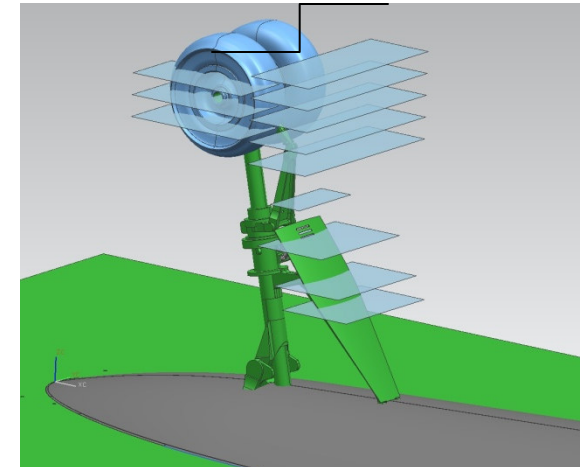
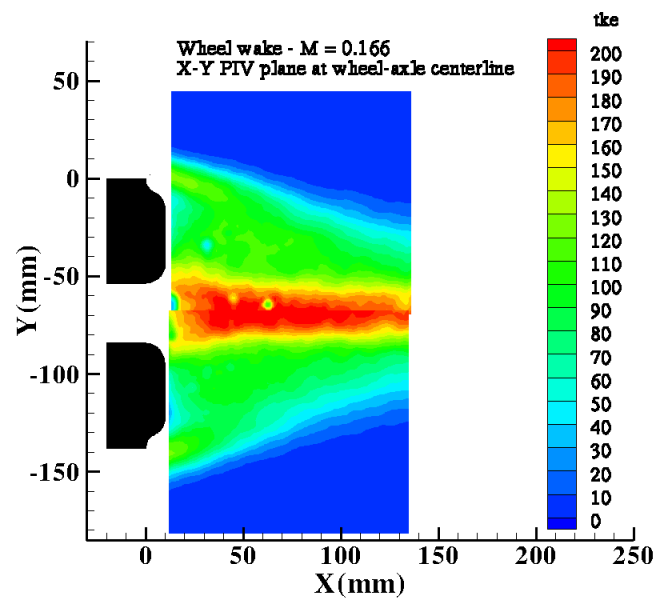


FUN3D-25M-HRLES

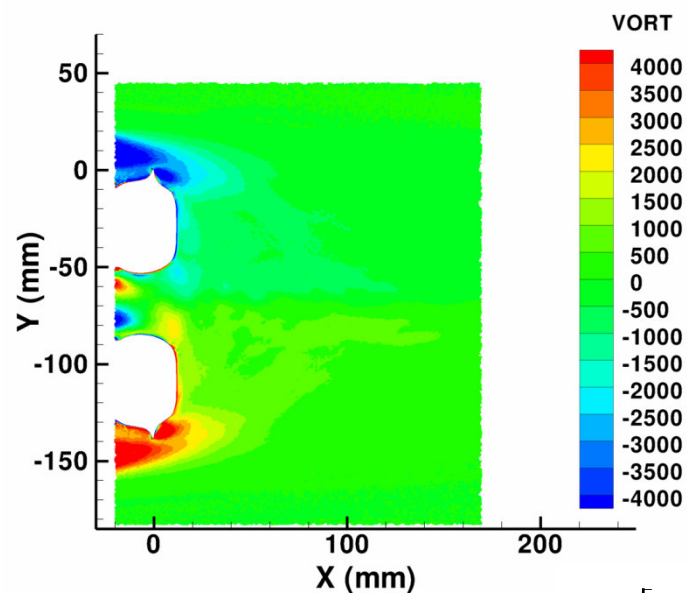


FUN3D-71M-HRLES

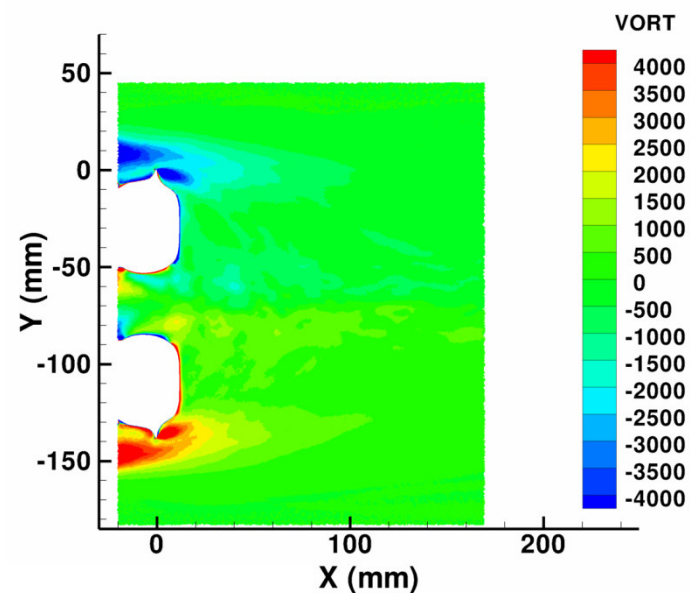
Exp. PIV data



Spanwise vorticity at wheel wake centerline

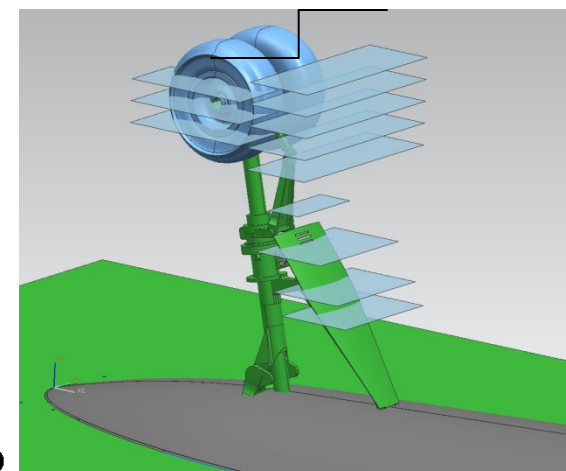
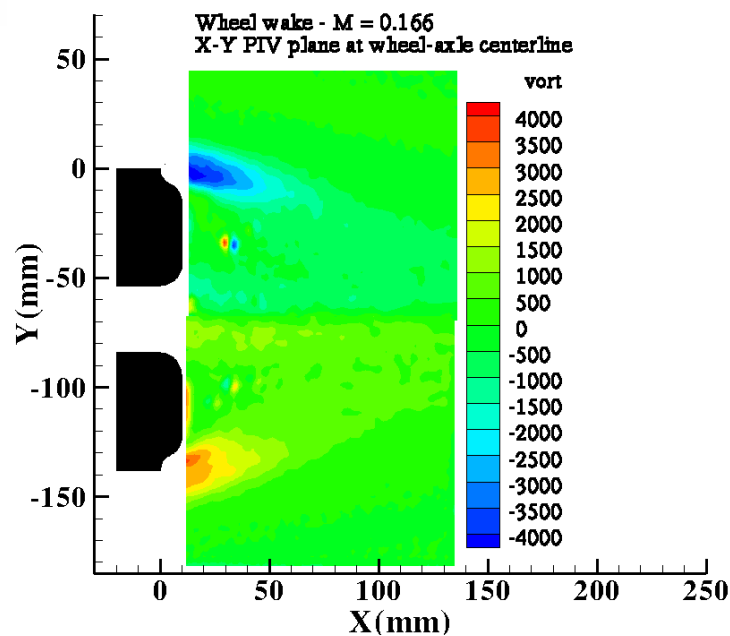


FUN3D-25M-HRLES



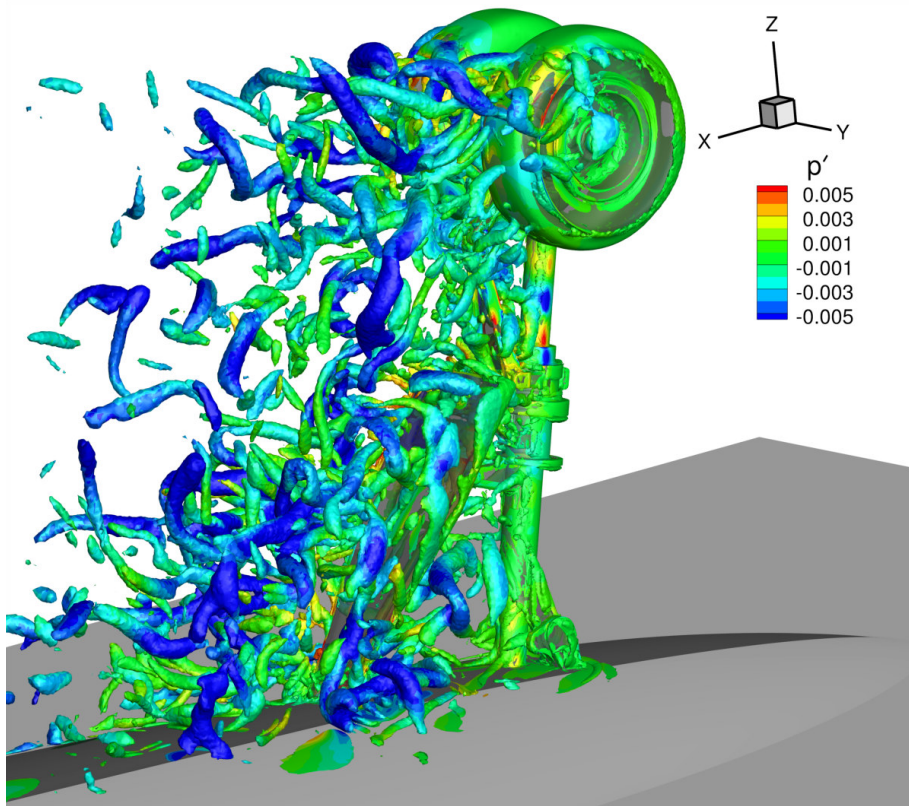
FUN3D-71M-HRLES

Exp. PIV data

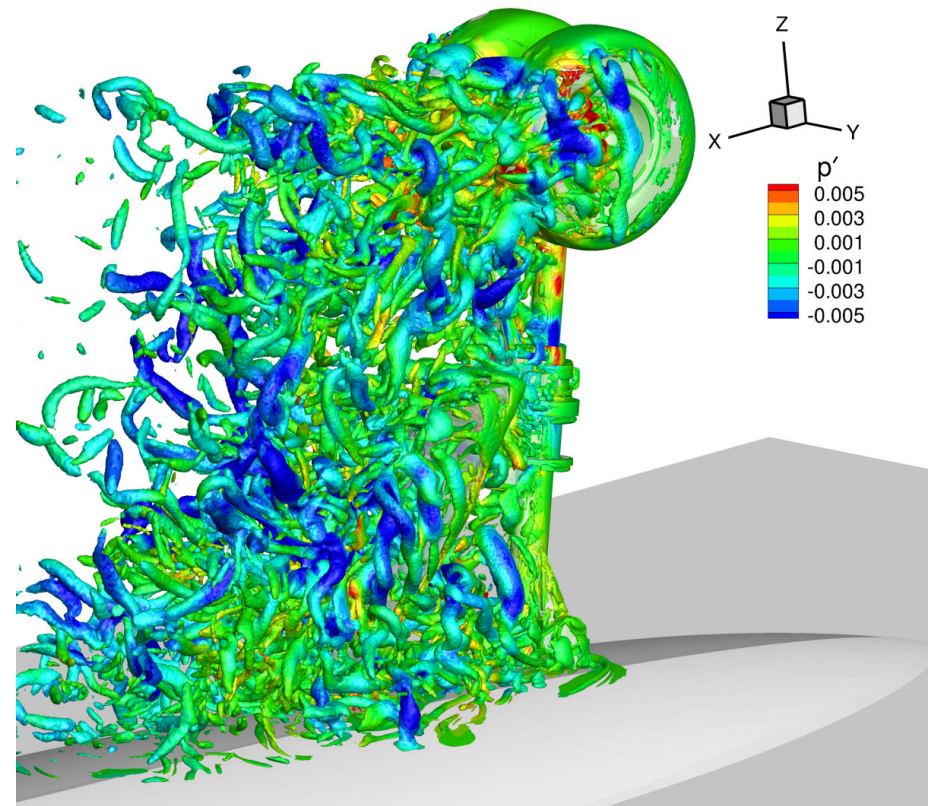


Iso-surfaces of Q-criterion

- Colored with perturbation pressure

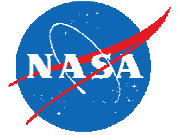


FUN3D-9M-HRLES

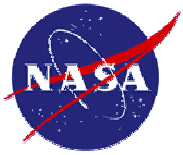


FUN3D-25M-HRLES

Discretization Studies

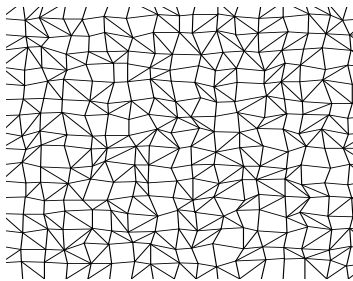


- Info provided by Jim Thomas
- Working with Boris Diskin (NIA)

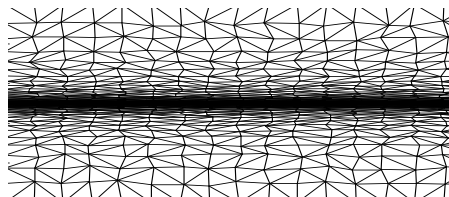


Cell Centered (CC) vs Node Centered (NC)

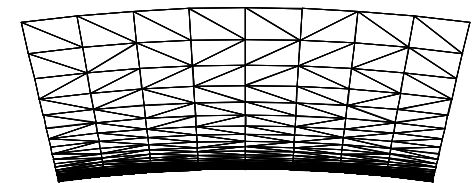
- **Compared in controlled environment**
 - Method of manufactured solutions
 - Consistently refined (irregular) grids
 - The same type of boundary conditions
- **Systematic studies**
 - Gradients in NIA Report 2008-12
 - Viscous (pure diffusion) in AIAA 2009-597
 - Convection in AIAA 2010-1079
 - Reynolds Averaged Navier-Stokes ongoing



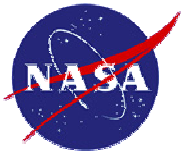
Isotropic



High AR



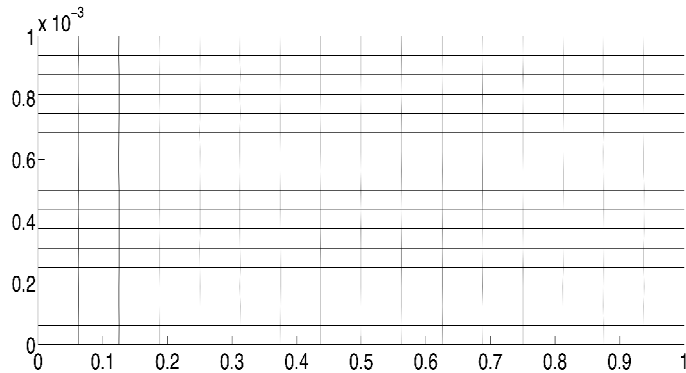
**High AR +
Curvature**



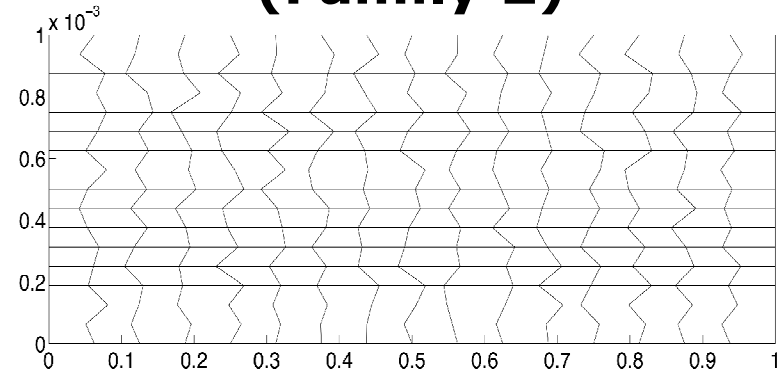
Which is the Better Grid?

High AR

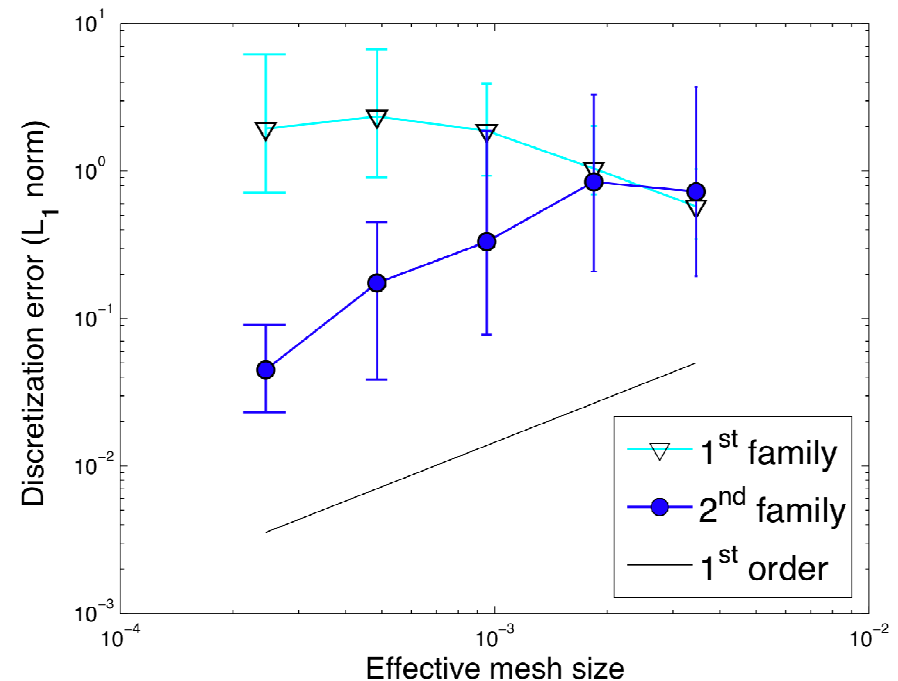
**Small perturbation in x
(Family 1)**

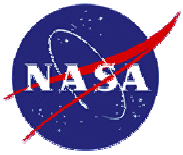


**Noticeable perturbation in x
(Family 2)**



The correct answer is scheme-dependent. For the node-centered weighted least-square scheme, Family 2 is better – Family 1 is nonconvergent.

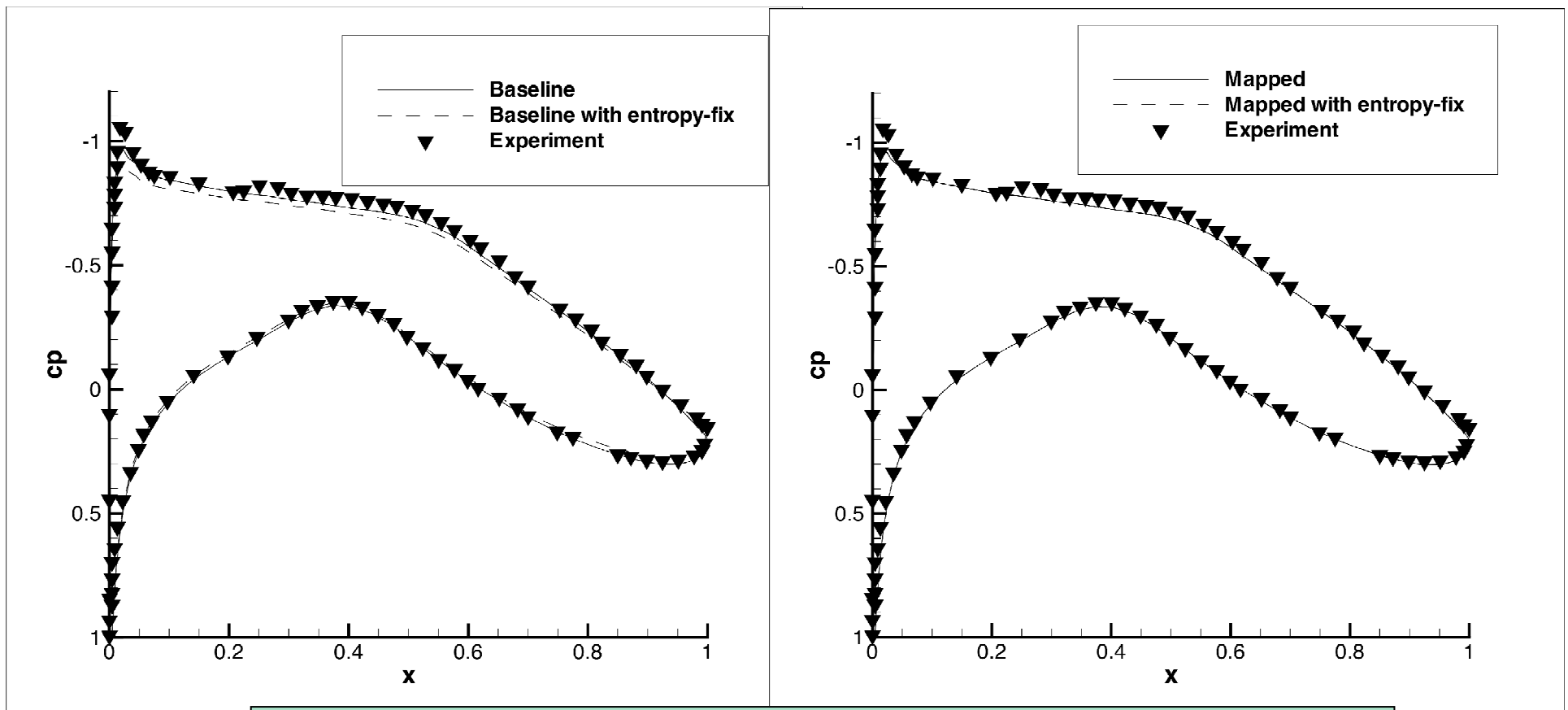




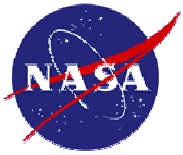
Improved Accuracy - New Mapped Scheme

RAE CASE 1 ; Subsonic Airfoil ; $Re=6$ Million
NC Scheme ; Quadrilateral Mesh

Sensitivity of Pressure to Added Dissipation



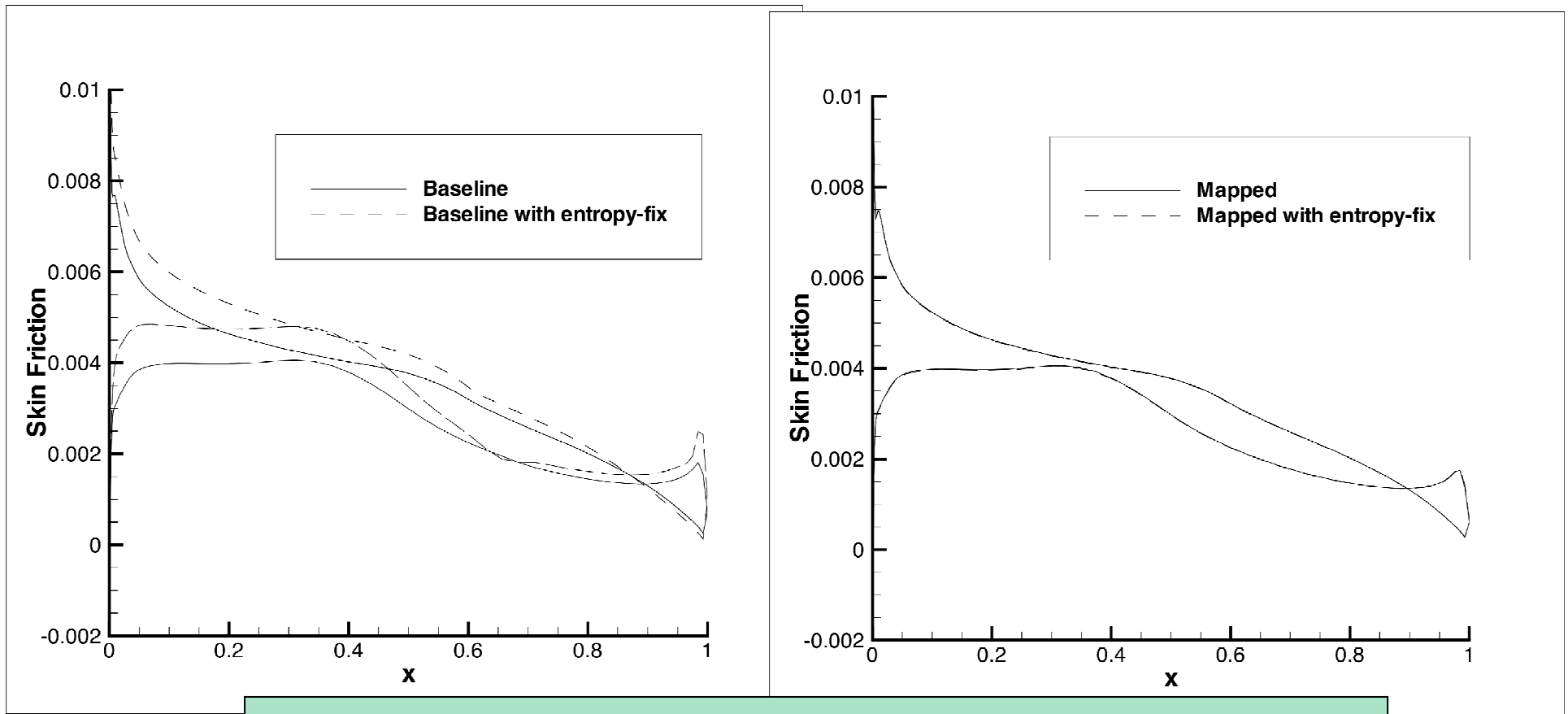
New Scheme Less Sensitive



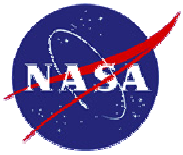
Improved Accuracy – New Mapped Scheme

RAE CASE 1 ; Subsonic Airfoil ; $Re=6$ Million
NC Scheme ; Quadrilateral Mesh

Sensitivity of Skin Friction to Added Dissipation



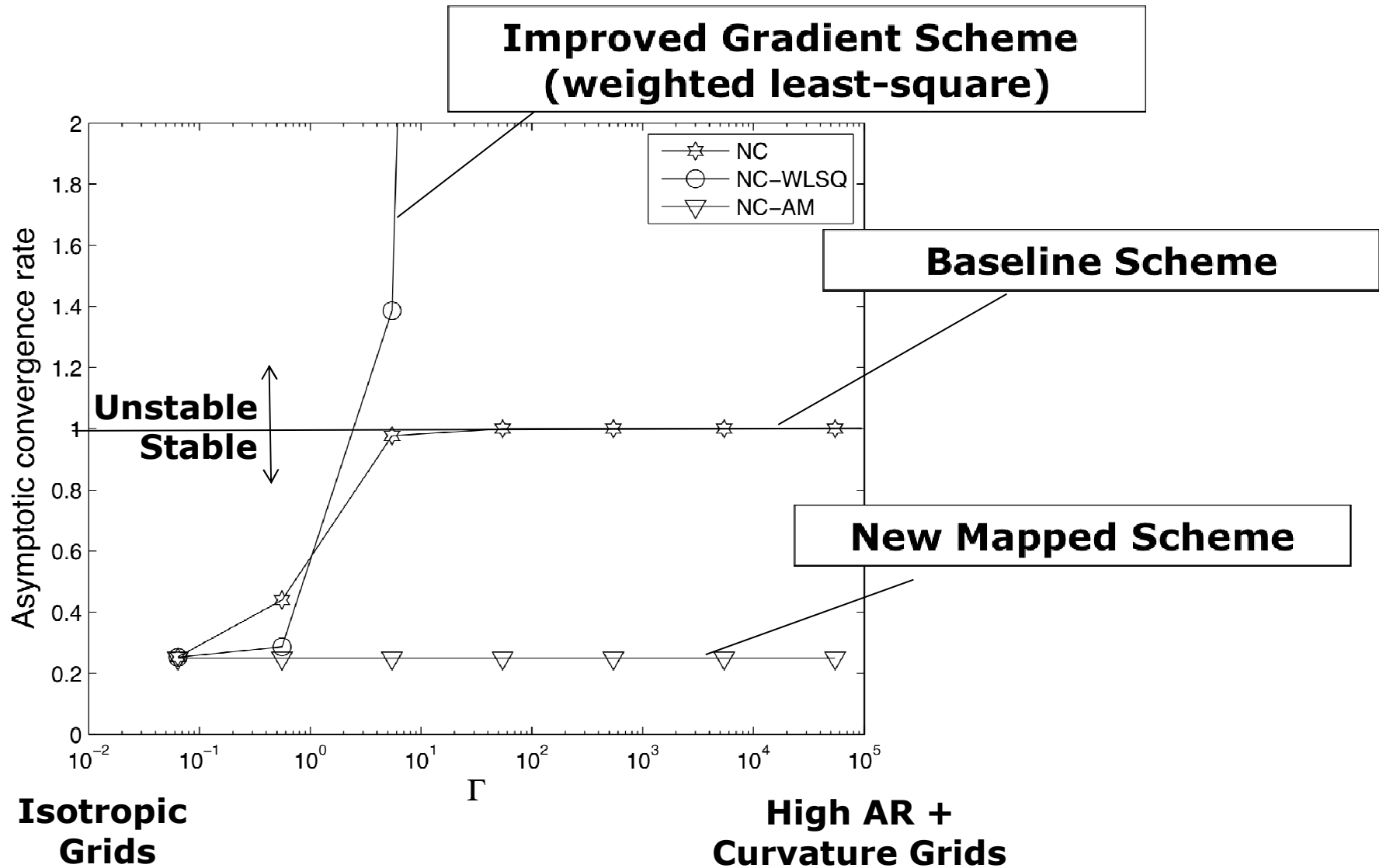
New Scheme Less Sensitive

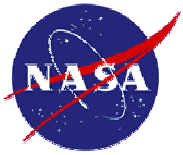


Improved Convergence – New Mapped Scheme

Defect Correction ; Convection Equation

NC Scheme ; Quadrilateral Mesh





Summary

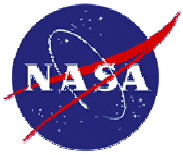
Comparison of CC and NC Schemes

NC and the best CC schemes are comparable

- Gradient accuracy deteriorates on high-aspect-ratio regions on irregular grids
- Improved accuracy in high-aspect-ratio curved grids with approximate mapping techniques
- Identified serious drawbacks of several existing schemes

Developed promising alternative CC scheme (least-squares)

- Lower complexity than existing schemes
- Equivalent accuracy



Publications

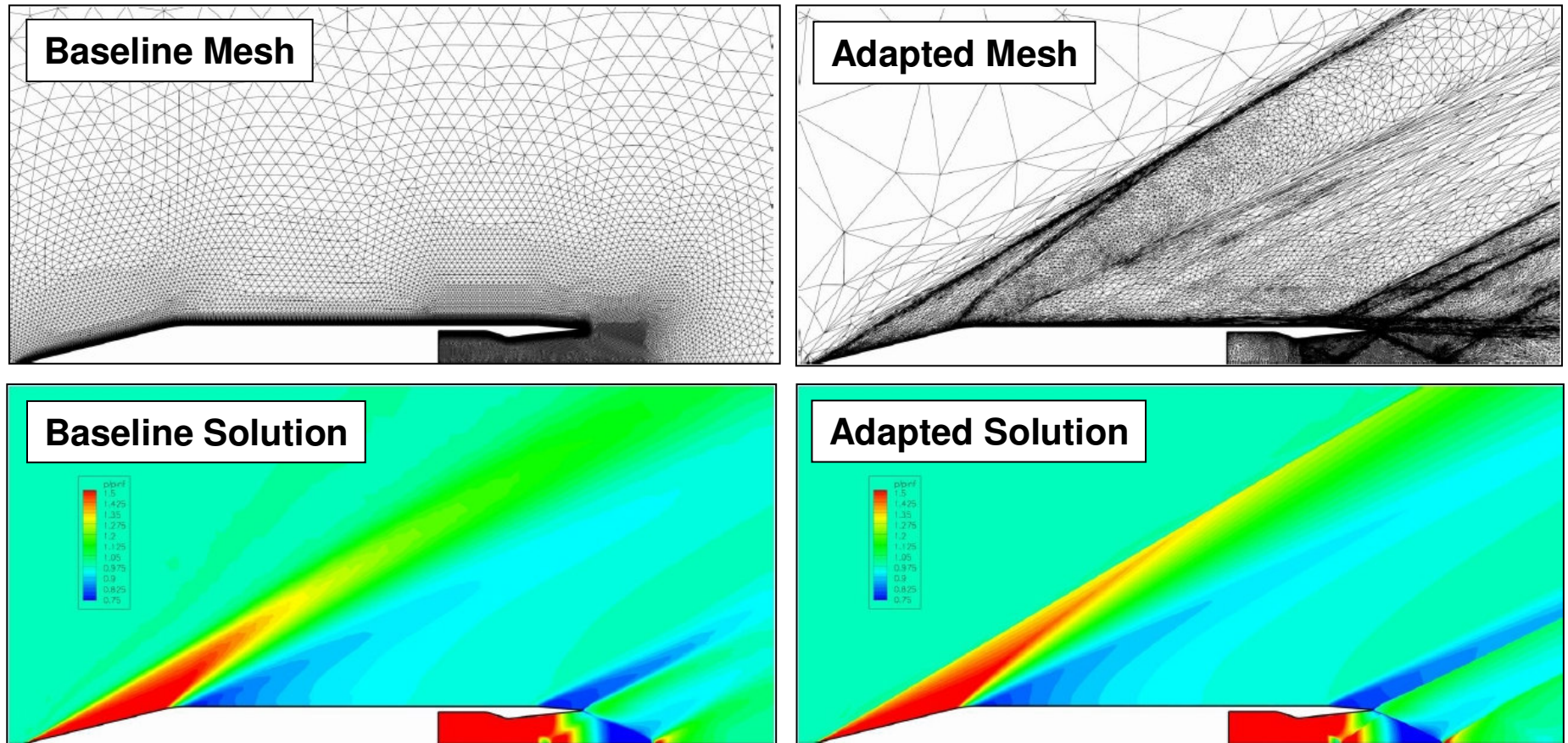
1. Diskin B., Thomas J. L., Nielsen E. J., Nishikawa H., and White J. A., "Comparison of node-centered and cell-centered unstructured finite-volume discretizations: viscous fluxes," accepted to *AIAA Journal*.
2. Diskin B. and Thomas J. L. "Notes on accuracy of finite-volume discretization schemes on irregular grids," *Applied Numerical Mathematics* 60(3), pp. 224-226, 2010, doi: 10.1016/j.apnum.2009.12.001
3. B. Diskin and J.L. Thomas, "Comparison of cell-centered and node-centered unstructured finite-volume discretizations: inviscid fluxes," AIAA-2010-1079, 2010.
4. H. Nishikawa, B. Diskin, and J. L. Thomas, "A critical study of agglomerated multigrid methods for *diffusion*," *AIAA Journal* 48(4), pp. 839-847, 2010; doi: 10.2514/1.J050055. (AIAA-2009-4138)
5. J. L. Thomas, B. Diskin, and H. Nishikawa "A critical study of agglomerated multigrid methods for diffusion on highly stretched grids," invited paper, to appear in *Computers & Fluids*.
6. Diskin B., Nishikawa H., and Thomas, J. L., "Development and application of agglomerated multigrid methods for complex geometries," AIAA-2010-4731, 2010 (Summer 2010).

Mesh Adaptation



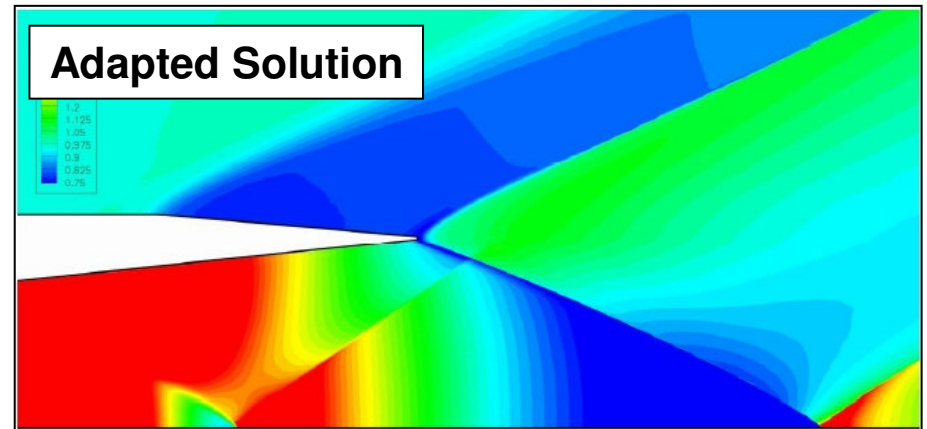
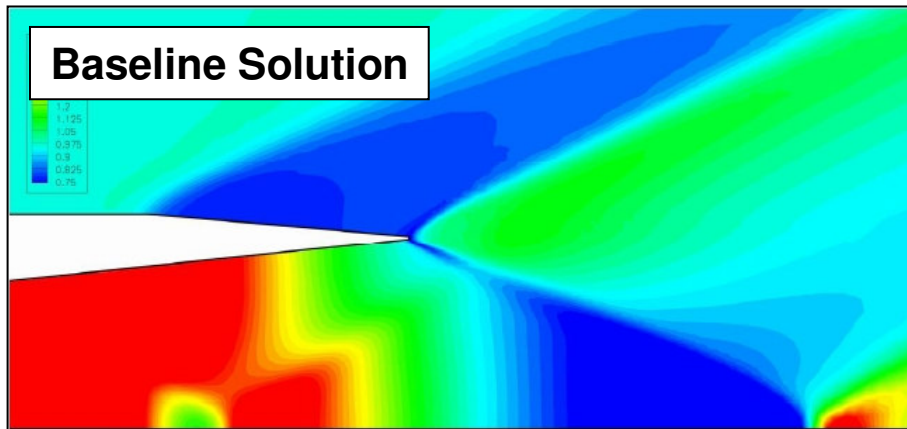
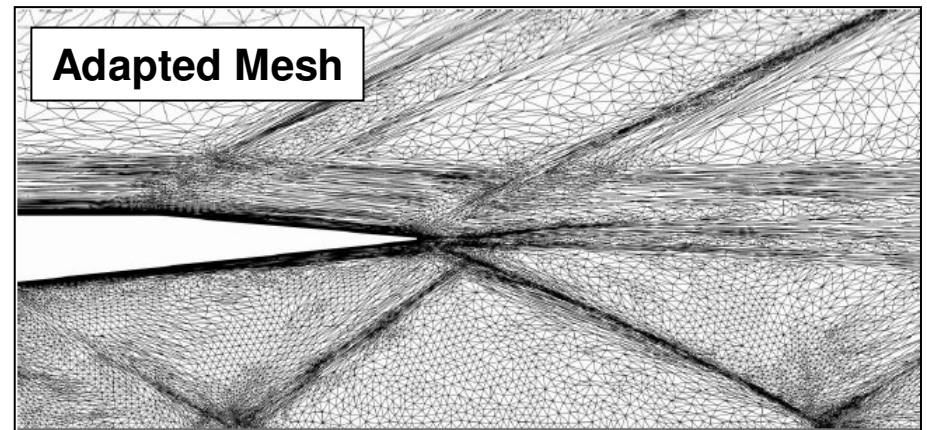
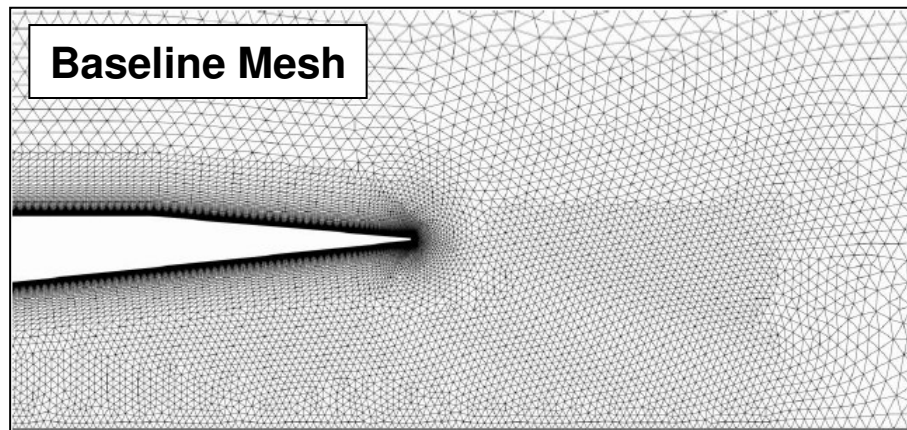
- Info provided by Mike Park

Mesh Adaptation for Jet Plume Flow

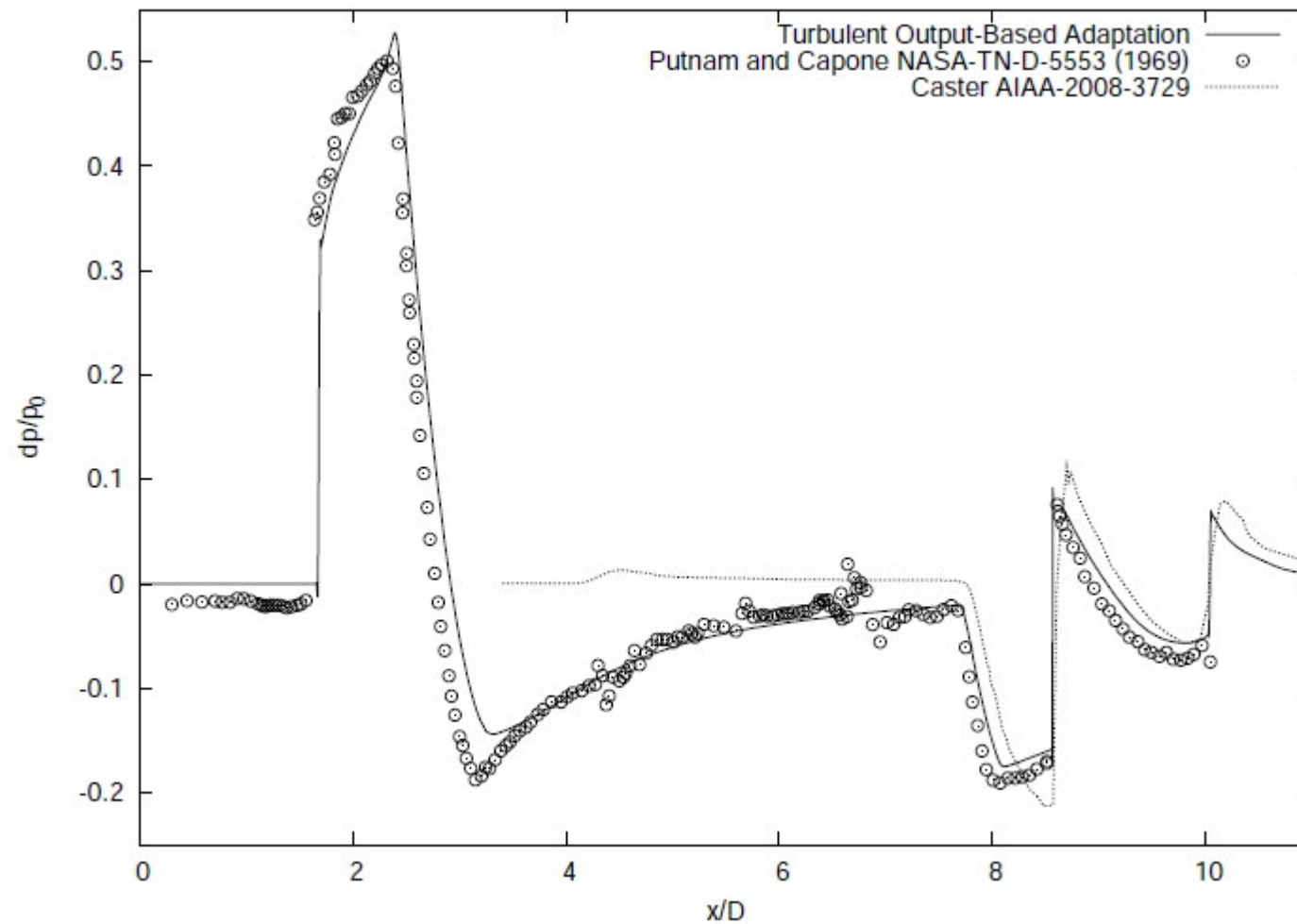


- Quarter of axisymmetric domain modeled; $M_\infty=2.2$, $Re_D=1.86M$
- Adjoint objective function is integrated pressure signal at 1D distance
- Mesh adapted from 1.3M nodes to 2.9M nodes

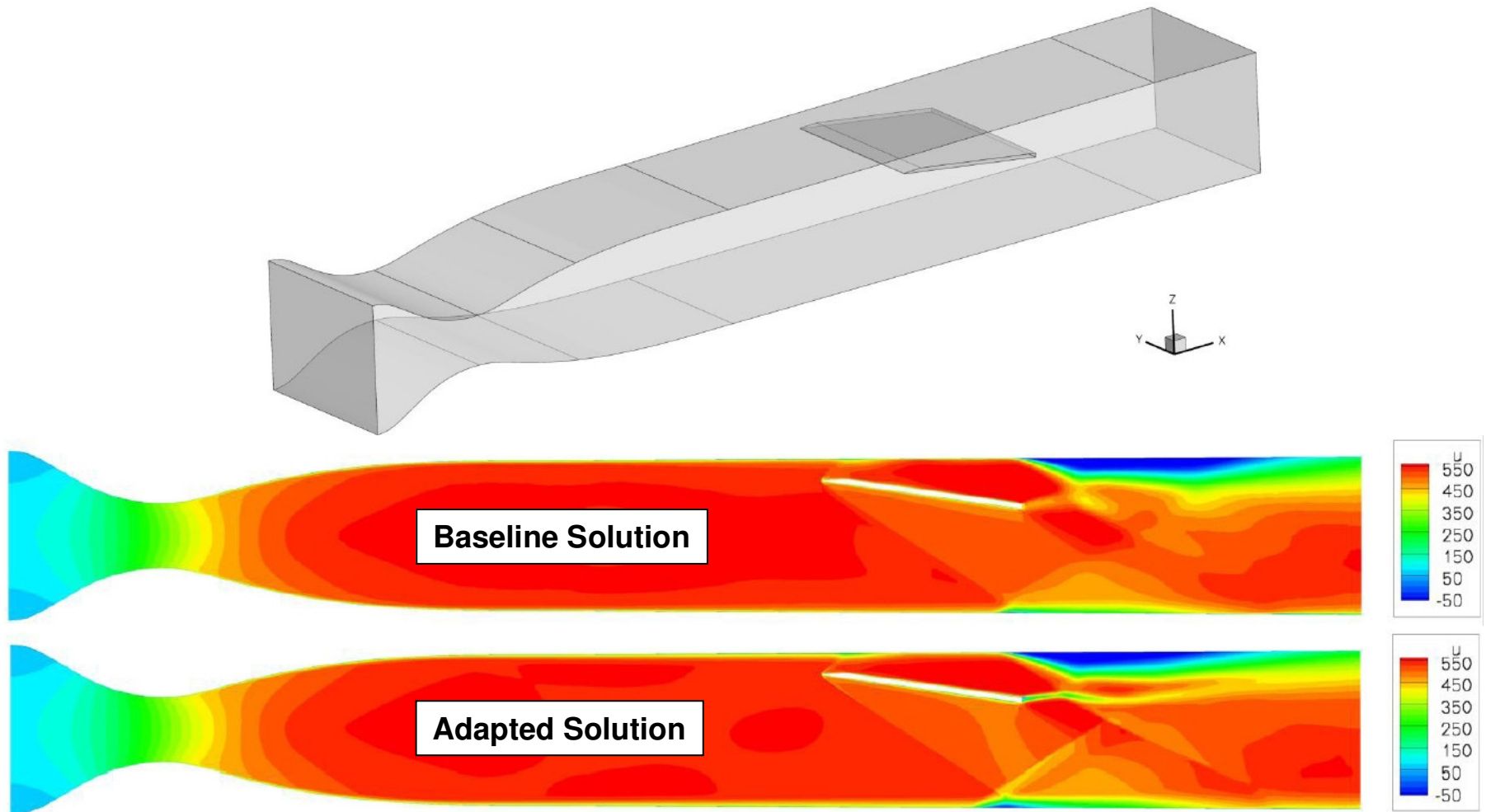
Mesh Adaptation for Jet Plume Flow



Mesh Adaptation for Jet Plume Flow

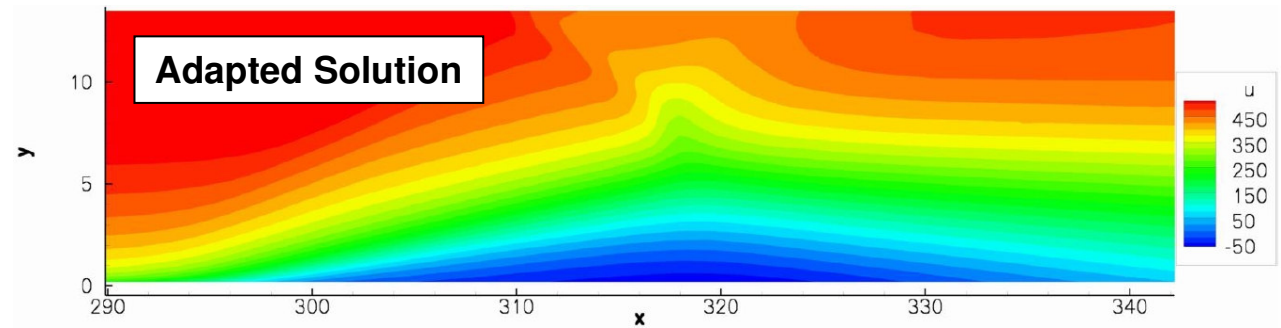
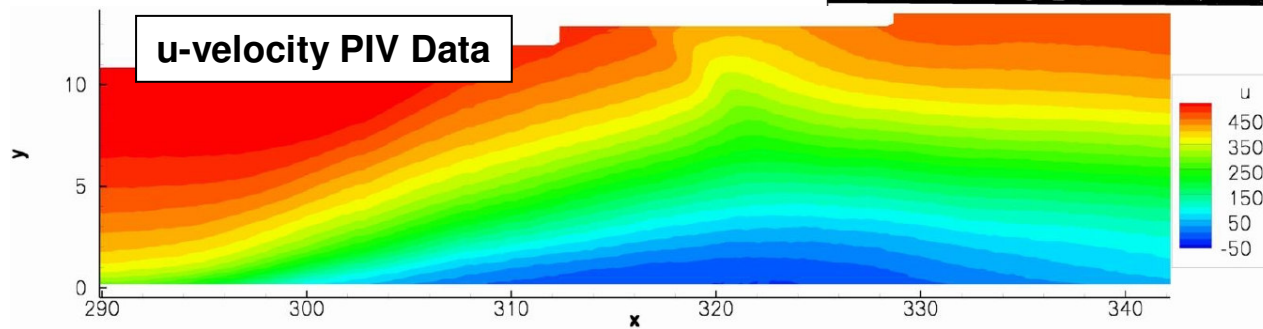
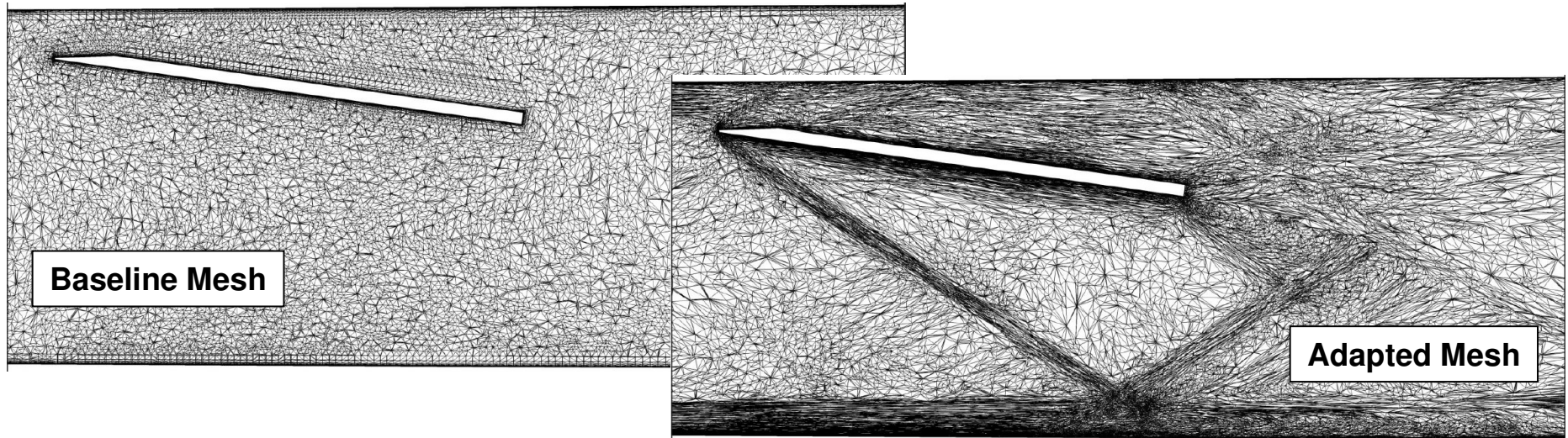


Mesh Adaptation for Shock-Boundary Layer Interaction

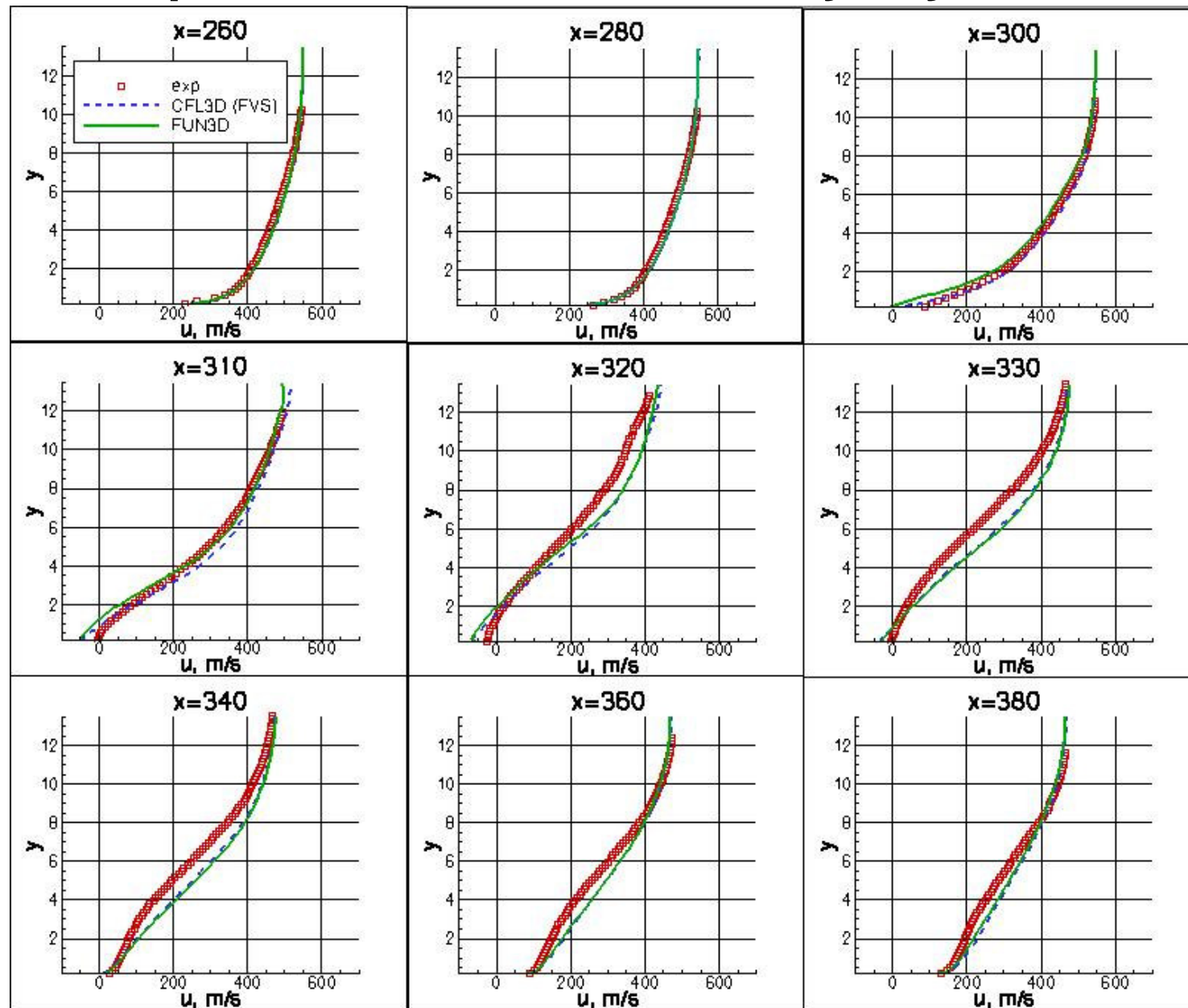


- Part of SBLI workshop at 2010 AIAA Orlando ASM conference
- $M_\infty=2.25$, $Re=5683/cm$
- Adjoint objective function is drag on lower wall
- Mesh adapted from 0.7M nodes to 1.3M nodes

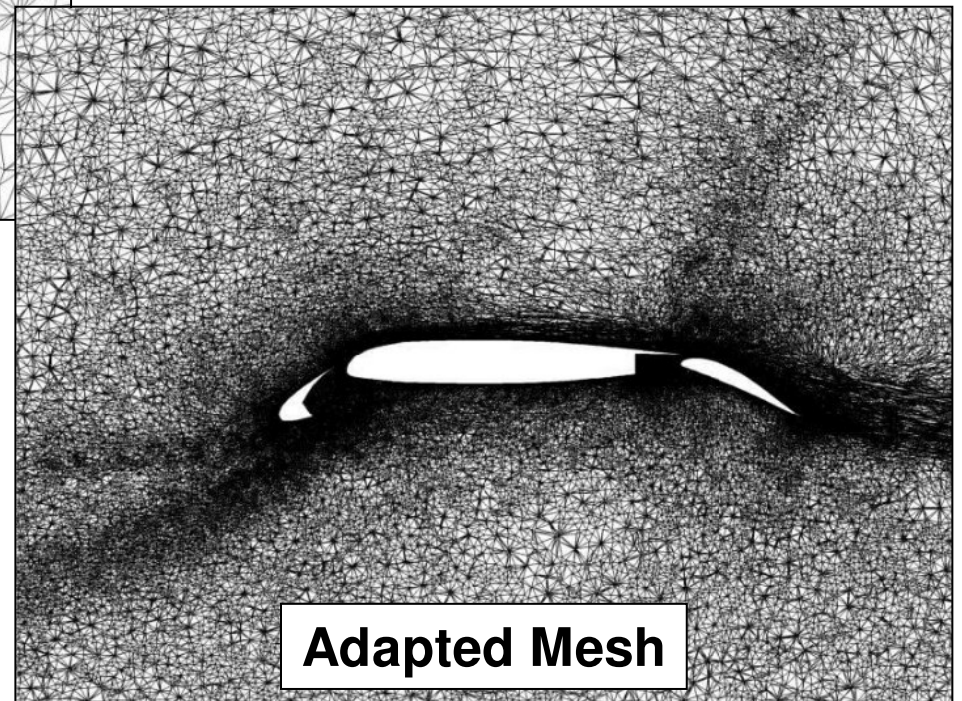
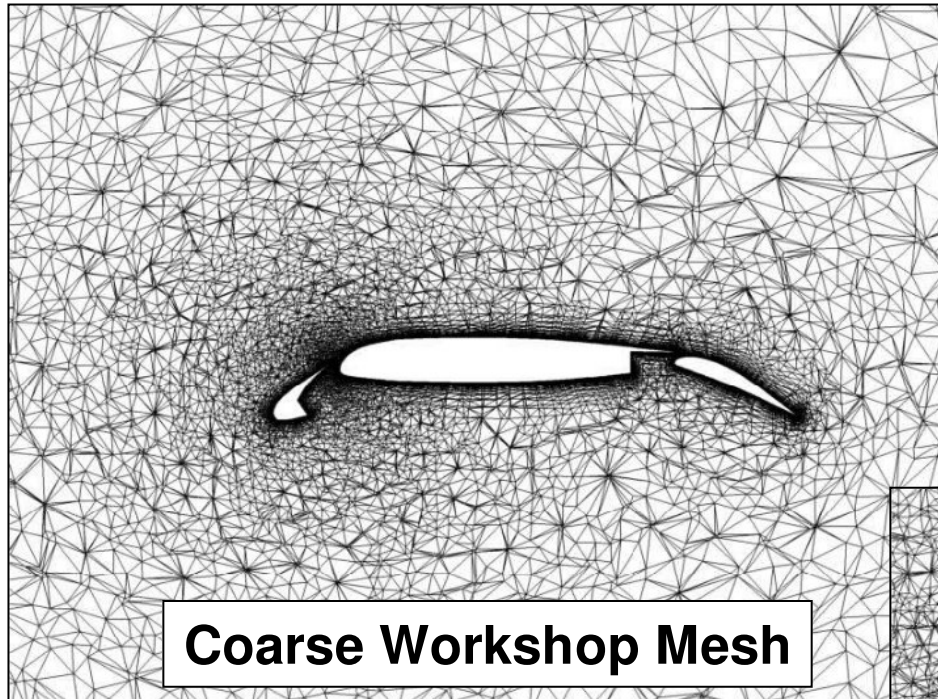
Mesh Adaptation for Shock-Boundary Layer Interaction



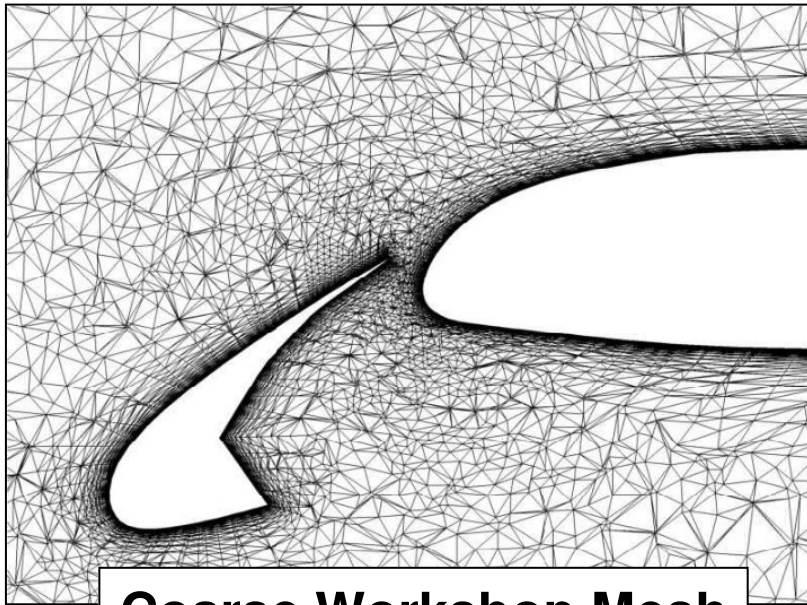
Mesh Adaptation for Shock-Boundary Layer Interaction



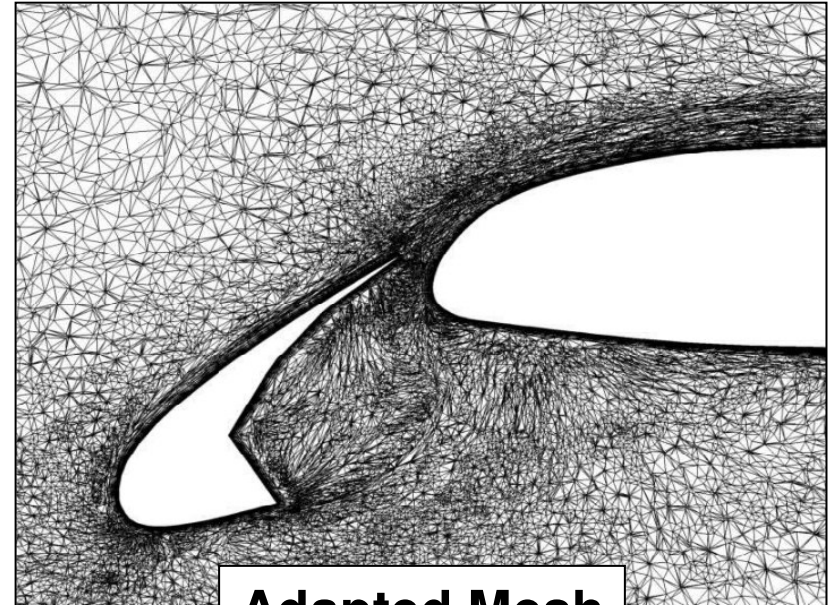
Mesh Adaptation for High-Lift Prediction Workshop



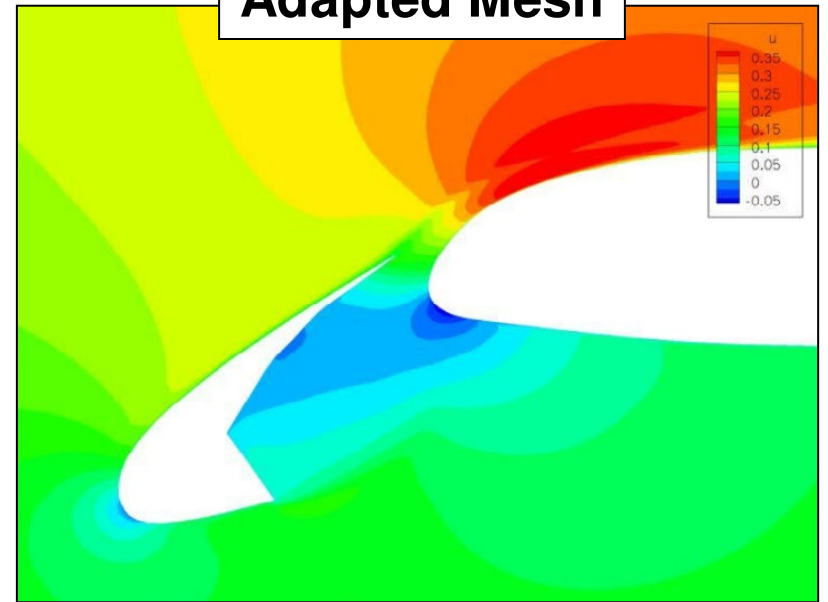
Mesh Adaptation for High-Lift Prediction Workshop



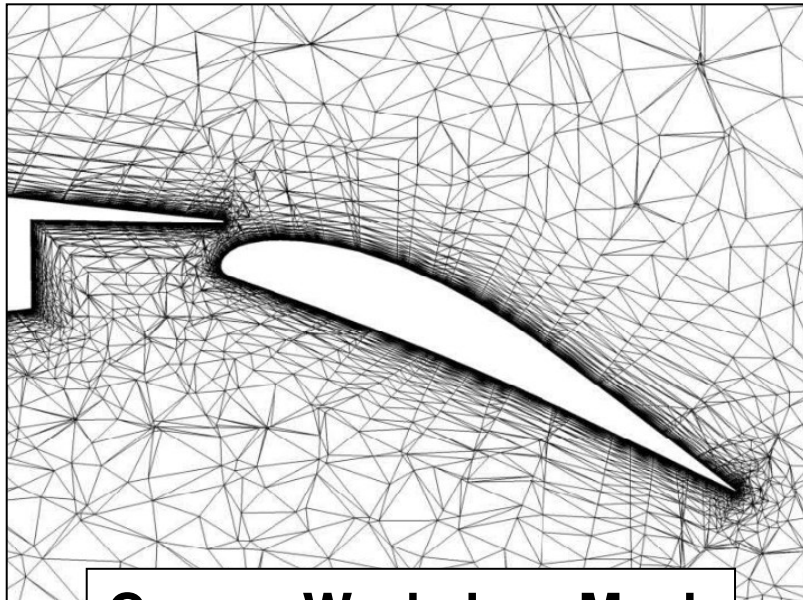
Coarse Workshop Mesh



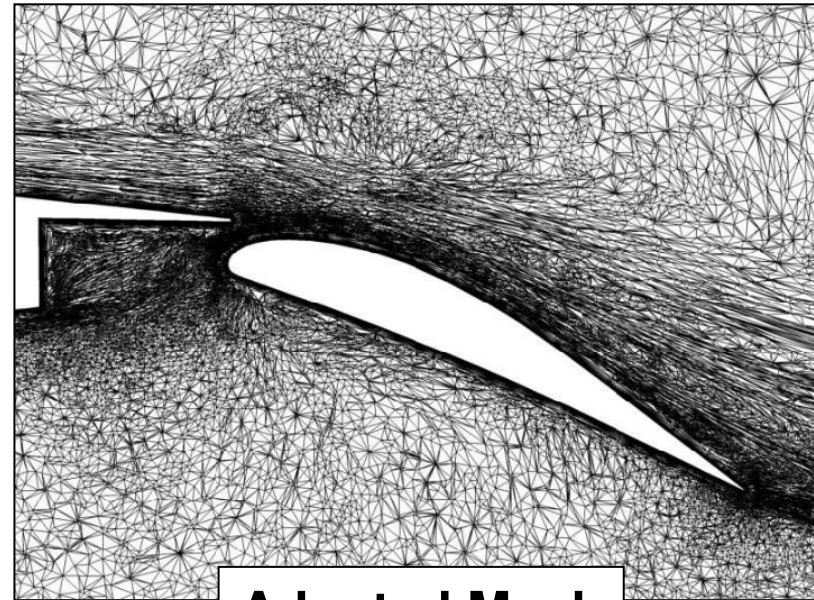
Adapted Mesh



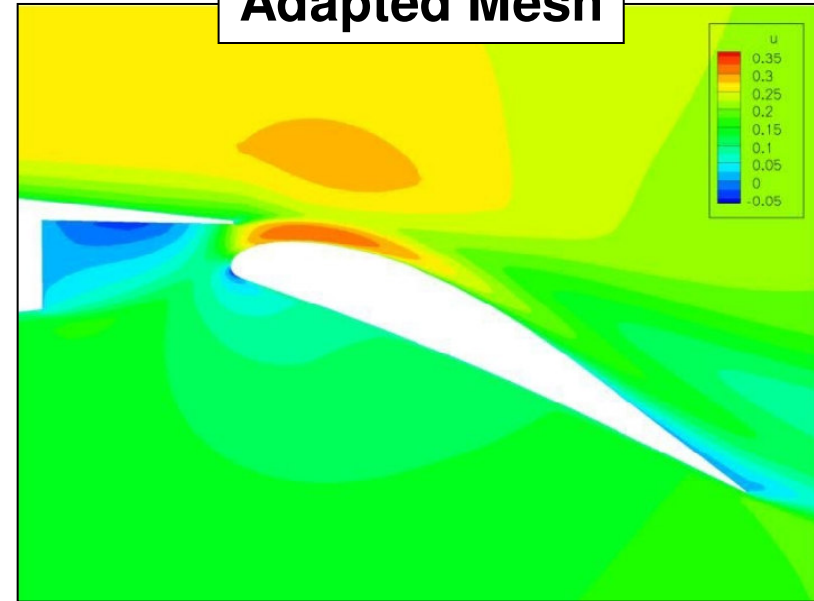
Mesh Adaptation for High-Lift Prediction Workshop



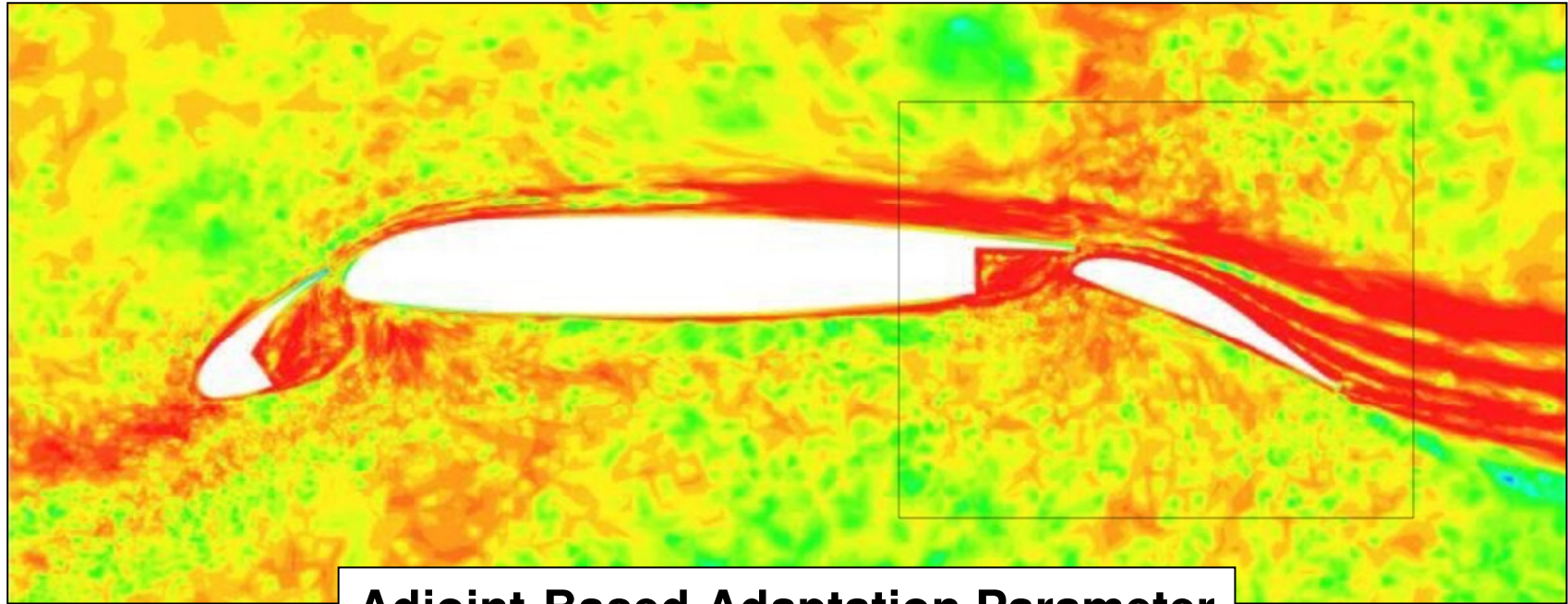
Coarse Workshop Mesh



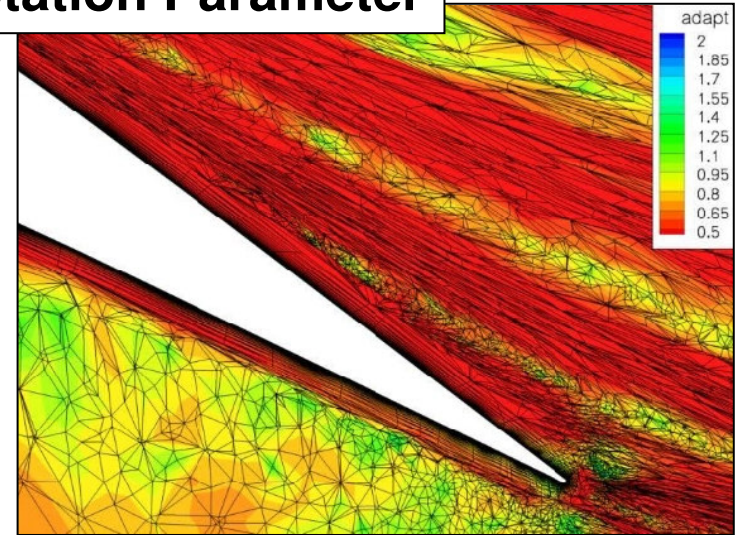
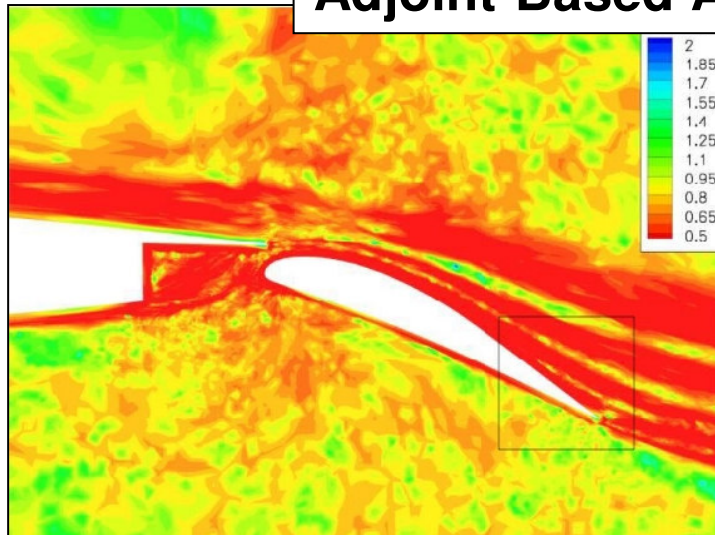
Adapted Mesh



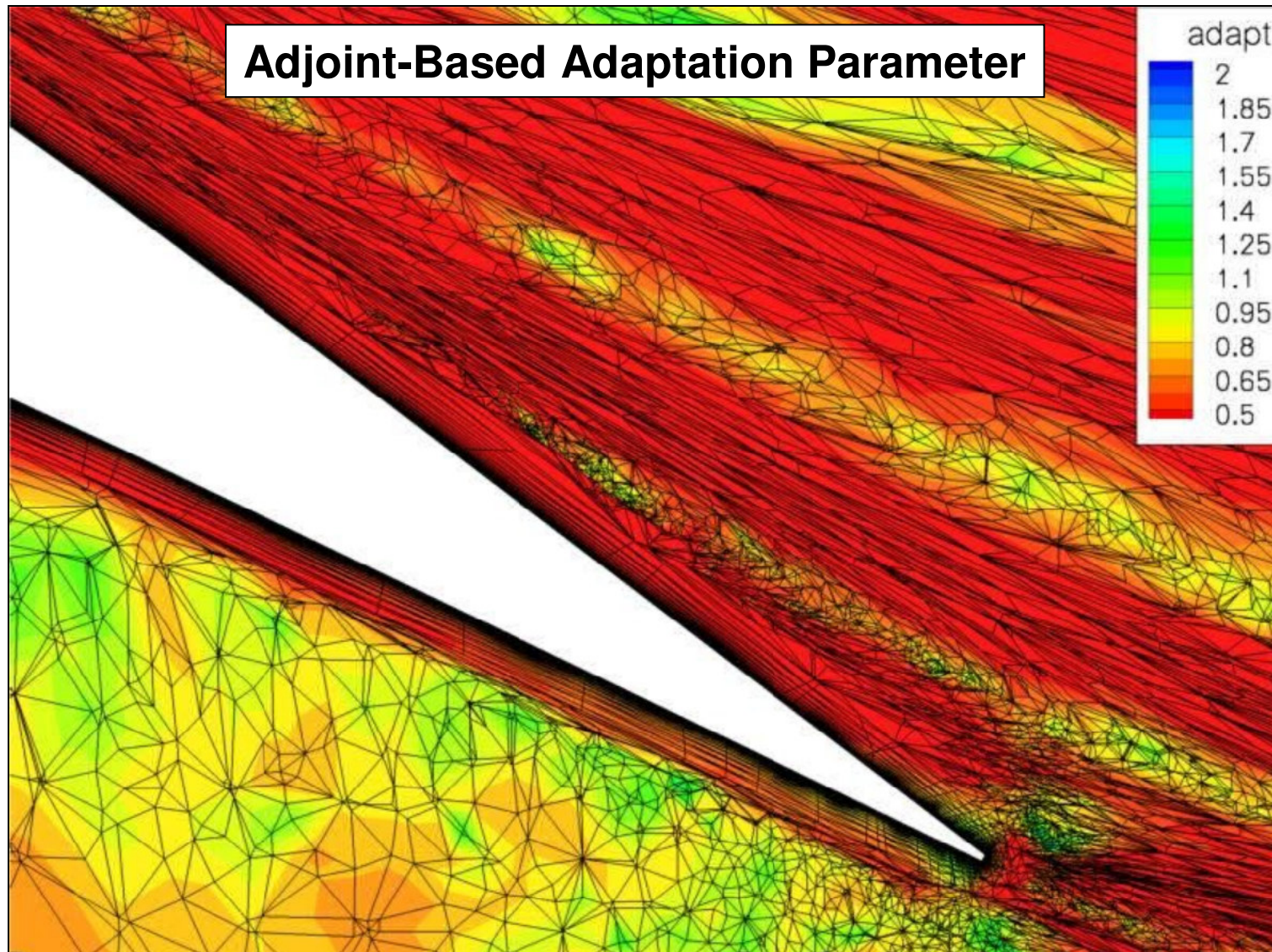
Mesh Adaptation for High-Lift Prediction Workshop



Adjoint-Based Adaptation Parameter



Mesh Adaptation for High-Lift Prediction Workshop



Aeroelastics



- Info provided by Bob Bartels of Aeroelasticity Branch

Mesh Refinement Studies Supporting Ares Crew Launch Vehicle CAE Analysis

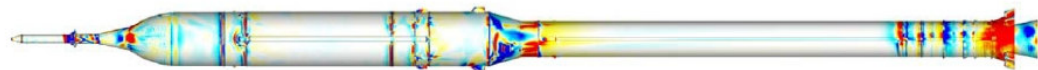
LaRC Aeroelasticity Branch



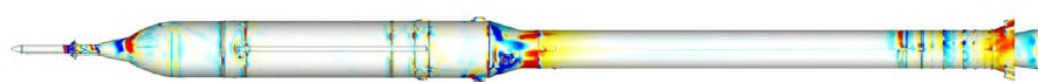
Grid	Total Number of Nodes
Extra Coarse	9.75M
Coarse	19.00M
Baseline	40.84M
Fine	83.37M

Surface pressures show converging, but not fully converged behavior from extra coarse to fine grid

Delta(Cp) Extra Coarse to Fine



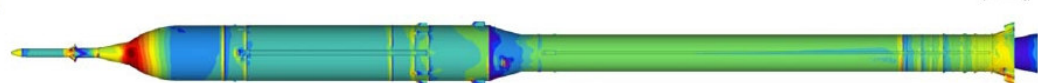
Delta(Cp) Coarse to Fine



Delta(Cp) Baseline to Fine



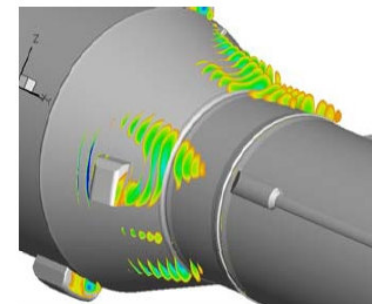
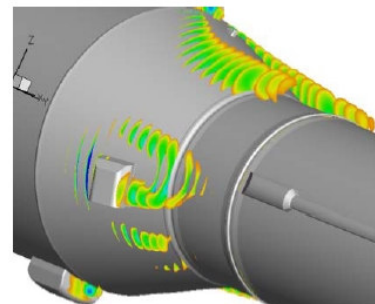
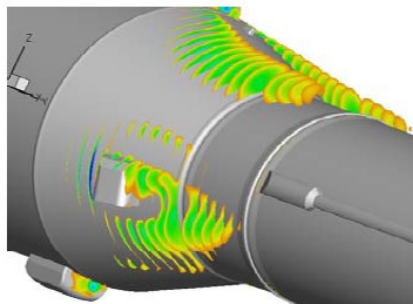
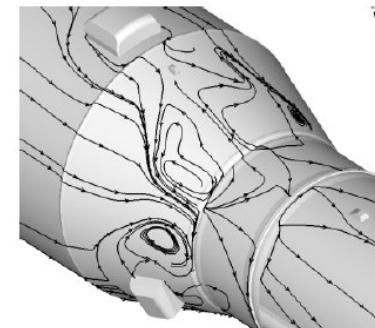
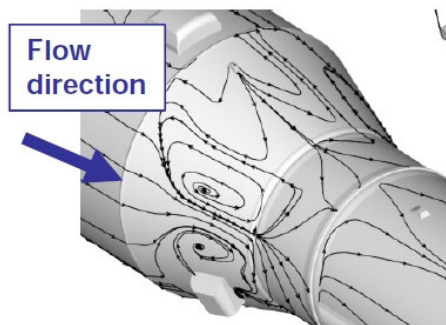
Cp Fine Grid



Bartels, R. E., Vatsa, V. N., Carlson, J.-R., Mineck, R., "FUN3D Grid Refinement and Adaptation Studies for the Ares Launch Vehicle," AIAA Applied Aerodynamics Conference, June 2010, to appear.

Mesh Refinement Studies Supporting Ares Crew Launch Vehicle CAE Analysis

LaRC Aeroelasticity Branch



As seen in velocity contour cuts and surface streamline patterns over frustum, horse shoe vortices and recirculation regions change position and size with grid refinement

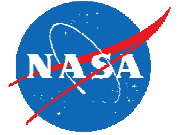
Bartels, R. E., Vatsa, V. N., Carlson, J.-R., Mineck, R., "FUN3D Grid Refinement and Adaptation Studies for the Ares Launch Vehicle," AIAA Applied Aerodynamics Conference, June 2010, to appear.

Supersonic Retropropulsion

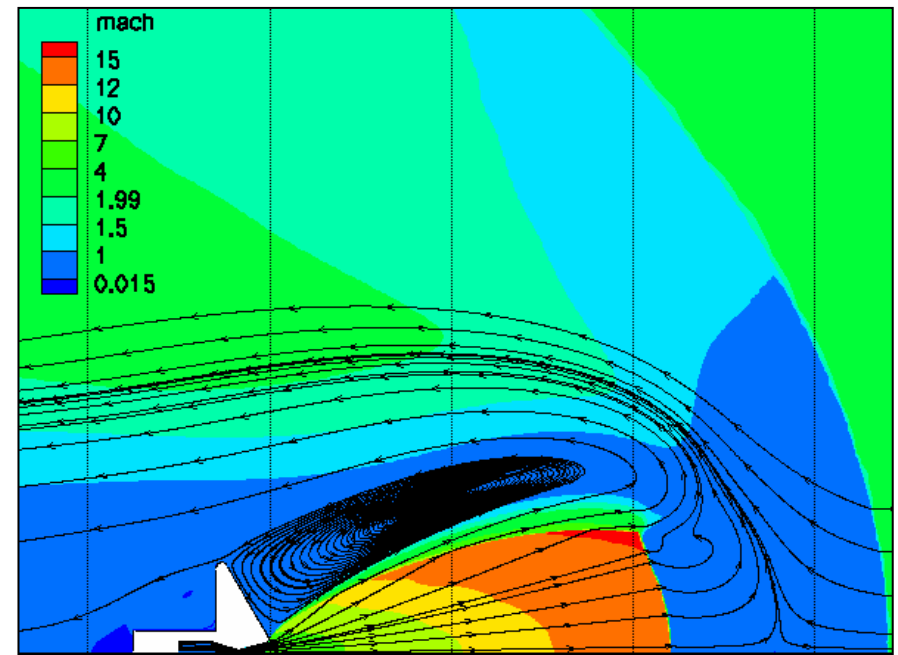


- Info provided by Bil Kleb of Aerothermodynamics Branch and Hicham Alkandry (U of Michigan PhD student visiting for summer)

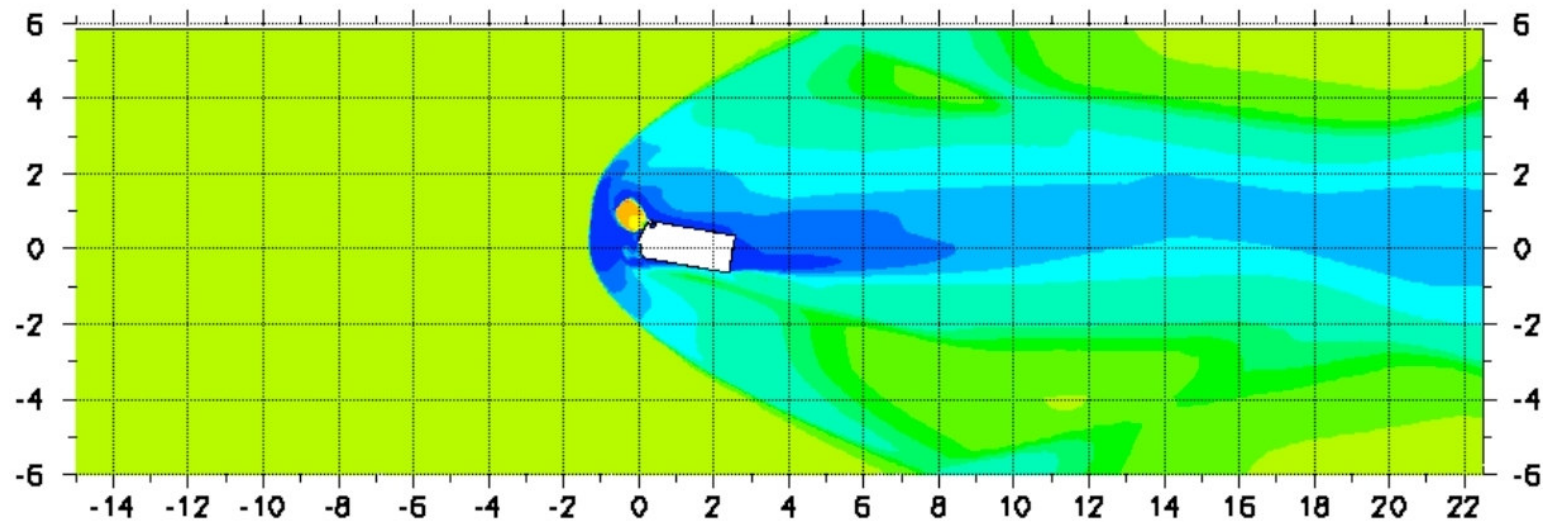
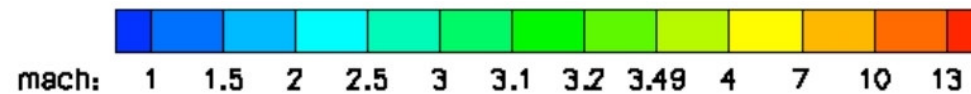
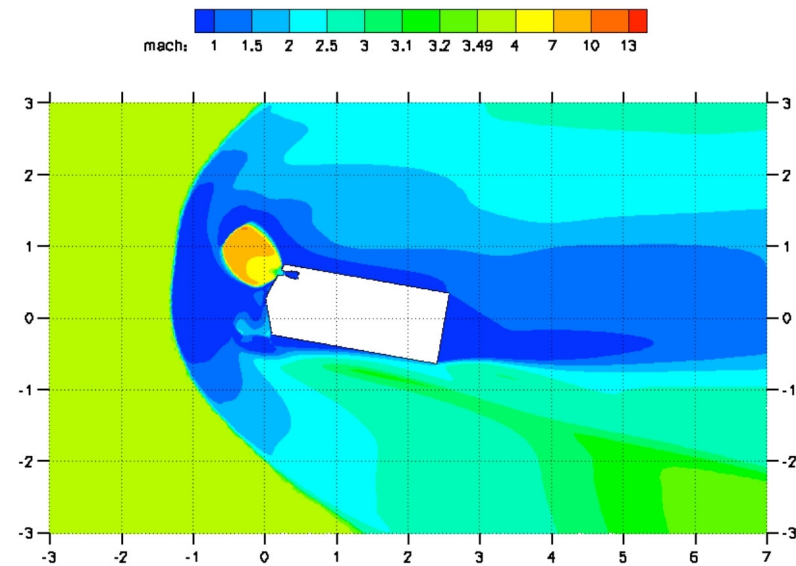
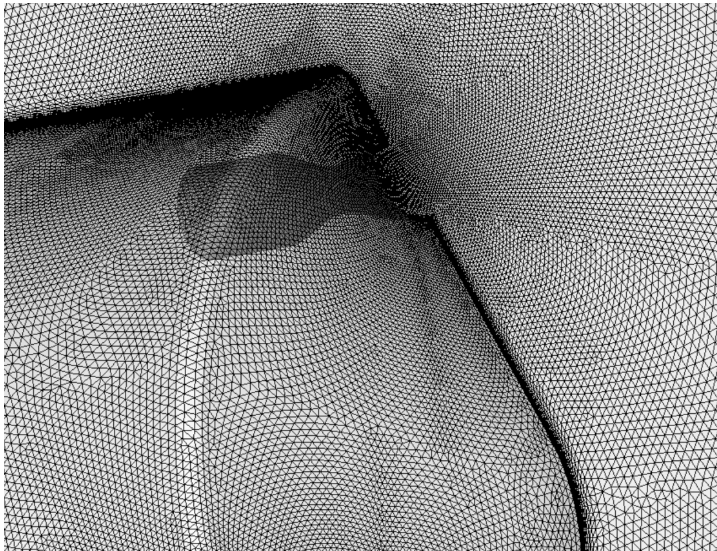
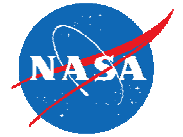
Supersonic Retropropulsion



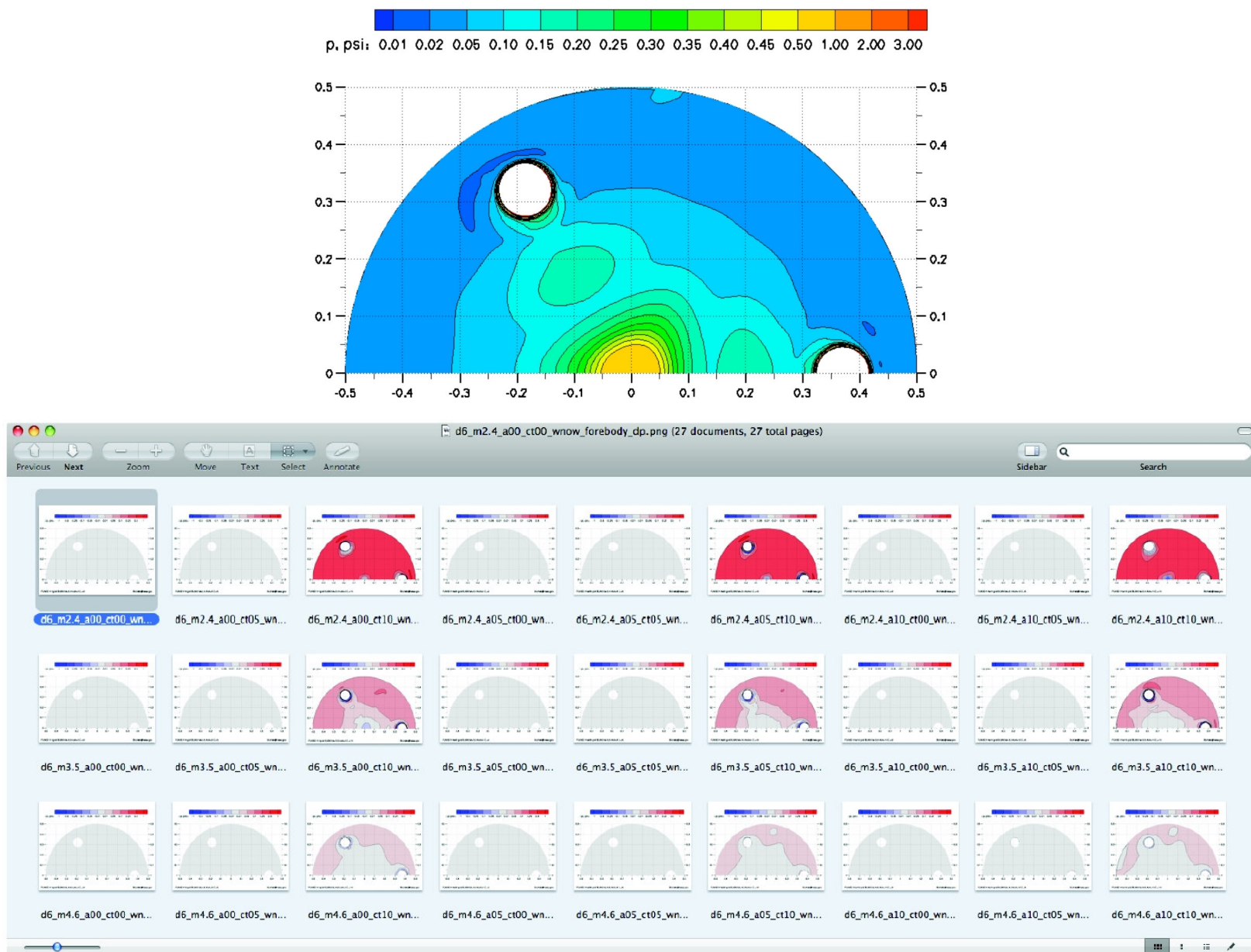
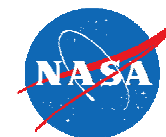
- Rapid turnaround requirements for pre-test predictions and planning
- Native CAD Part
- GridEx driving AFLR3 or VGRID
- Free-air or including tunnel geometry
- Geometry to volume grid in 1-2 hours
- ~2 hours to solution on 512 cores
- Matrices of hundreds of solutions run and post-processed simultaneously using scripting process and Tecplot macros
- Uses FUN3D's coprocessing for binary Tecplot visualization files
 - Sampling surfaces, slices
 - Nozzle performance
- Feature- and adjoint-based adaptation



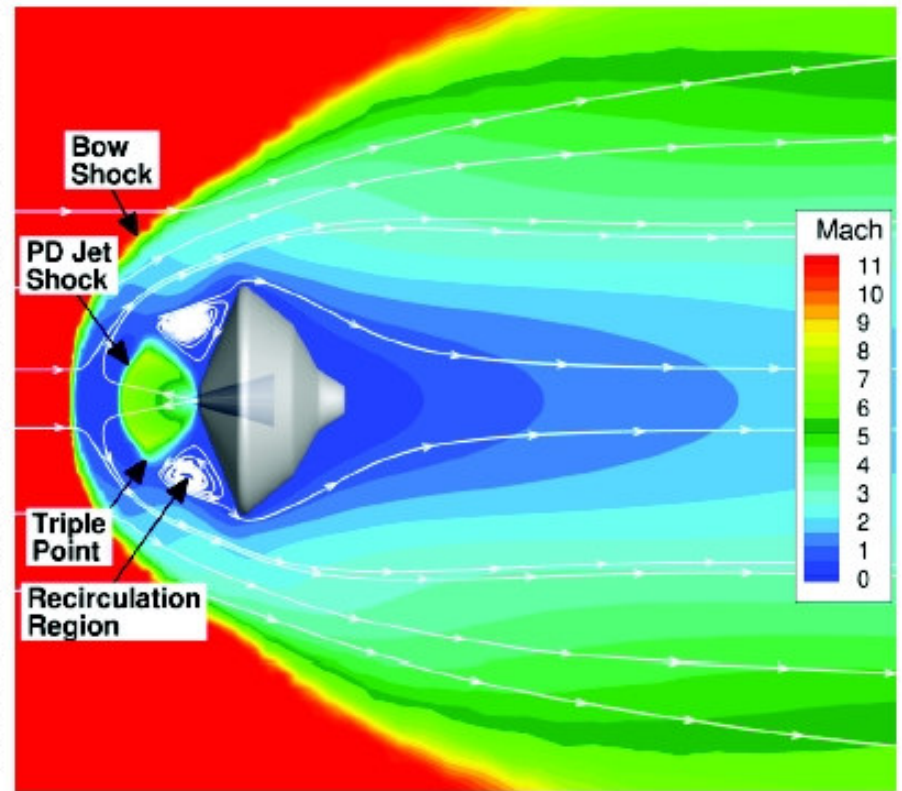
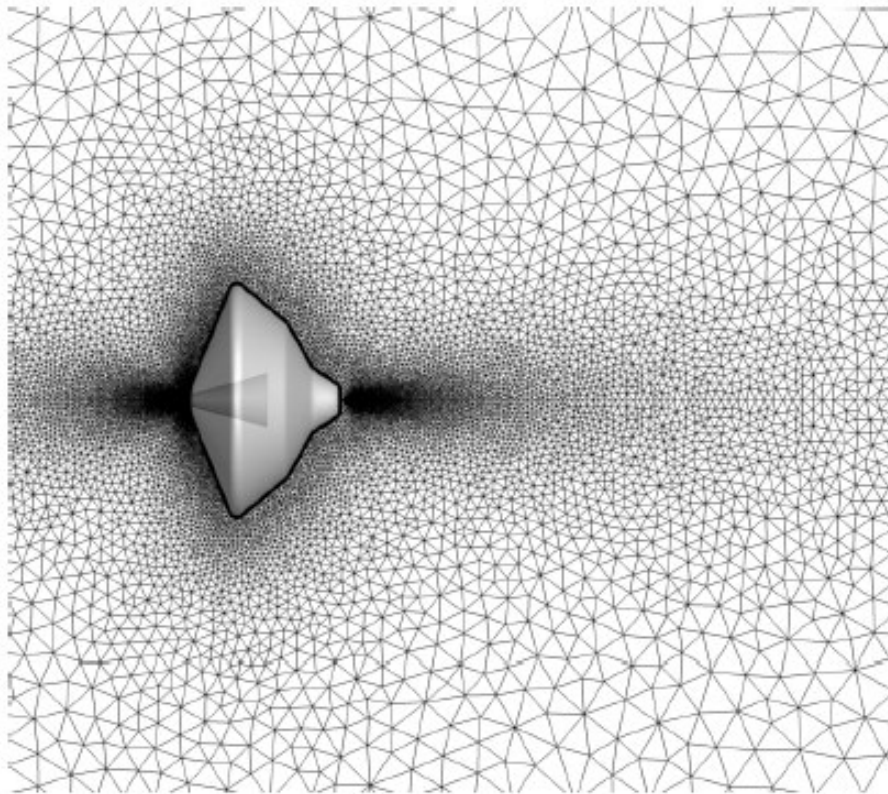
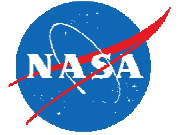
Supersonic Retropropulsion



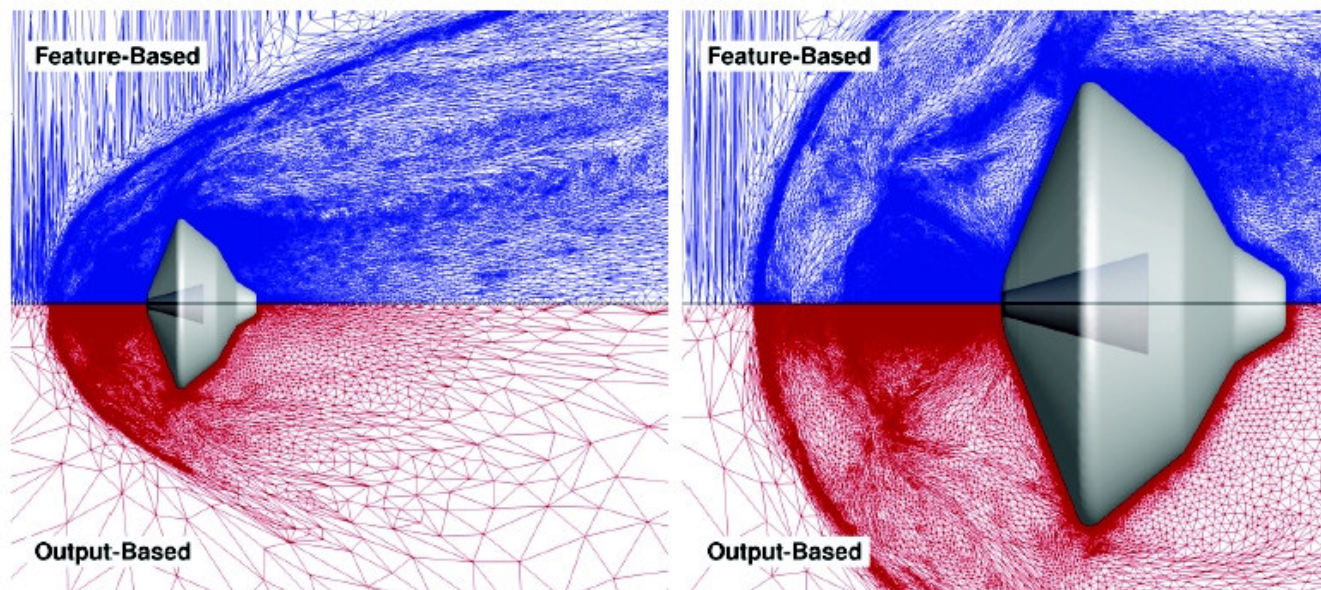
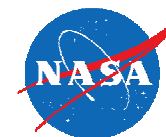
Supersonic Retropropulsion



Supersonic Retropropulsion



Supersonic Retropropulsion



(a) Symmetry plane

(b) PD jet details

Table 1. Grid size ($\times 10^6$ nodes).

	Feature-based	Output-based
Initial	0.7	0.7
1 st Cycle	1.6	1.5
2 nd Cycle	4.1	3.1
3 rd Cycle	10.2	4.3
4 th Cycle	23.7	7.7

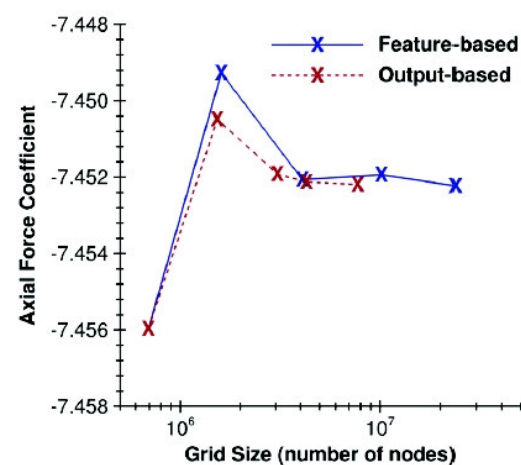
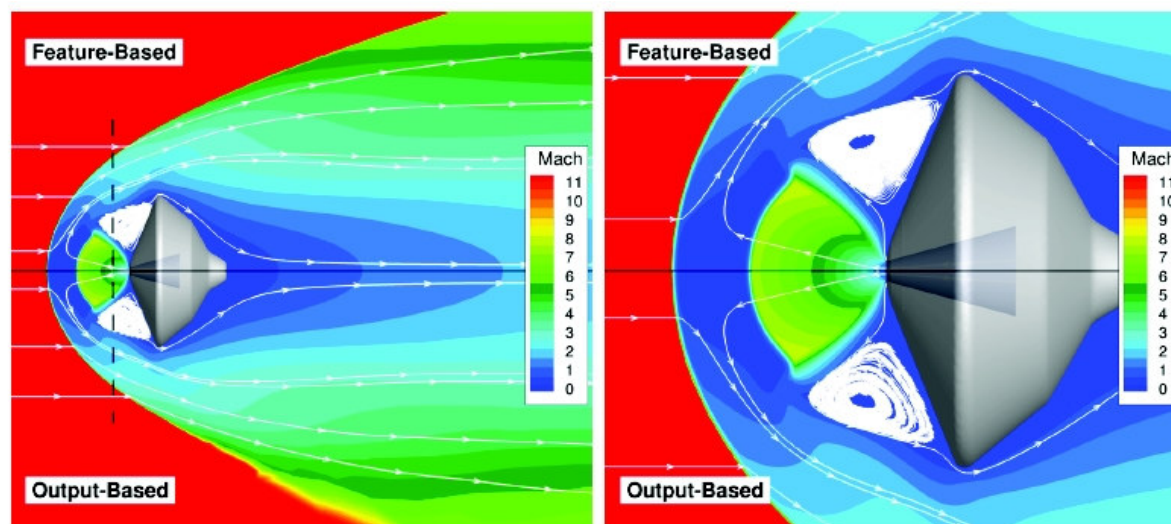
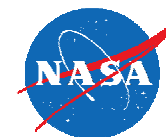


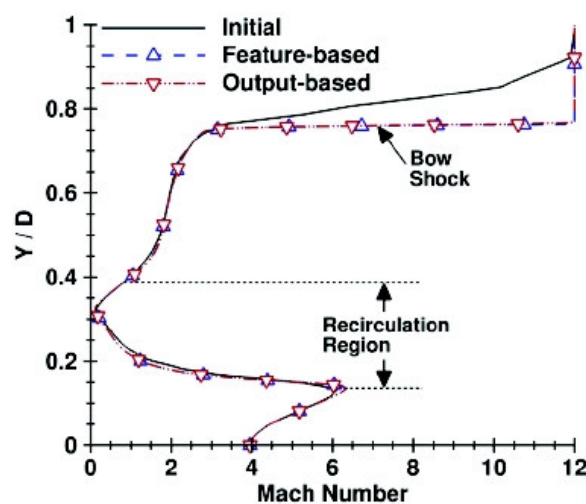
Fig. 2. Axial force coefficient.

Supersonic Retropropulsion

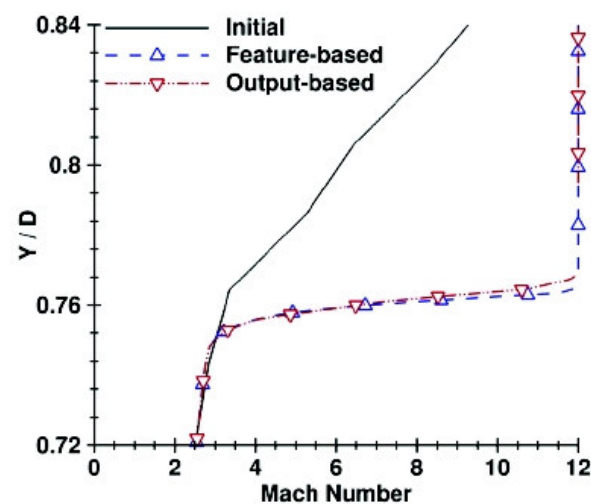


(a) Symmetry plane

(b) PD jet details

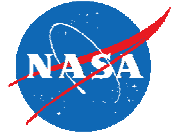


(c) $X/D = -0.15$

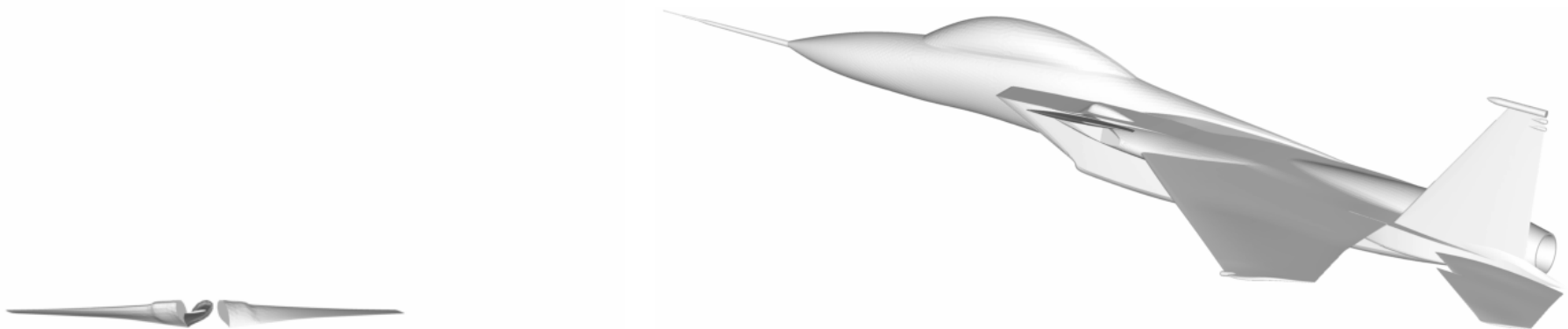
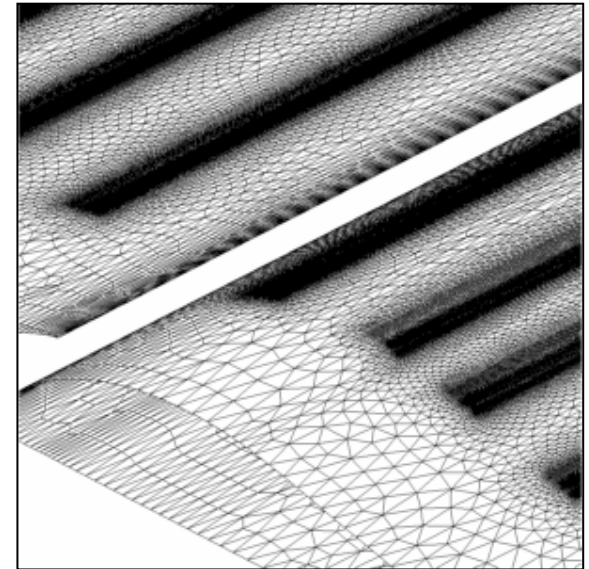


(d) Bow shock details

Unsteady Adjoint-Based Design Optimization



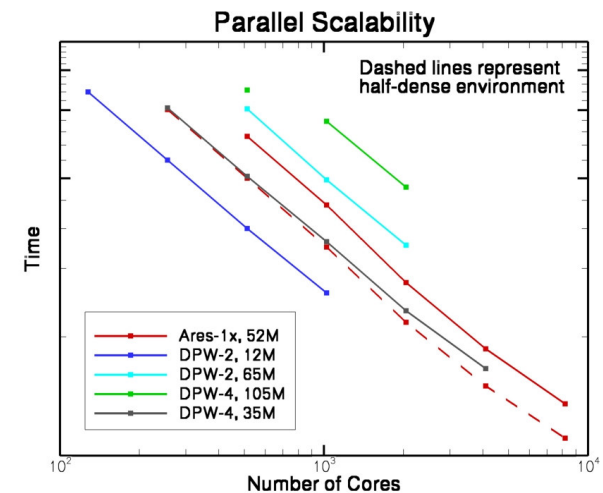
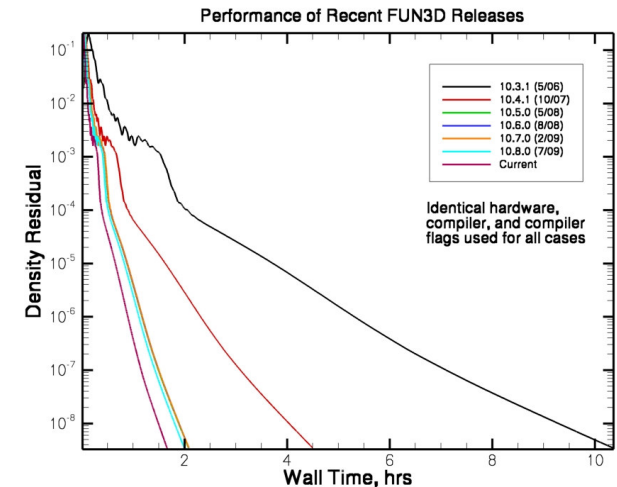
- Most recent application: Active flow control for high-lift
 - Entire talk available if interested
 - Demonstrated design capability for high-lift wing section with oscillatory blowing
 - Design variables included frequency/velocity/phase of each jet, jet location and incidence angle, external wing shape
 - Implemented asynchronous I/O for massively parallel environments



High-Performance Computing



- FUN3D now completely parallel from end-to-end
 - Pre-processing, solver, restart read/writes, co-processing for visualization
 - Still fine-tuning, adding some bells and whistles
 - 105M node (600M element) DPW-4 grid now loaded directly by solver and preprocessed in 5 minutes on 1024 distributed processors – used to take ~2 weeks sequentially with 800 GB shared memory and file I/O
- Parallel I/O using MPI-IO layer in MPI-2 or native FUN3D approach with Fortran 2003 stream I/O
- Still optimizing the use of ParMetis
 - Final communication pattern depends heavily on the number of callers – split off from the FUN3D communicator and call from as few cores as possible
 - No easy way to determine node layout, memory, etc – must be very conservative in your “guess”
- Porting FUN3D to GPU's in a multicore environment – full talk available if interested
- Scaling to 8,192 cores; have performed memory scaling tests to 32,768 cores
 - Takes weeks to get many cores on NASA systems – run as “capacity” not “capability”
 - NAS to reserve 55,000 cores for testing in next couple of weeks for SC 2010
- Also testing on systems at Oak Ridge (‘jaguar’ #1 on Top500 – 250,000 cores)
- Presenting in Doug Ball’s “HPC in the Aerospace Industry” session at HPC Forum next month



High-Performance Computing



CFD Code
Acceleration on
Hybrid
Many-Core
Architectures

Austen C. Duffy

Introduction

GPU Computing
Background
Related Work

Accelerating
FUN3D

Test Problems

Results

Timing -
Speedup
Scaling
Discussion

Conclusion

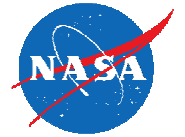
CFD Code Acceleration on Hybrid Many-Core Architectures

Austen C. Duffy

NASA Langley Research Center

August 2, 2010

Training Workshops



- Held several training workshops this year
 - March: 30 LaRC civil servants and contractors
 - April: 30 external users in-person, 15 via WebEx
 - July: At NAVAIR-Pax River
- All slides and demos available on website
 - Entire April workshop pro-shot and available via streaming video online
 - ~15 sessions covering overview of FUN3D, installation, and all major capabilities and application areas
- Open to training requests from external groups

