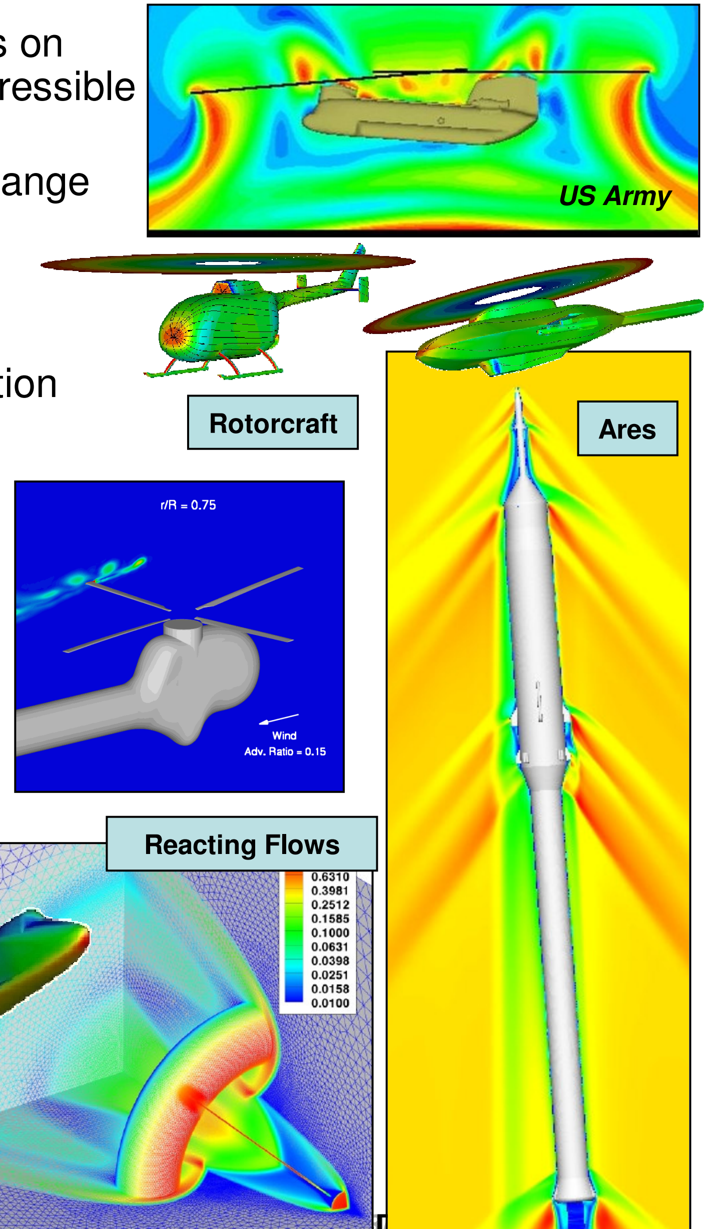
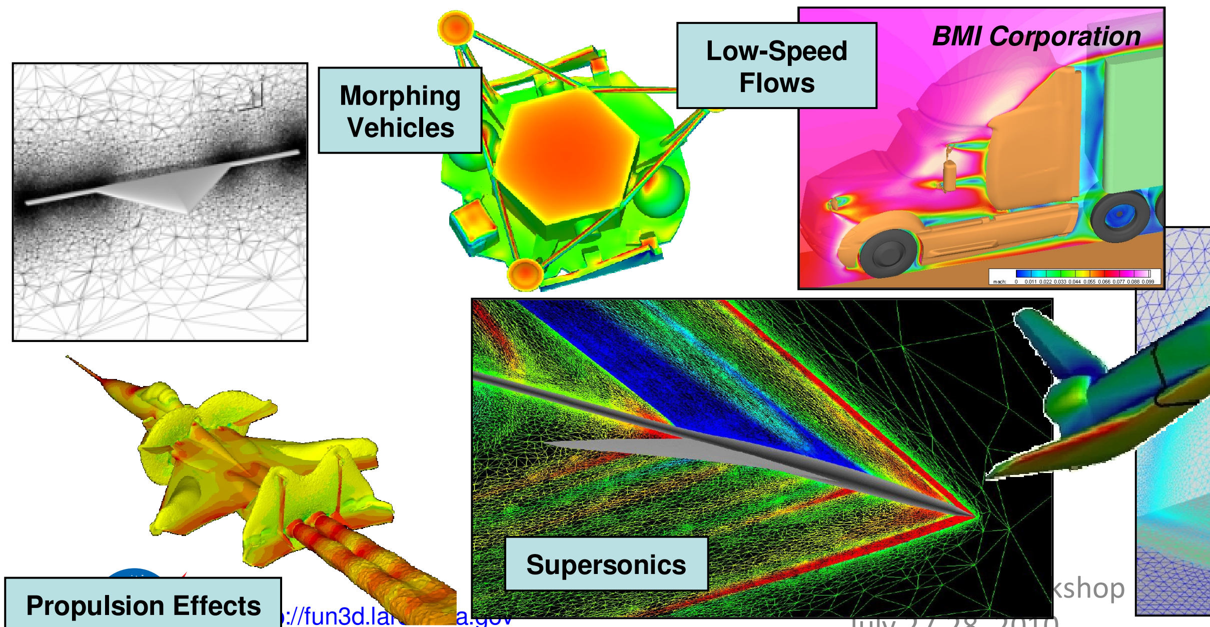
Session 2: Capabilities and Applications Overview

Eric Nielsen

FUN3D Core Capabilities

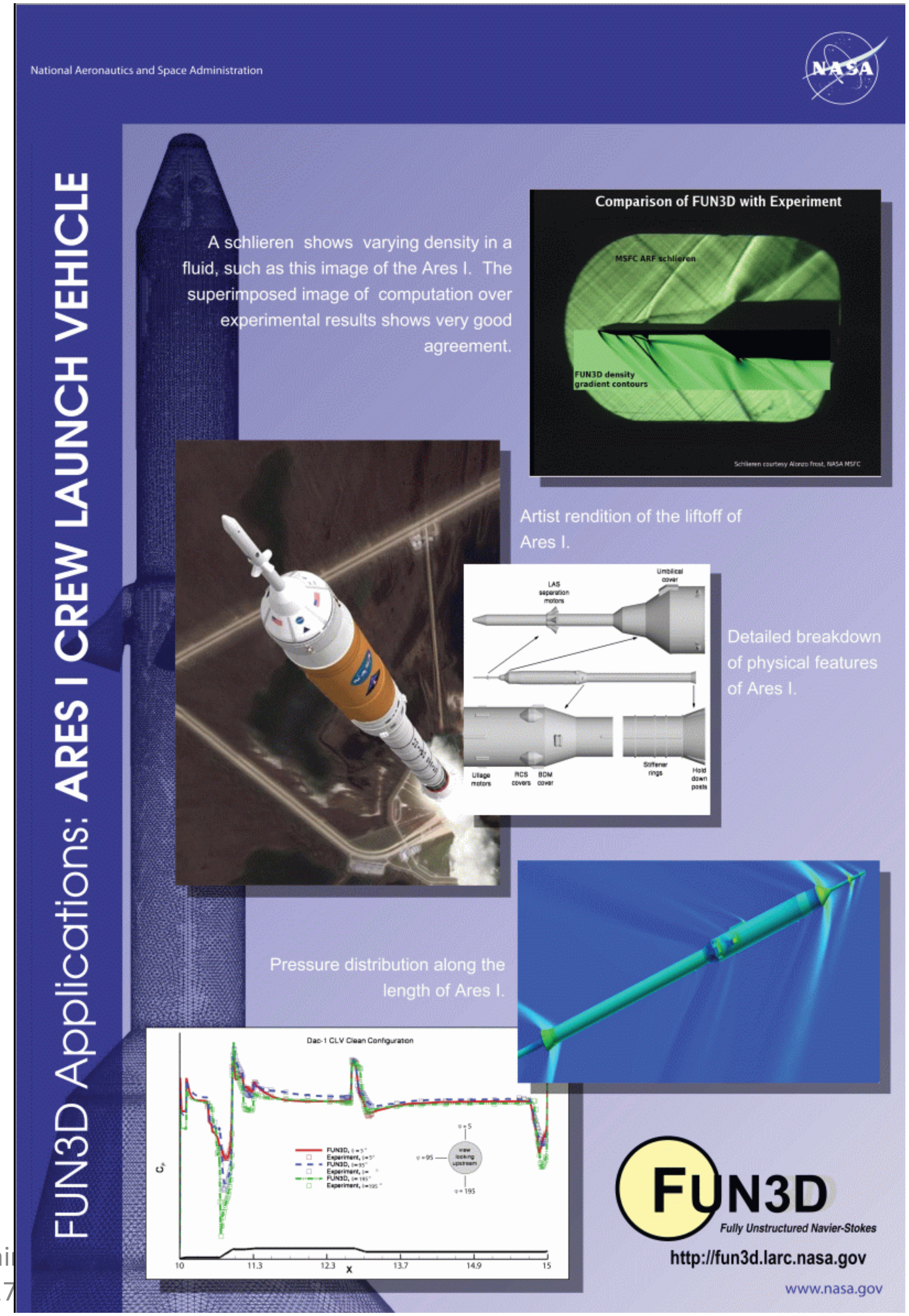
- FUN3D effort started in late 80's - roughly 21 years old now
- Solves 2D/3D steady and unsteady Euler and RANS equations on node-based mixed element grids for compressible and incompressible flows; cell-centered schemes being investigated
- Supports numerous internal/external efforts across the speed 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, tutorials, etc





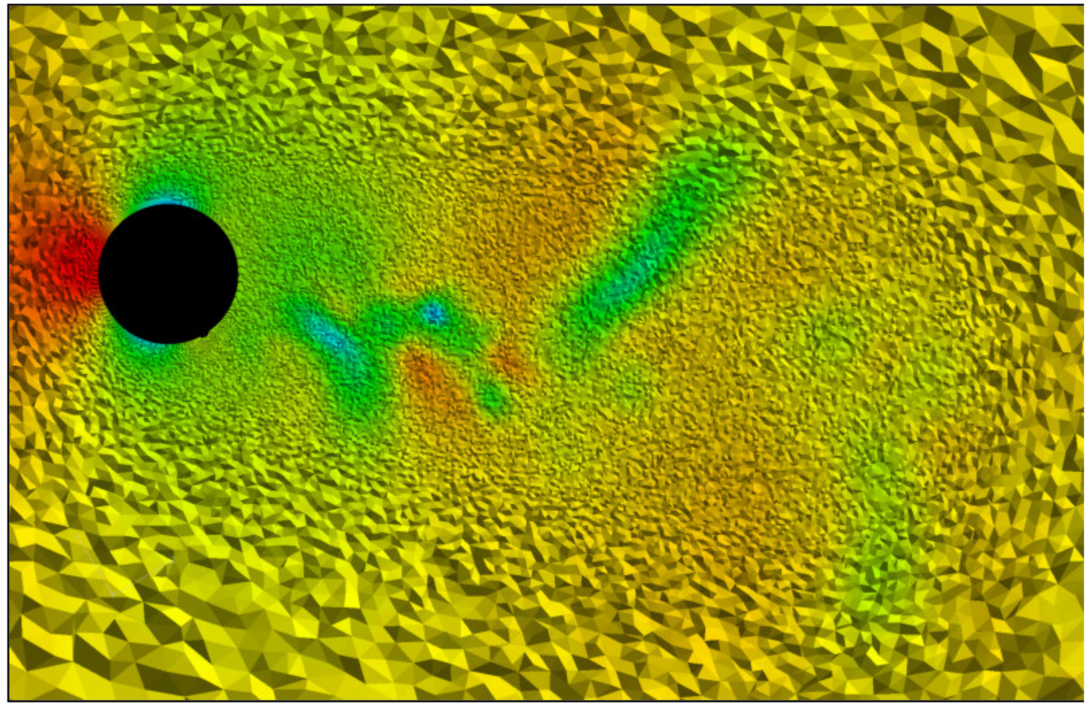
NASA Applications: ARES I

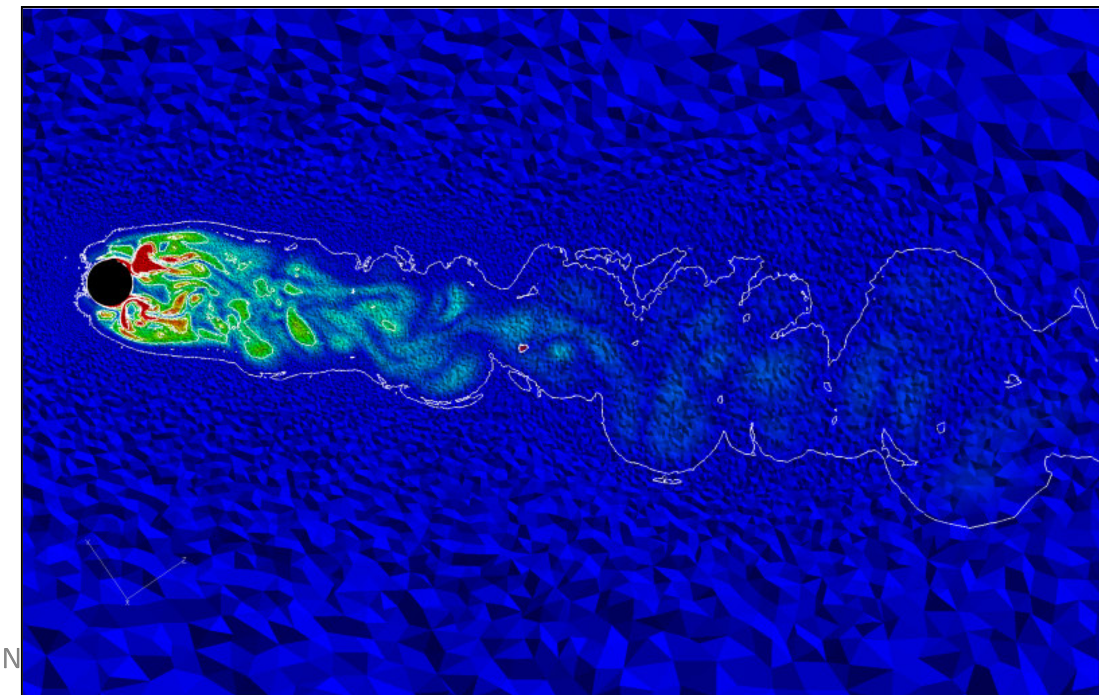
- Providing forces/moments and sectional data for ascent aero
  - Successfully predicting roll moments
- Mach numbers ranging from 0.5 to 4.5
- Wind tunnel and flight Re (>1 billion based on length)
- Alpha sweeps from 0 to 7 degrees, roll from 0 to 360 degrees
- Provided hundreds of simulations over 2-year period
- In general, compares well with tunnel data and other CFD
- FUN3D also being used for full-stack aeroelastic characterization (unsteady simulations)
- Geometric details down to 0.1” step heights on 146” diameter body (<0.1%)
- Typical grid sizes of 35M nodes/200M elements, ranging up to ~80M nodes

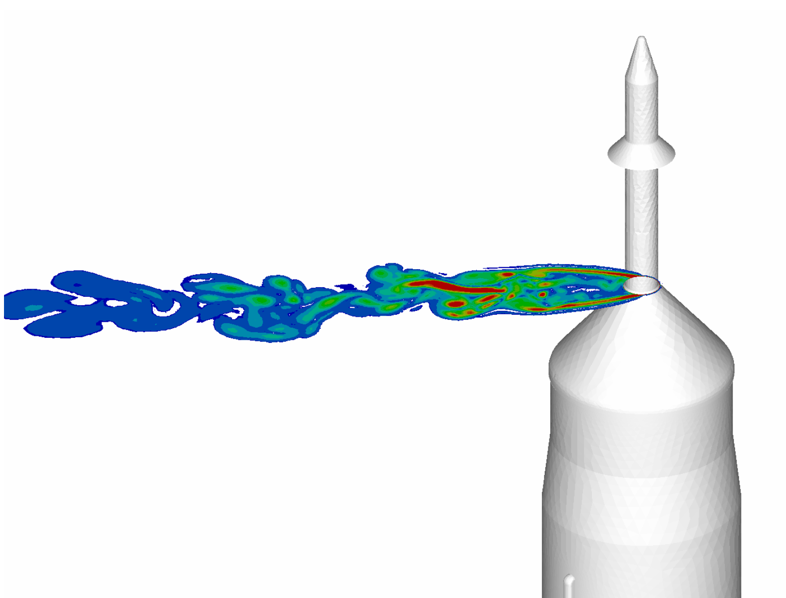


NASA Applications: ARES I

- Ground wind load simulations
- Objective is to provide frequency content to load and structures group
- DES with BDF2
- 21.5M nodes, 126M elements
- 256 cores (32 dual-socket, quad-core) for 3-4 weeks







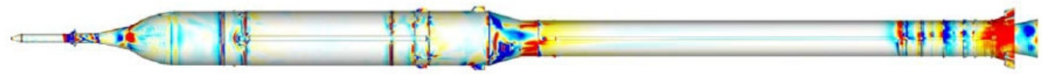
Mesh Refinement Studies Supporting Ares Crew Launch Vehicle CAE Analysis

LaRC Aeroelasticity Branch

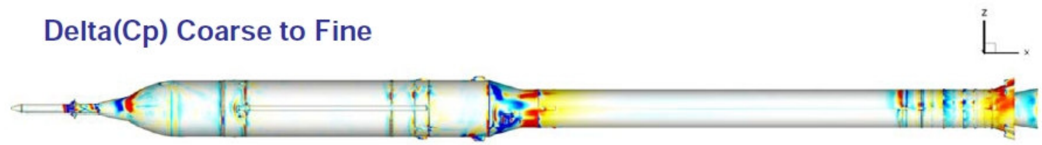
Grid	Total Number of Nodes
Extra Coarse	9.75M
Coarse	19.00M
Baseline	40.84M
Fine	83.37M

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

Delta(Cp) Extra Coarse to Fine

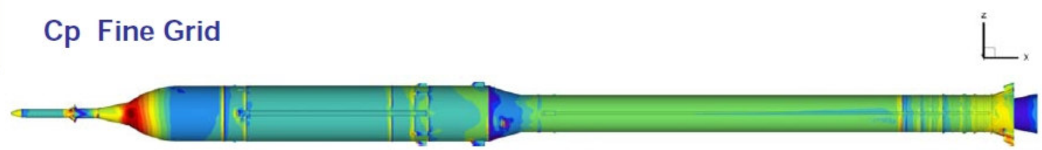


Delta(Cp) Coarse to Fine



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

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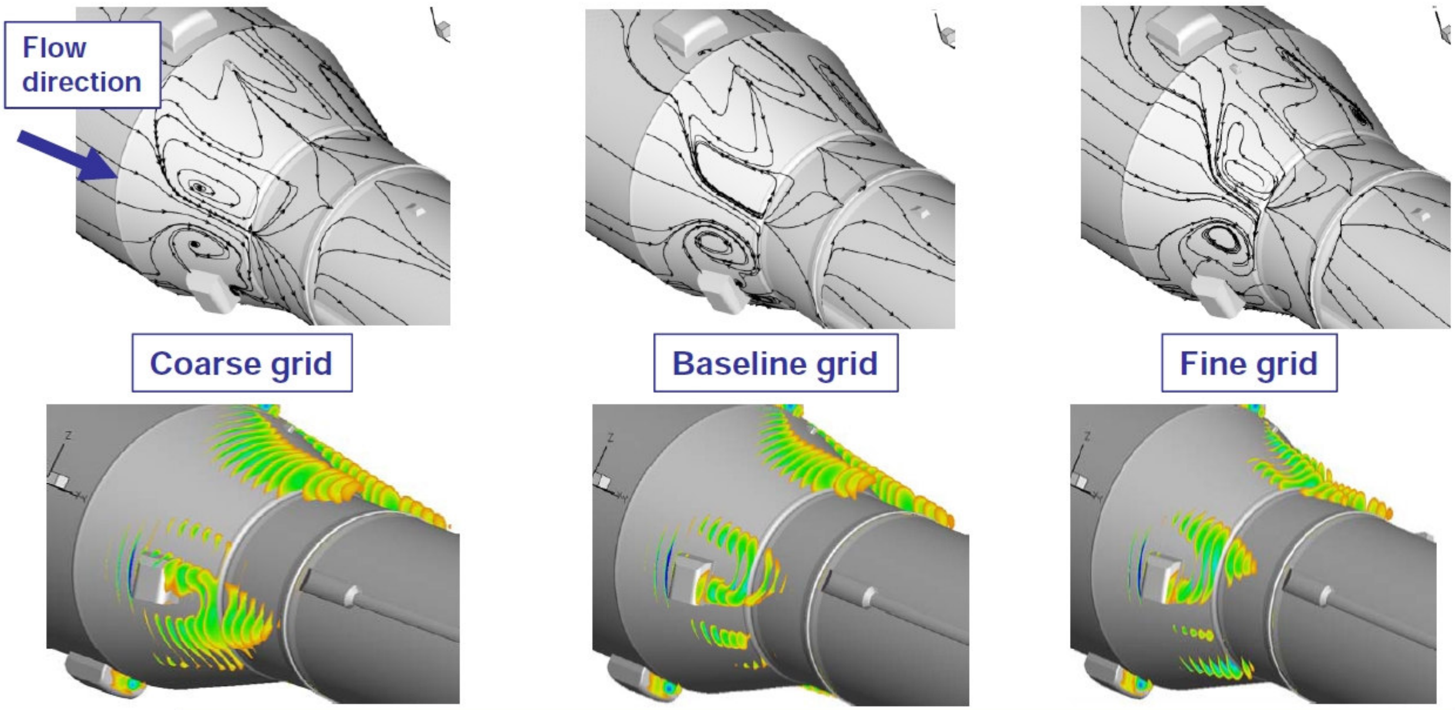
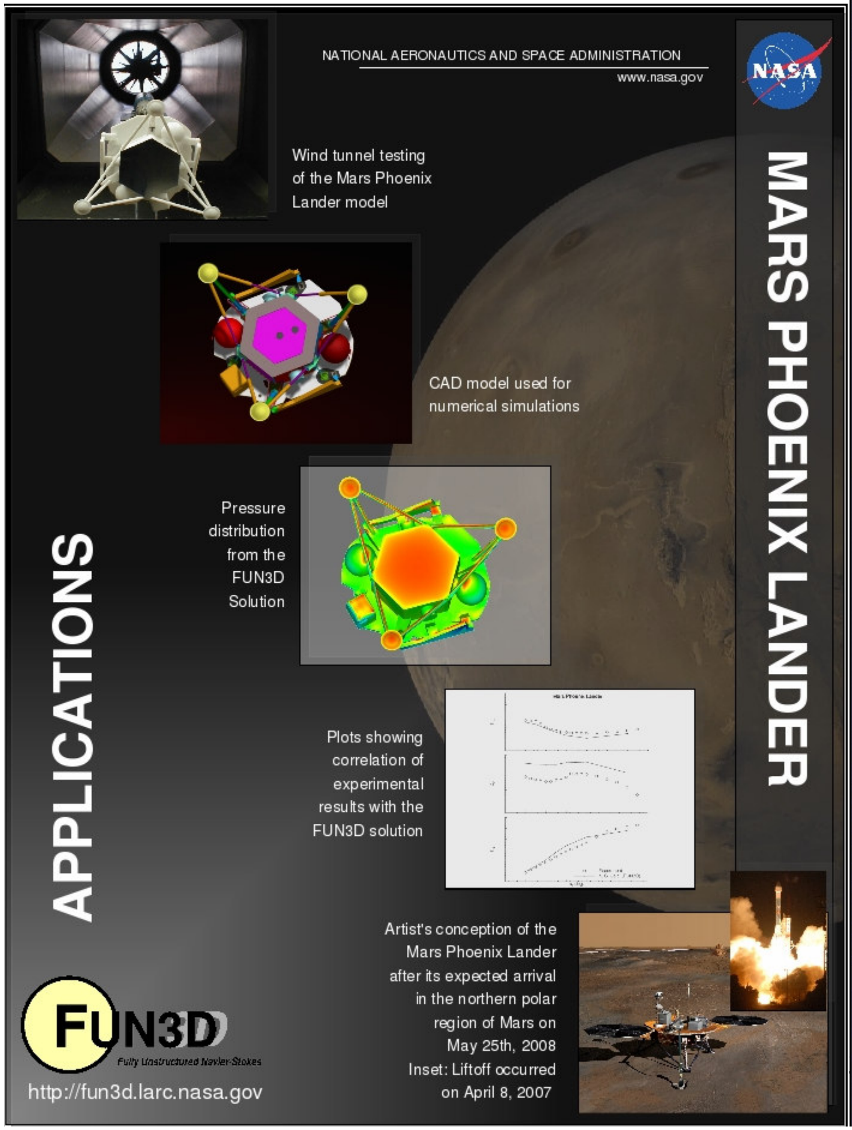
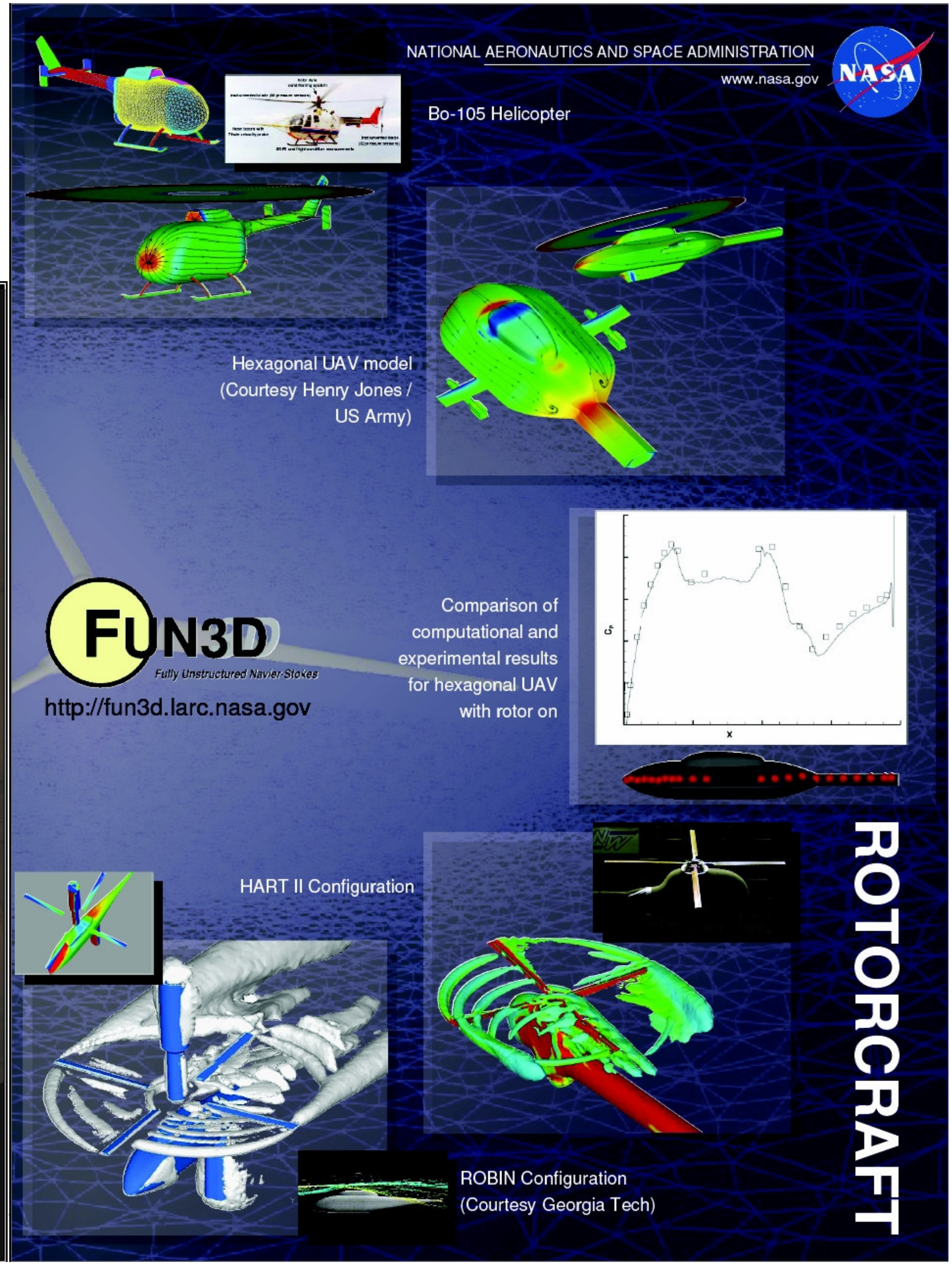


As seen in velocity contour cuts and surface streamline patterns over frustum, horse shoe vortices and recirculation regions change position and size with grid refinement

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.

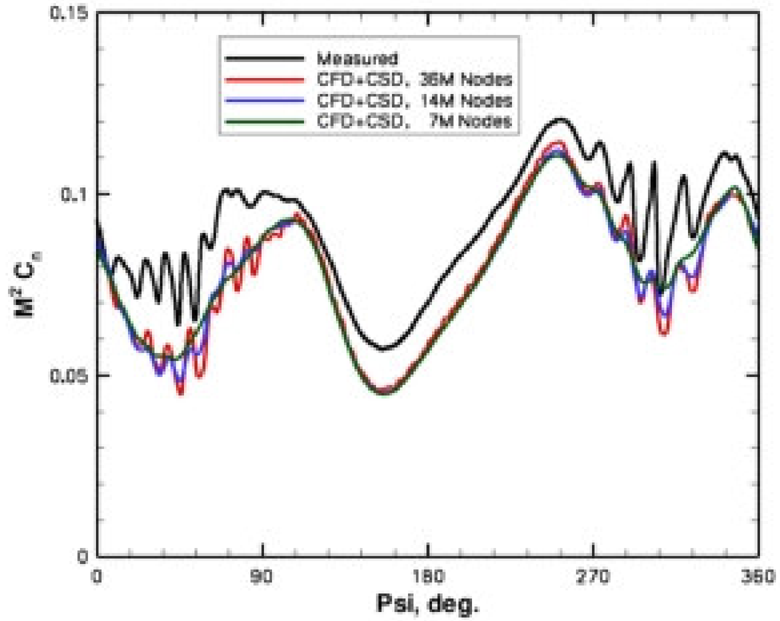
NASA Applications: Mars Phoenix Lander, Rotorcraft

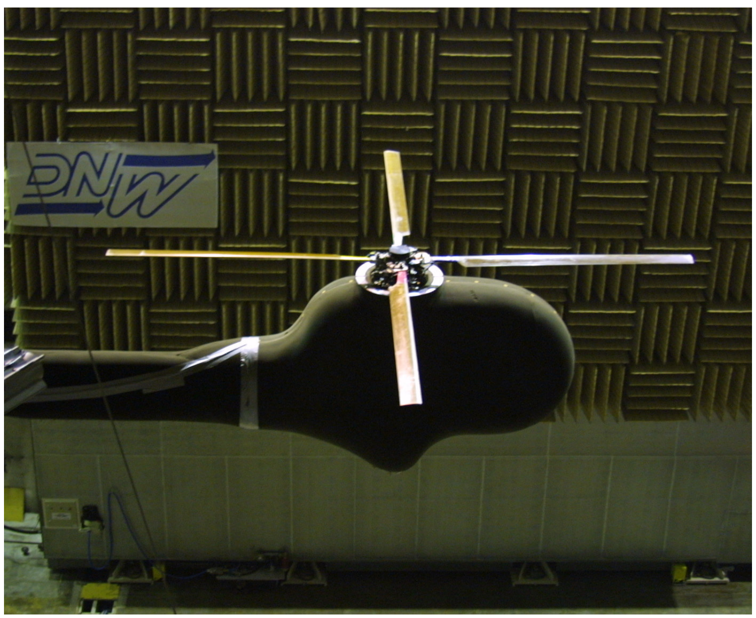


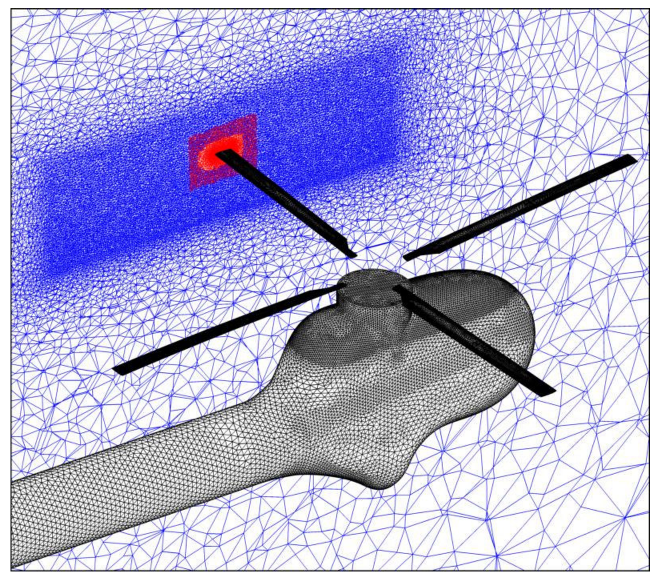


Rotorcraft Analysis - HART-II BL Model

- FUN3D + CAMRAD II
- Aeroelastic and trim interactions
- Computations on meshes from 7-36M nodes
- BVI resolution improves with mesh refinement

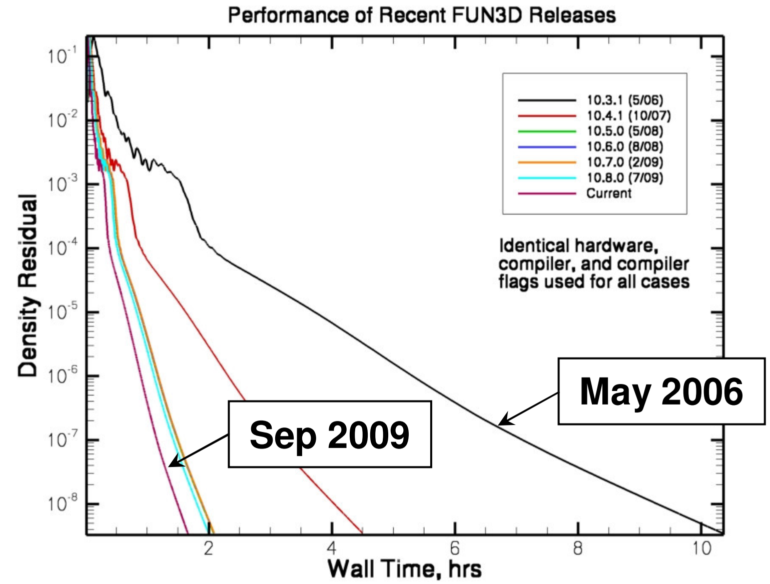


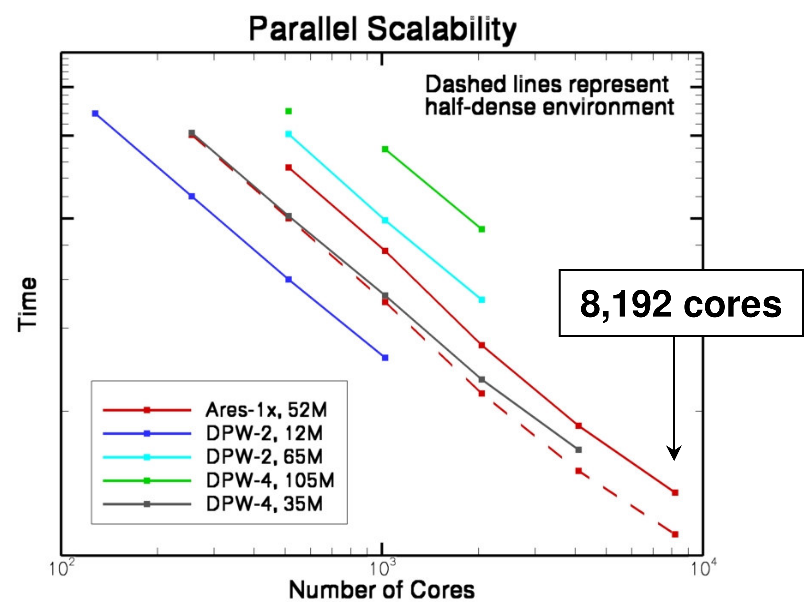




FUN3D Computational Performance

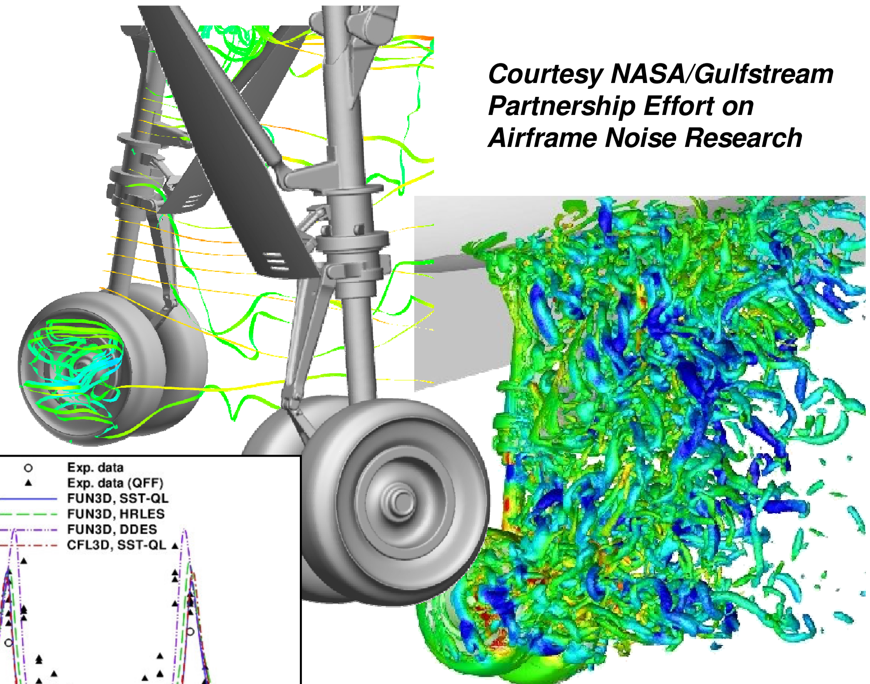
- Effort initiated in 2006 to study and improve computational performance of solver
- Many low-level aspects examined
  - Cache reuse
  - MPI communication
  - Alternative ordering techniques for grid/linear algebra operations
  - Inlining
  - Basic blocks
- Experimented with hierarchical partitioning strategies; will revisit at higher core densities
- 6.5x speedup demonstrated (hardware, compiler and options held fixed)
- Linear scaling demonstrated to 8,192 cores on pleiades (queue becomes limiting factor)
- Working with Oak Ridge staff to continue improving massively parallel performance
  - Recently attended 3-day computational performance workshop at ORNL
  - Experimenting on ORNL Jaguar system (250,000 cores; #1 on Top500)



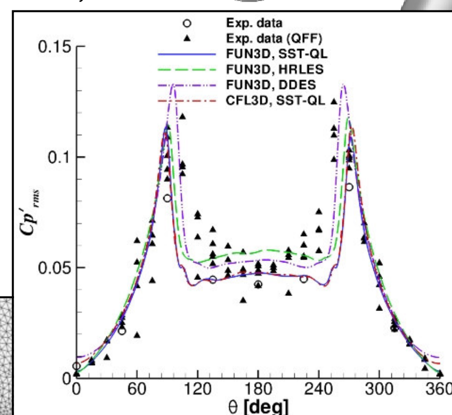


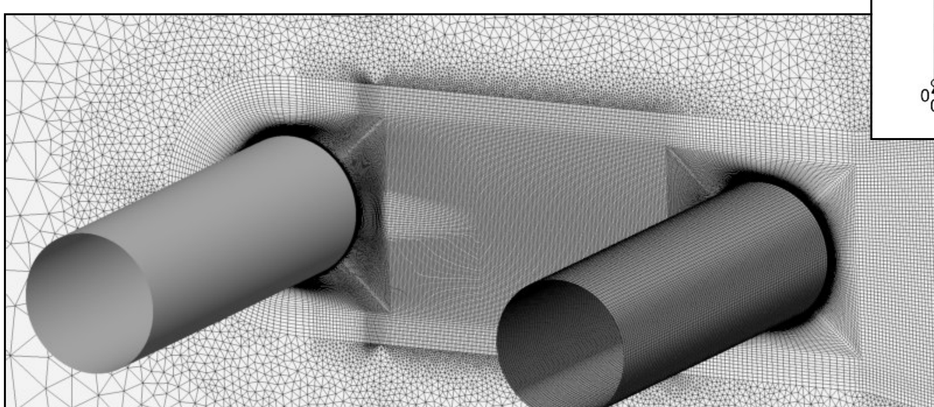
Unsteady Flows / Aeroacoustics

- 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

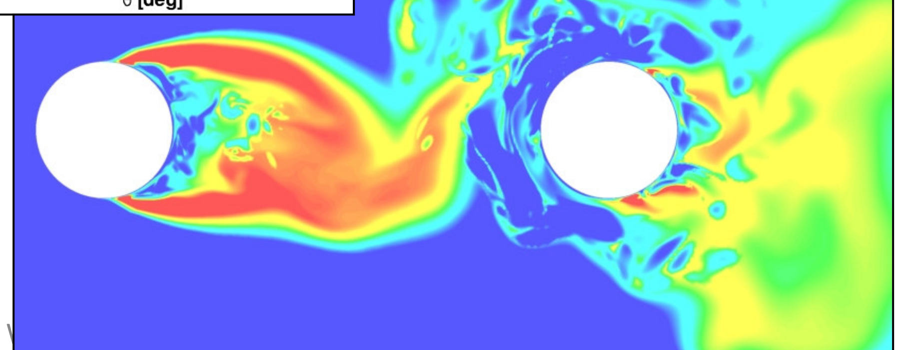


Courtesy NASA/Gulfstream Partnership Effort on Airframe Noise Research





Hybrid 97-plane periodic grid



Multigrid Algorithms

Towards grid-independent convergence for fully unstructured grids

Elements of Multigrid

* **Fast Agglomeration Scheme:**

Advancing-front algorithm.
Line agglomeration in the viscous region.
Requires negligible CPU time.

* **Restriction/Prolongation:**

Volume-average/Linear interpolation.

* **Robust Coarse Grid Viscous Discretization:**

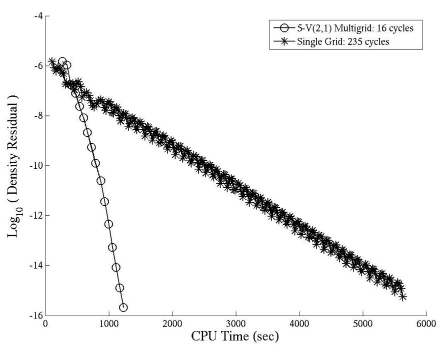
Developed a robust edge-based viscous discretization.

* **Relaxation:**

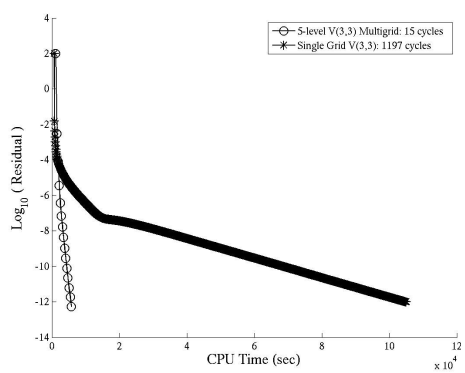
Defect correction with line relaxation in the viscous region.

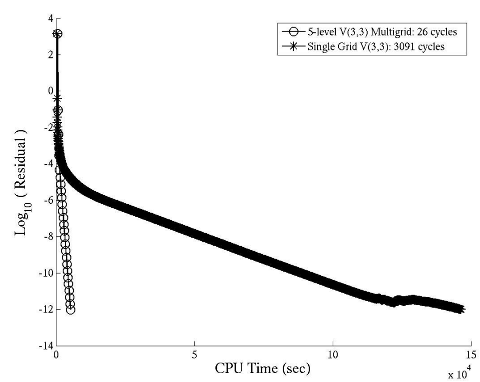
Current Status

Satisfied with performance for Euler problems. All mechanics are in place for viscous flows, including line agglomeration and relaxation. Extensive study is being performed for scalar equation with realistic geometries. Preparing for full RANS. ***Initial RANS results now in-hand***

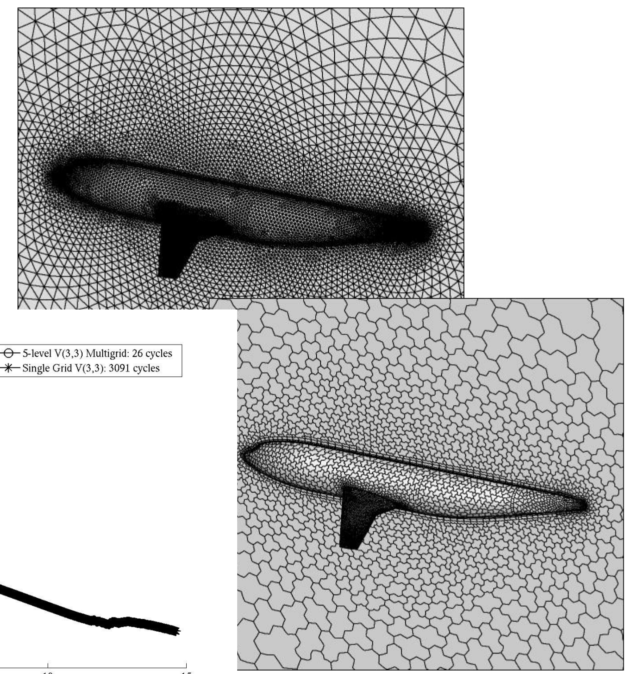


Euler wing-body results: roughly 6 times faster, including time to generate coarse grids.





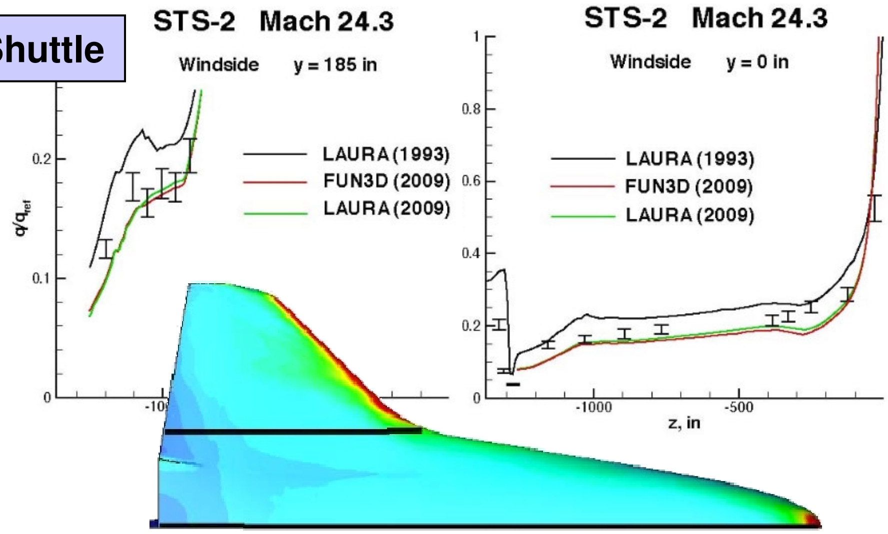
DPW-W2 and DLR-F6: Diffusion equation on highly-stretched grids.



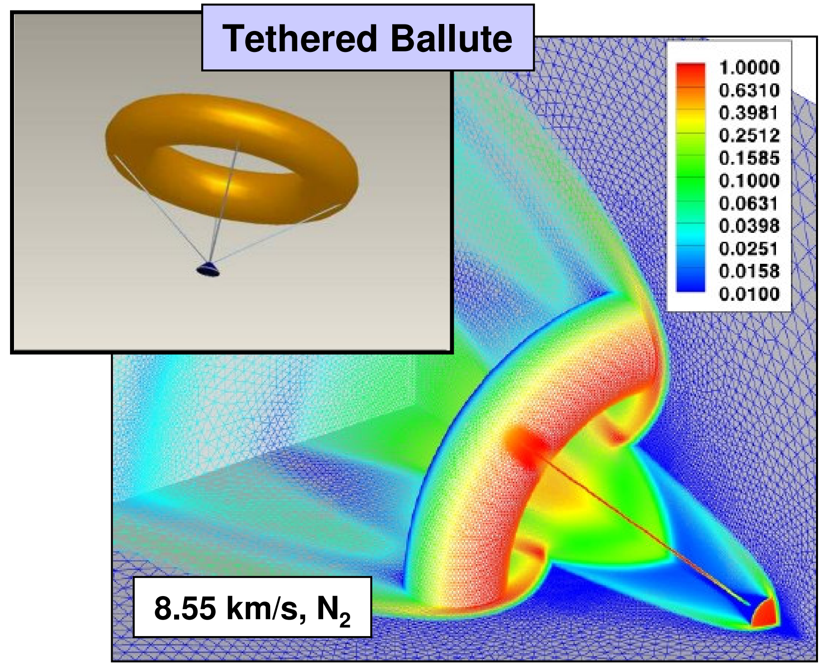
DLR-F6 WB:
Viscous mesh

High-Energy Flows

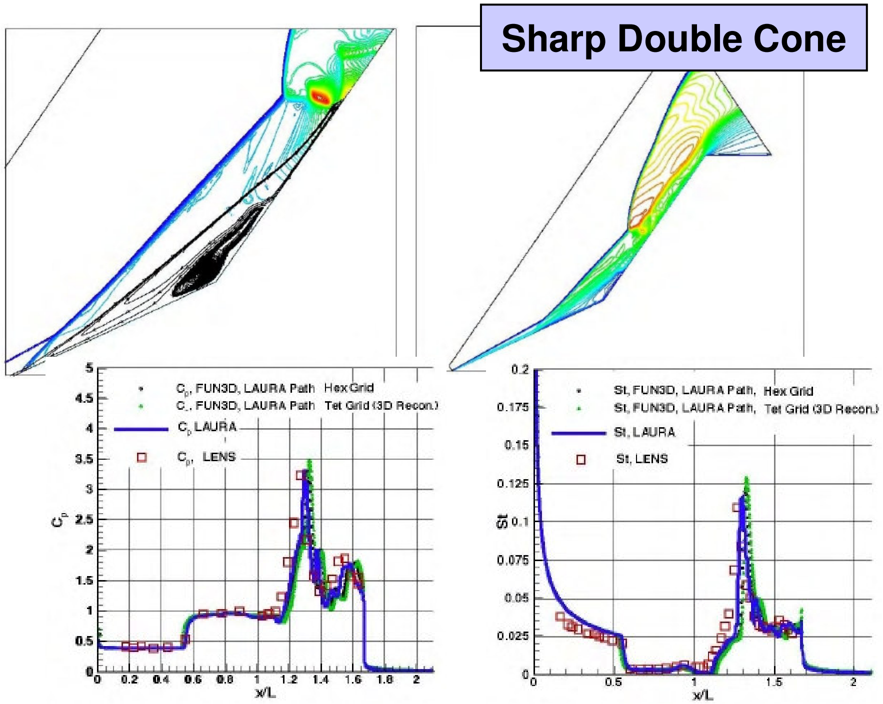
Shuttle



Tethered Ballute



Sharp Double Cone



- Predicting accurate heating on tetrahedral grids is extremely challenging – conventional schemes fail miserably
  - Can skirt issue by gridding with prismatic elements, but approach not general enough
- New multidimensional reconstruction approach (Gnoffo) very promising

Mesh Adaptation Research

- Feature-based or adjoint-based indicators
- Mesh adaptation mechanics fully parallelized
  - Coarsening and refinement, node movement and smoothing
  - Highly anisotropic with directional information from Mach Hessian
  - Dynamic load-balancing
  - Optional CAD interface via CAPrI
  - Body-fitted or cut-cell (Euler) discretizations
- Adapting highly anisotropic body-fitted grids near curved boundaries remains an Achilles heel
  - Options to “freeze” these regions
  - Hierarchical subdivision strategy being implemented

Adjoints for Error Estimation and Mesh Adaptation

It is apparent that:

$$\Lambda_f \equiv \frac{\partial f}{\partial \mathbf{R}}$$

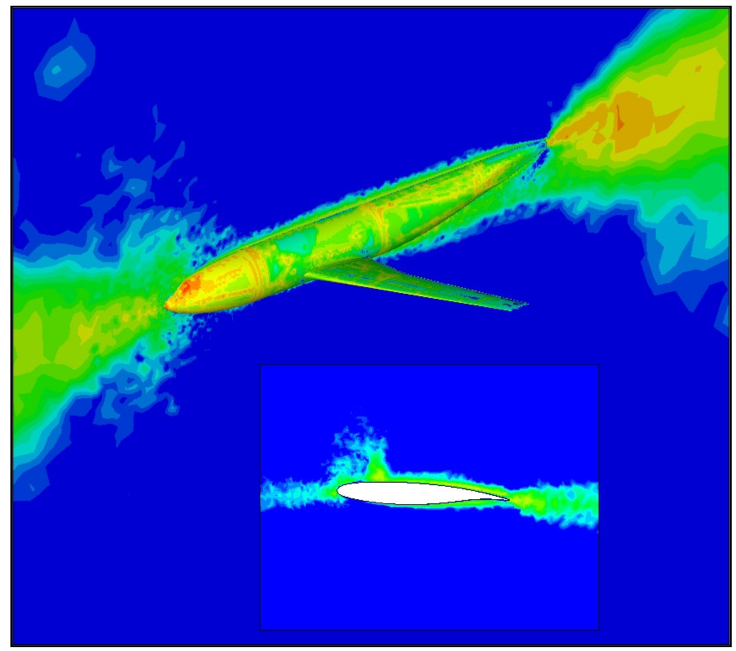
$\longrightarrow$ *Direct relationship between local equation error and the output we are interested in!*

- These relationships can be used to get error estimates on f
- Also used to compute a scalar field explicitly relating local point spacing requirements to output accuracy for a user-specified error tolerance
- Often yields non-intuitive insight into gridding requirements
- Relies on underlying mathematics to adapt, rather than heuristics such as solution gradients

User no longer required to be a CFD expert to get the right answer

Transonic Wing-Body:

"Where do I need to put grid points to get 10 drag counts of accuracy?"



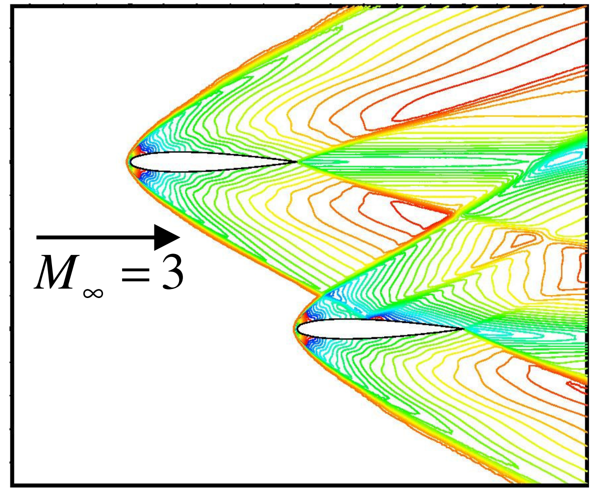
Blue=Sufficient Resolution
Red=Under-Resolved

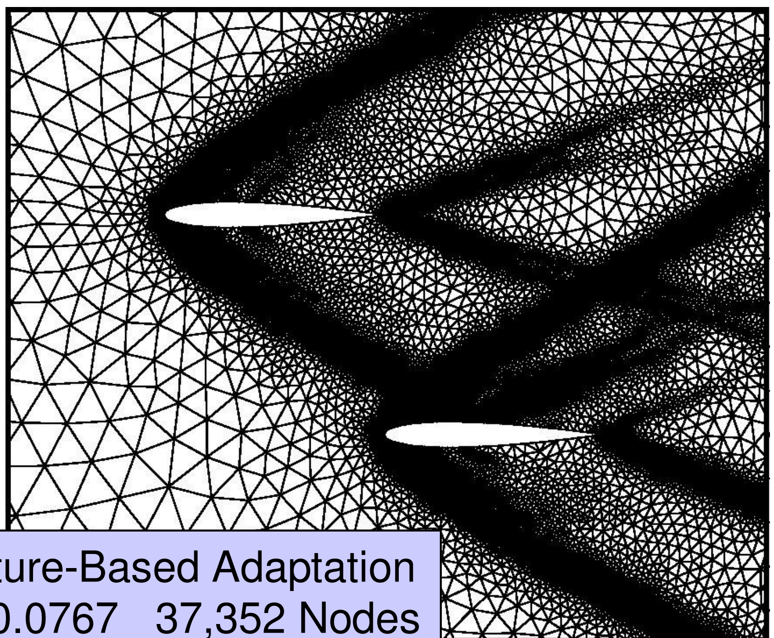
Supersonic Adjoint-Based Mesh Adaptation

Collaboration with Venditti/Darmofal of MIT using FUN2D

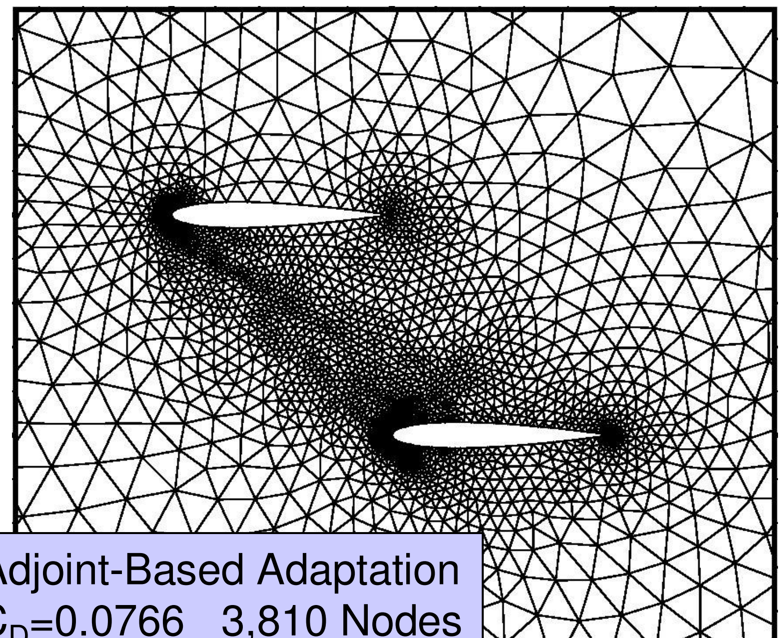
- **Objective:** Adapt grid to compute drag on lower airfoil as accurately as possible

- **Result of adjoint-based adaptation:**
  - Uniformly-resolved shocks are not required
  - Drag is computed accurately with a 90% smaller grid





Feature-Based Adaptation
C_D=0.0767   37,352 Nodes

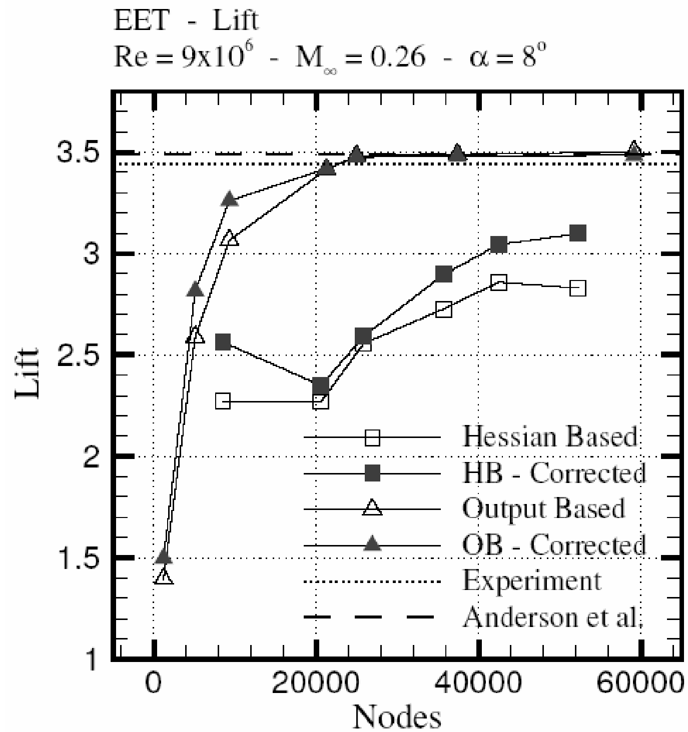


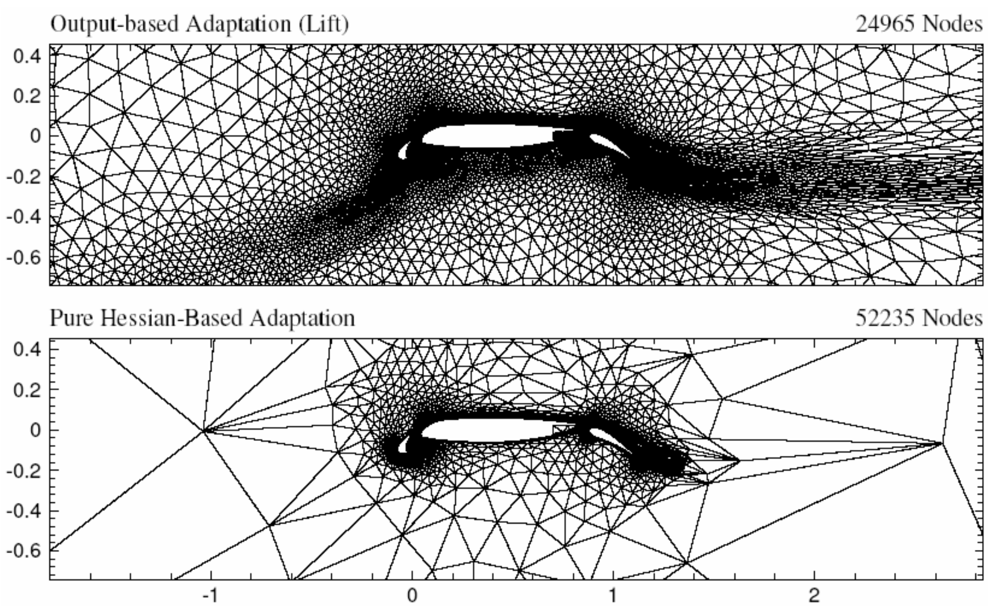
Adjoint-Based Adaptation
C_D=0.0766   3,810 Nodes

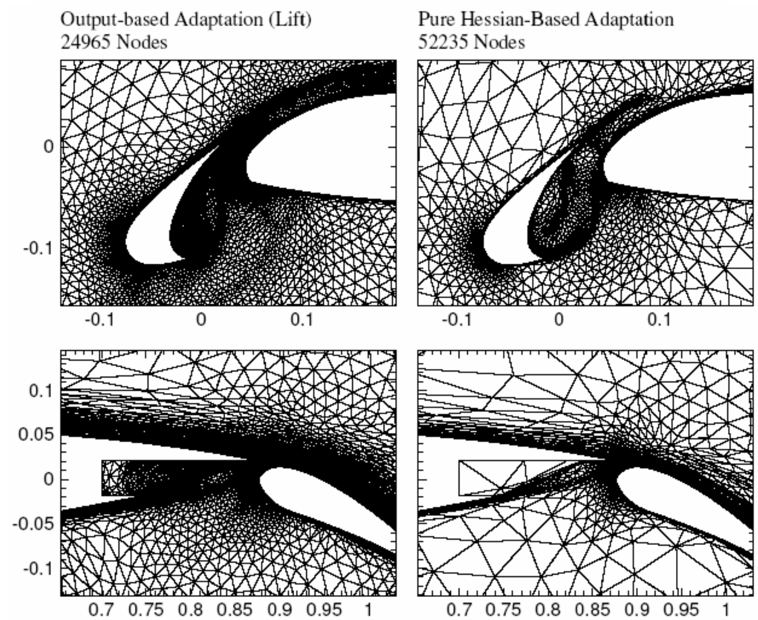
Adjoint-Based Mesh Adaptation for High Lift

Collaboration with Venditti/Darmofal of MIT using FUN2D

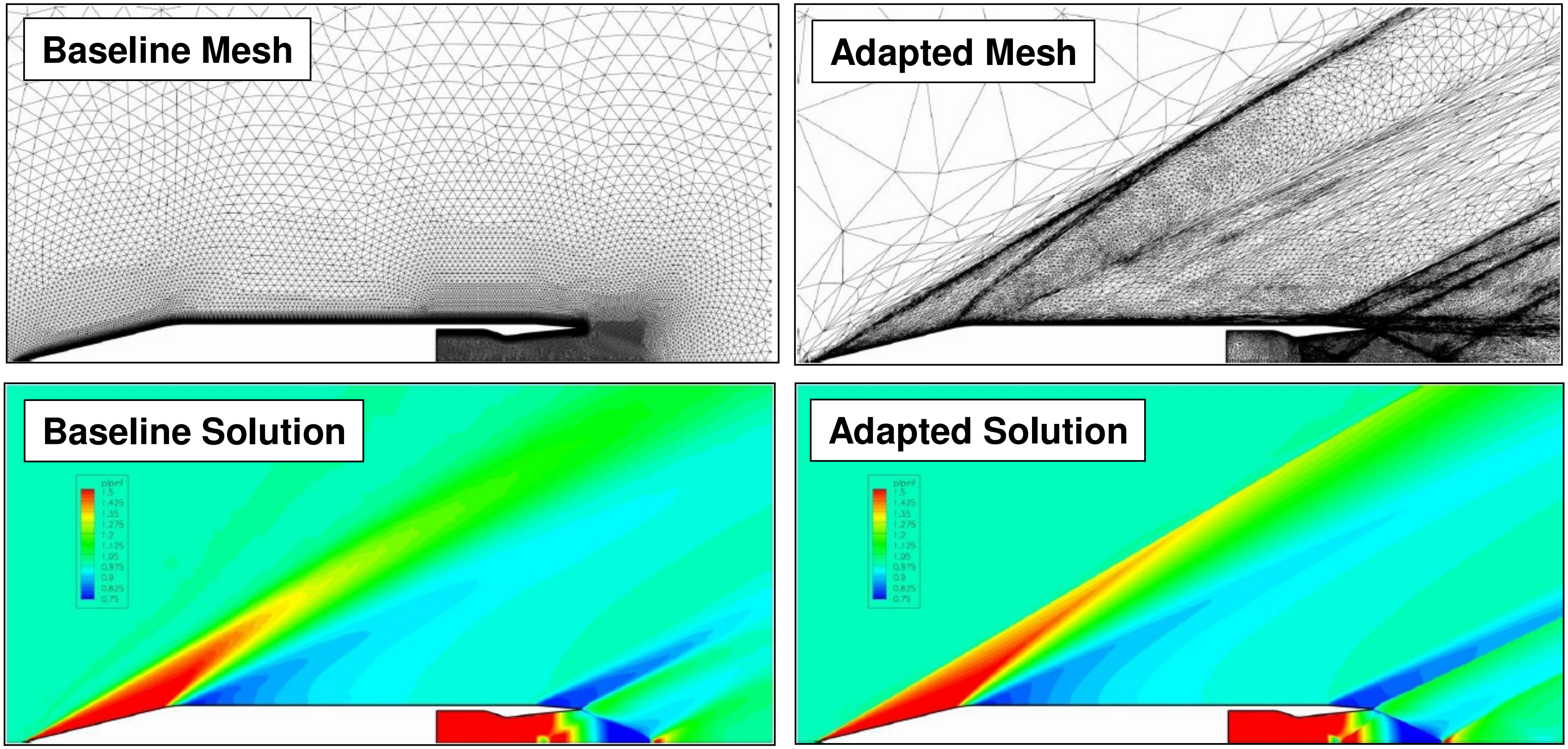
- Initial grid was coarse Euler mesh
- Pressure-based indicator only resolves strong flow curvature
- Adjoint-based indicator also includes important smooth regions, stagnation streamline and wakes





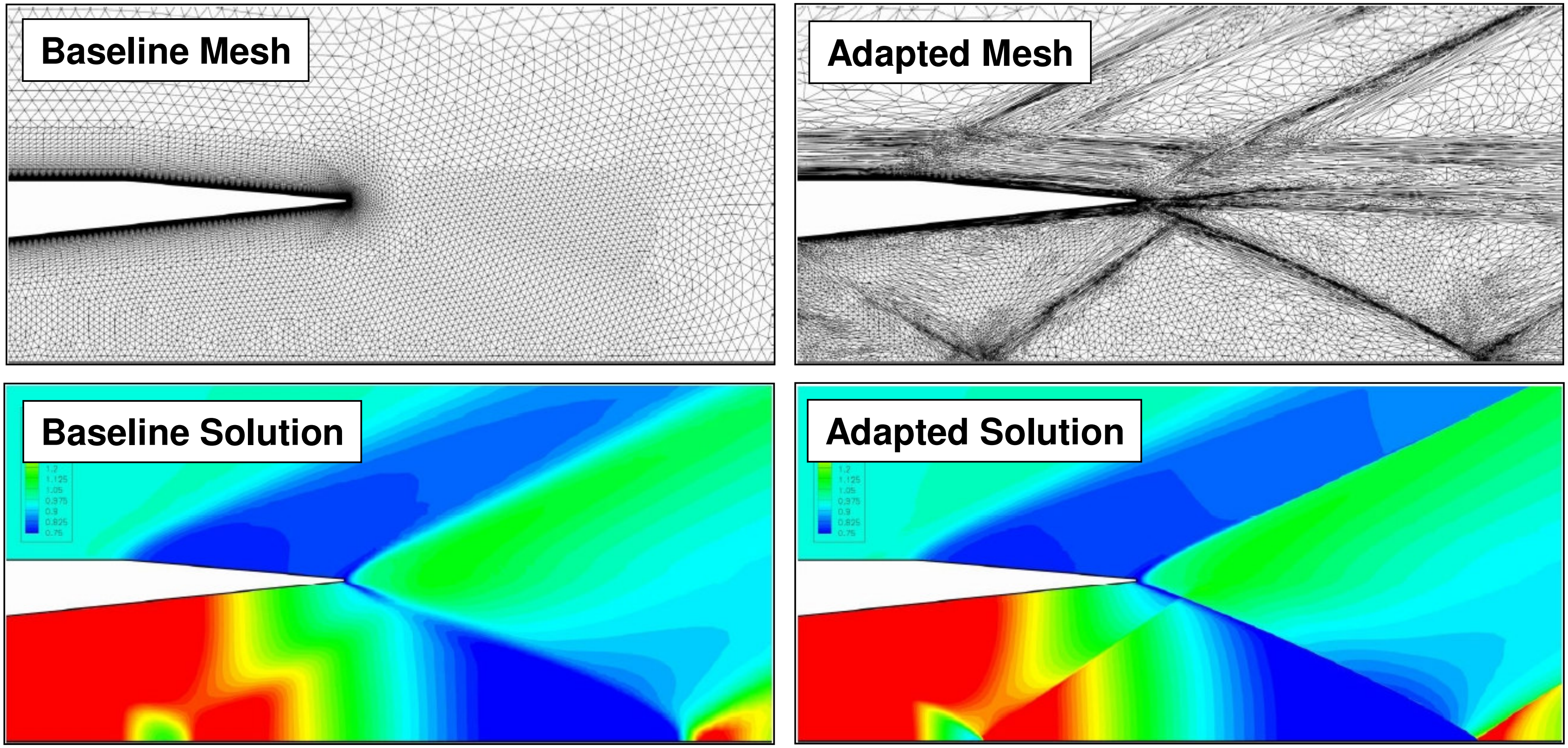


Mesh Adaptation for Jet Plume Flow



- Quarter of axisymmetric domain modeled; M_∞=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



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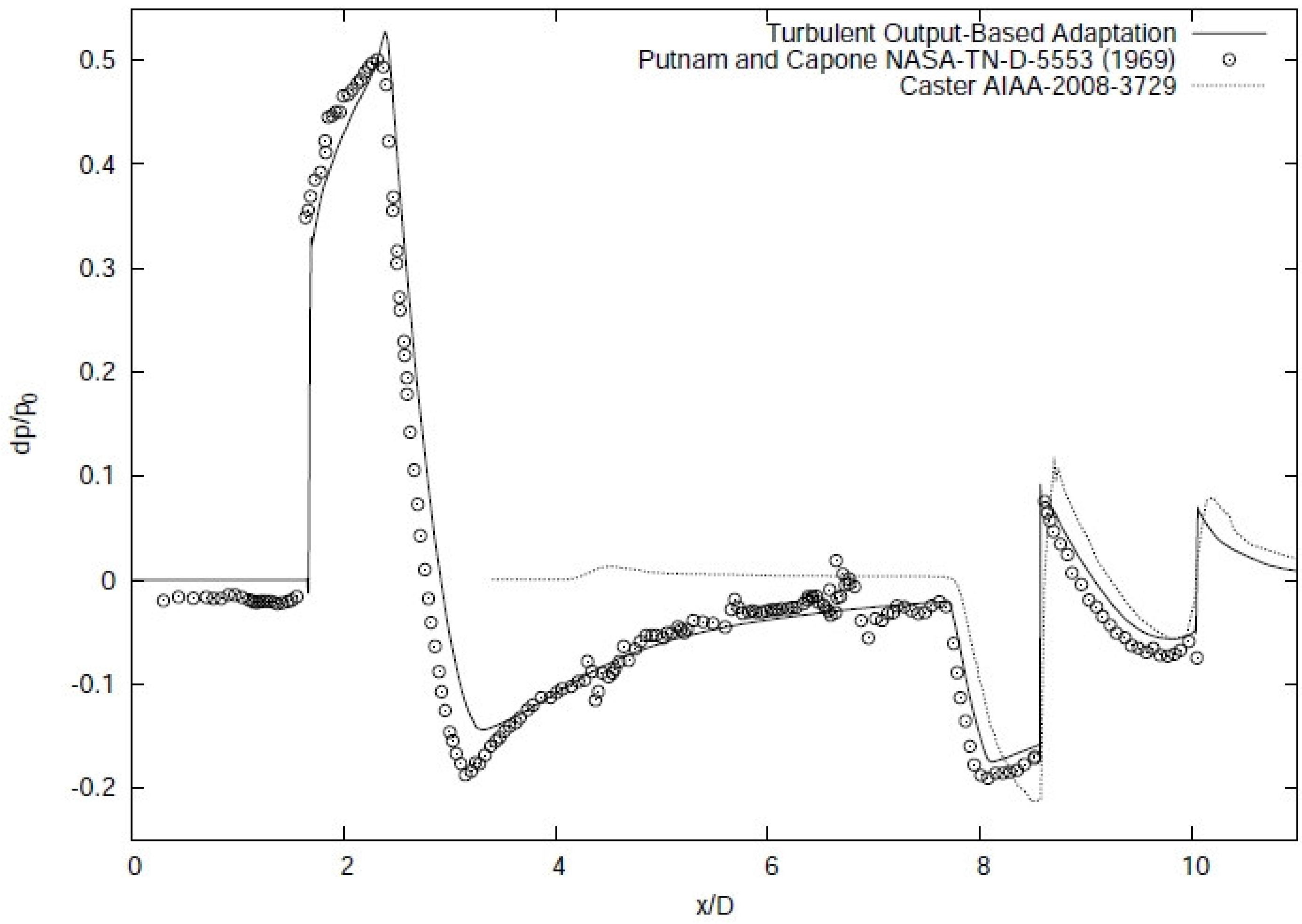
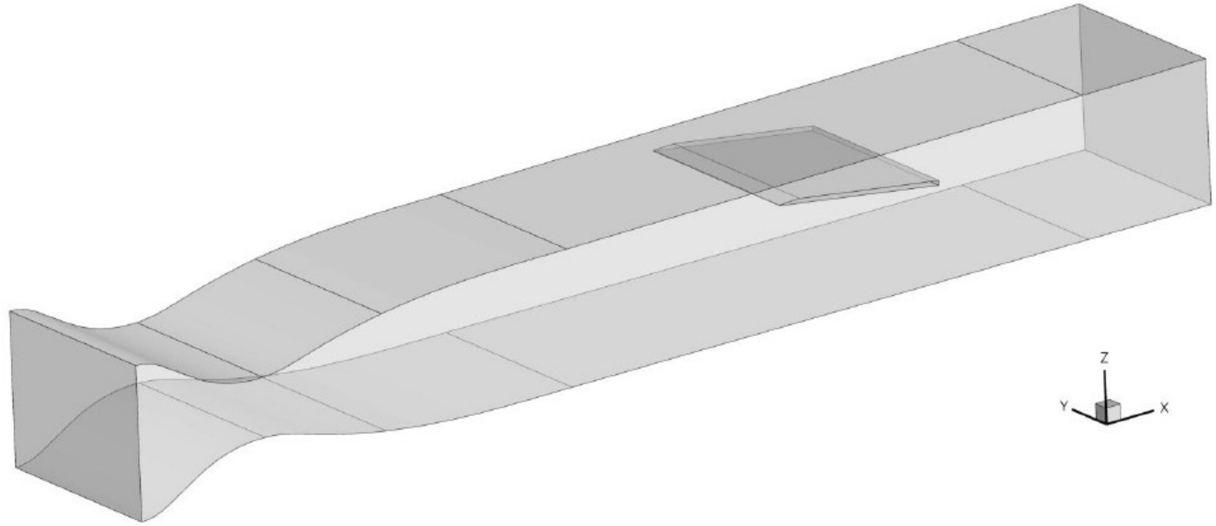
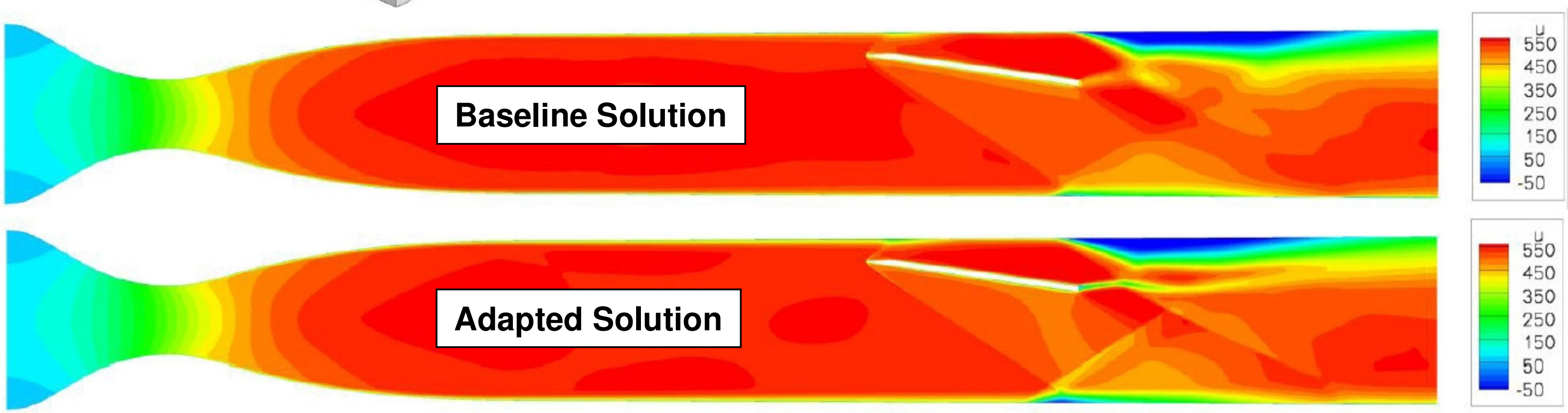


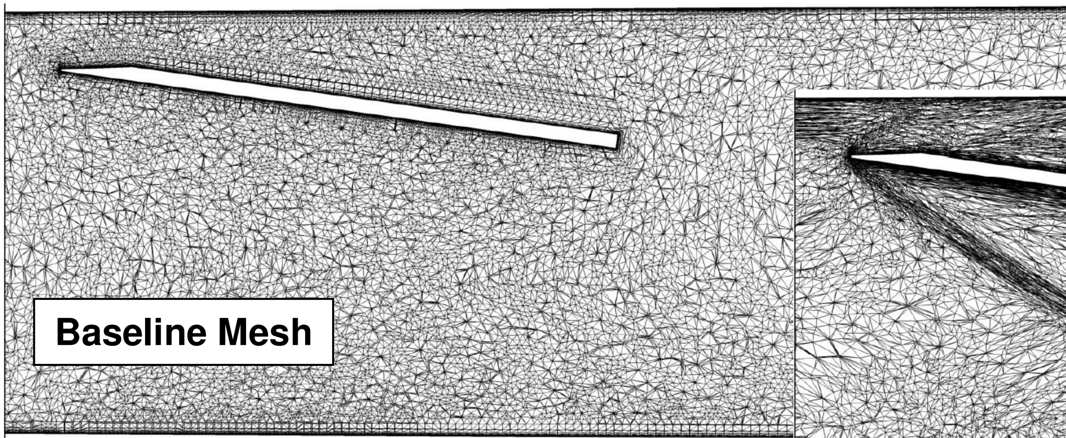
Mesh Adaptation for Shock-Boundary Layer Interaction

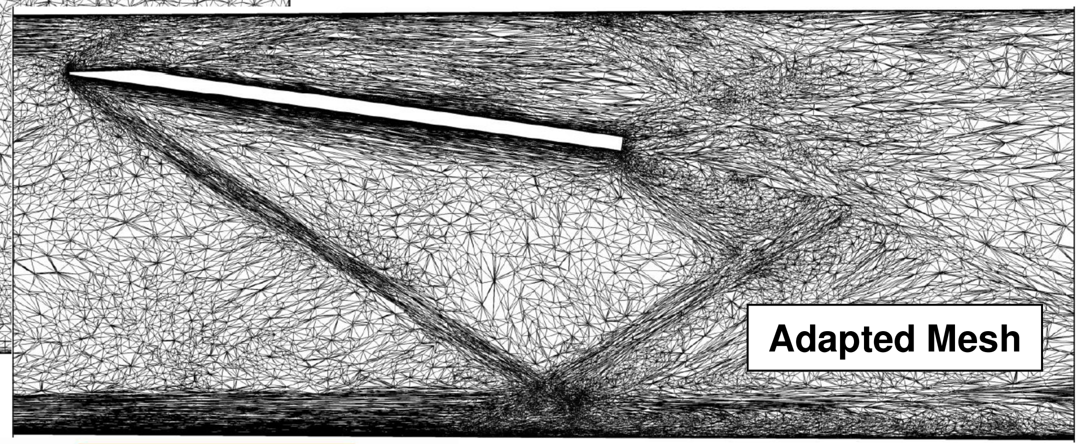


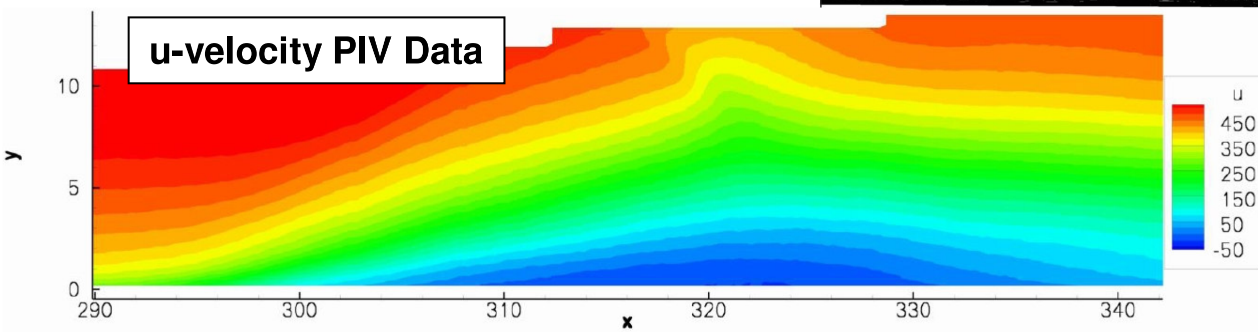


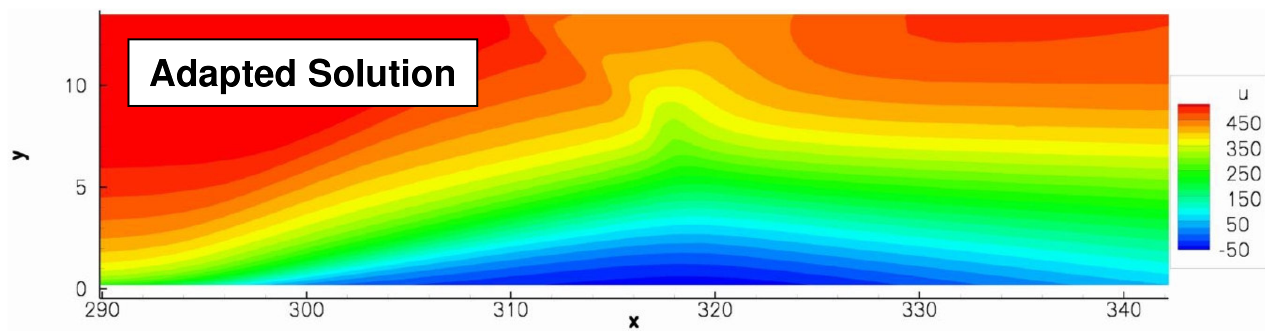
- Part of SBLI workshop at 2010 AIAA Orlando ASM conference
- M_∞=2.25, Re=5683/cm
- Adjoint objective function is drag on lower wall
- Mesh adapted from 0.7M nodes to 1.3M nodes

Mesh Adaptation for Shock-Boundary Layer Interaction









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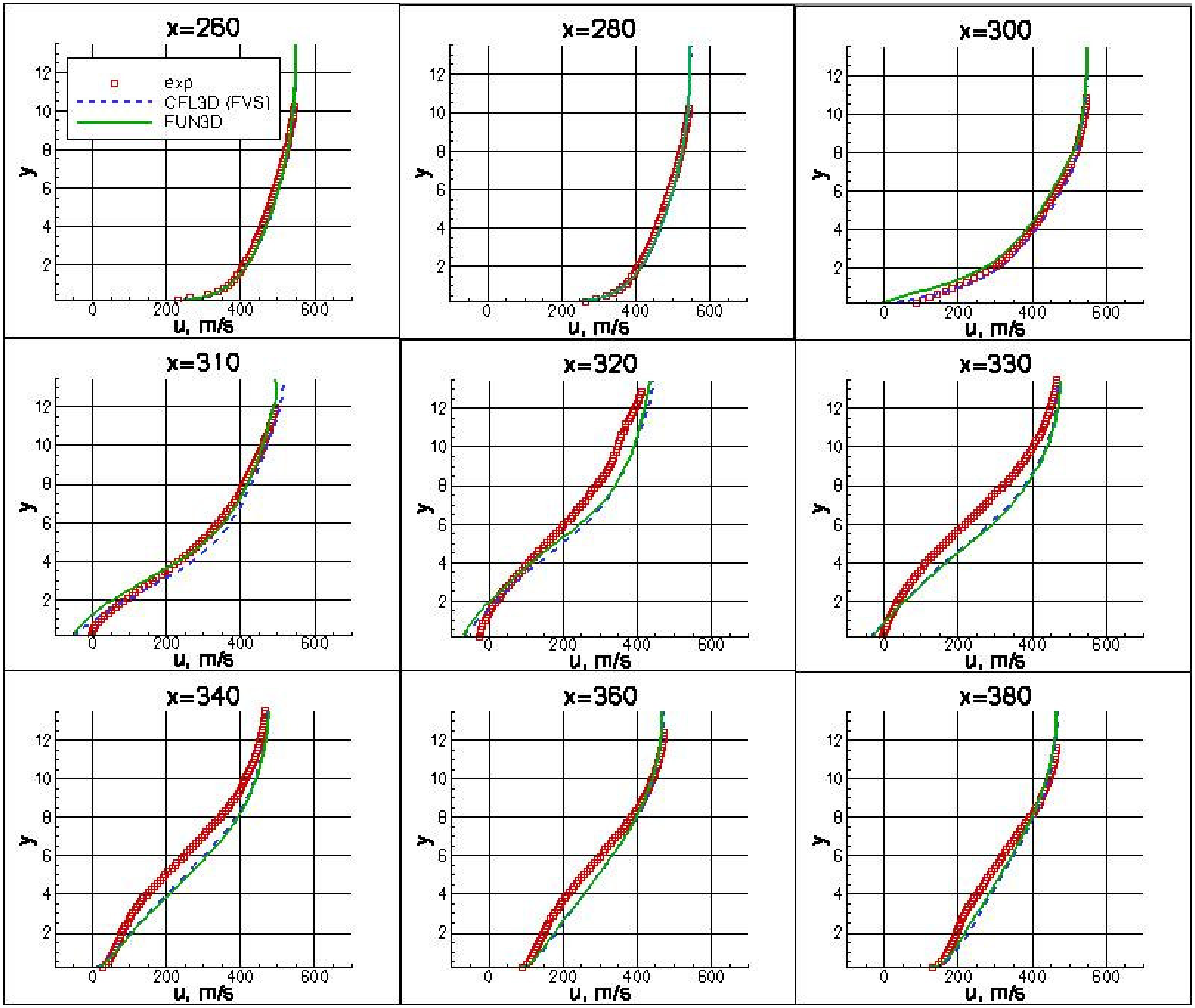
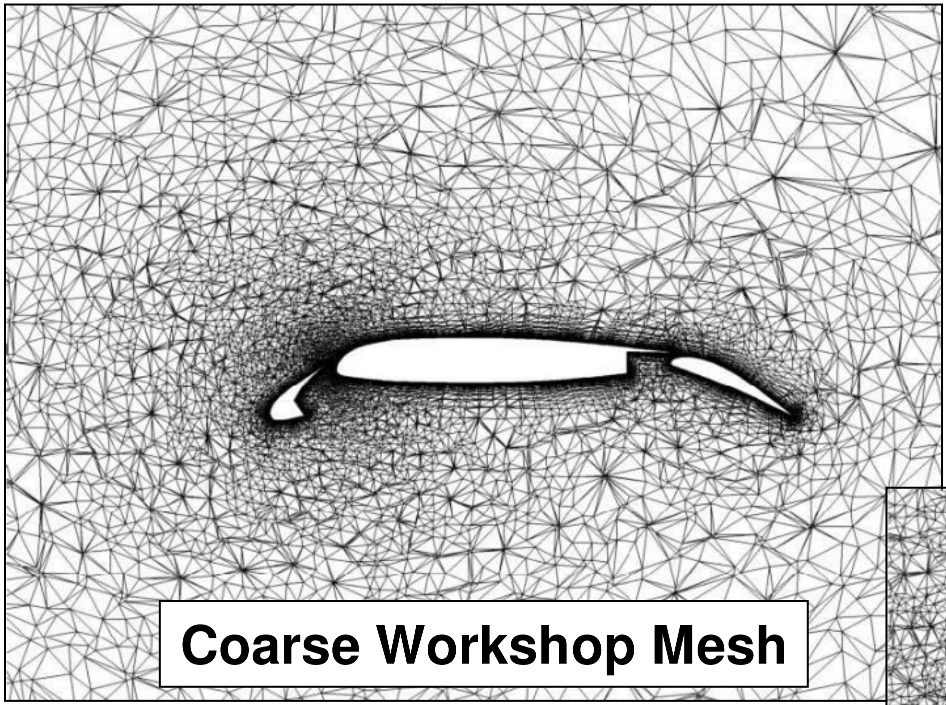
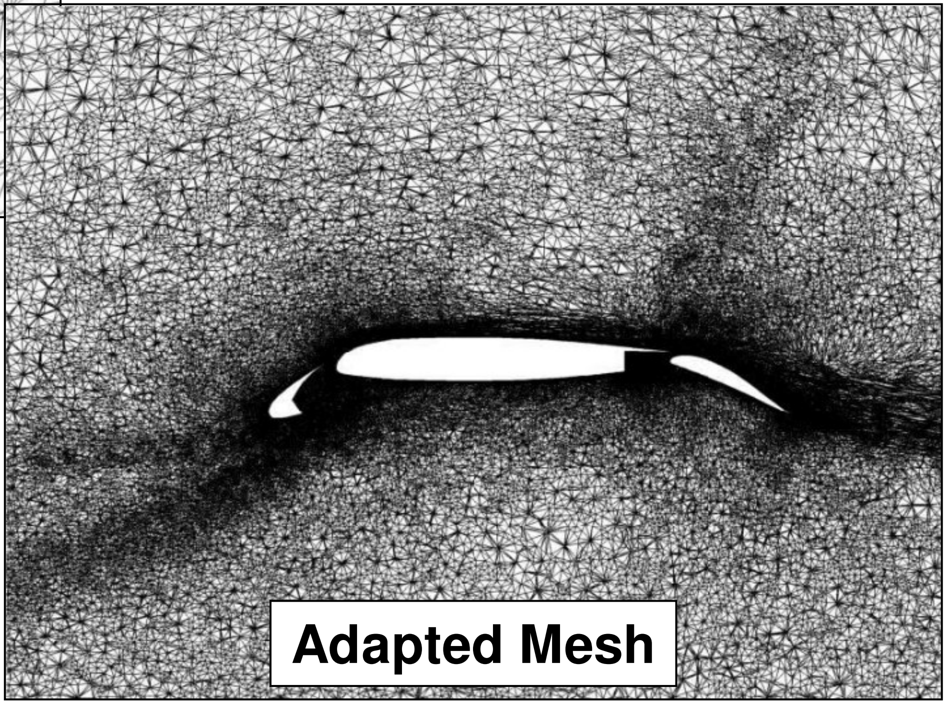


Mesh Adaptation for High-Lift Prediction Workshop

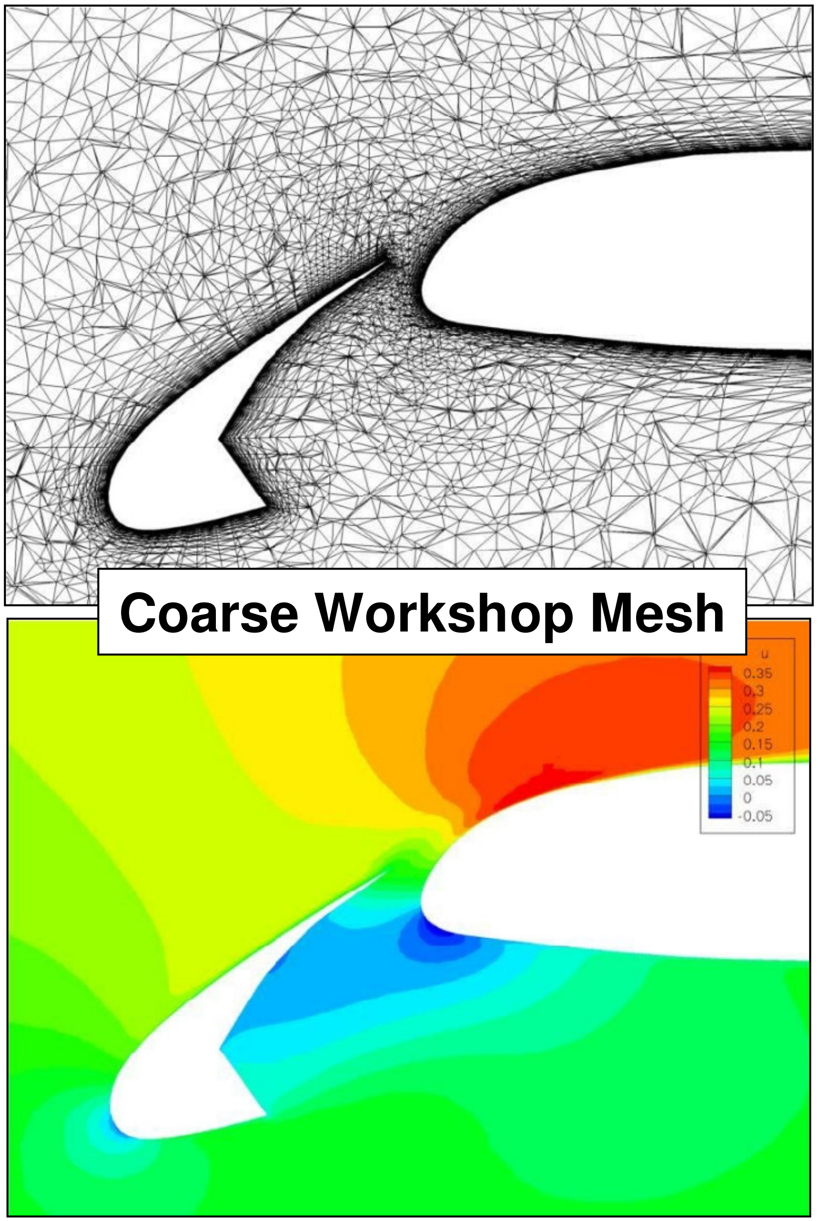
Held at Recent AIAA Summer Meeting in Chicago

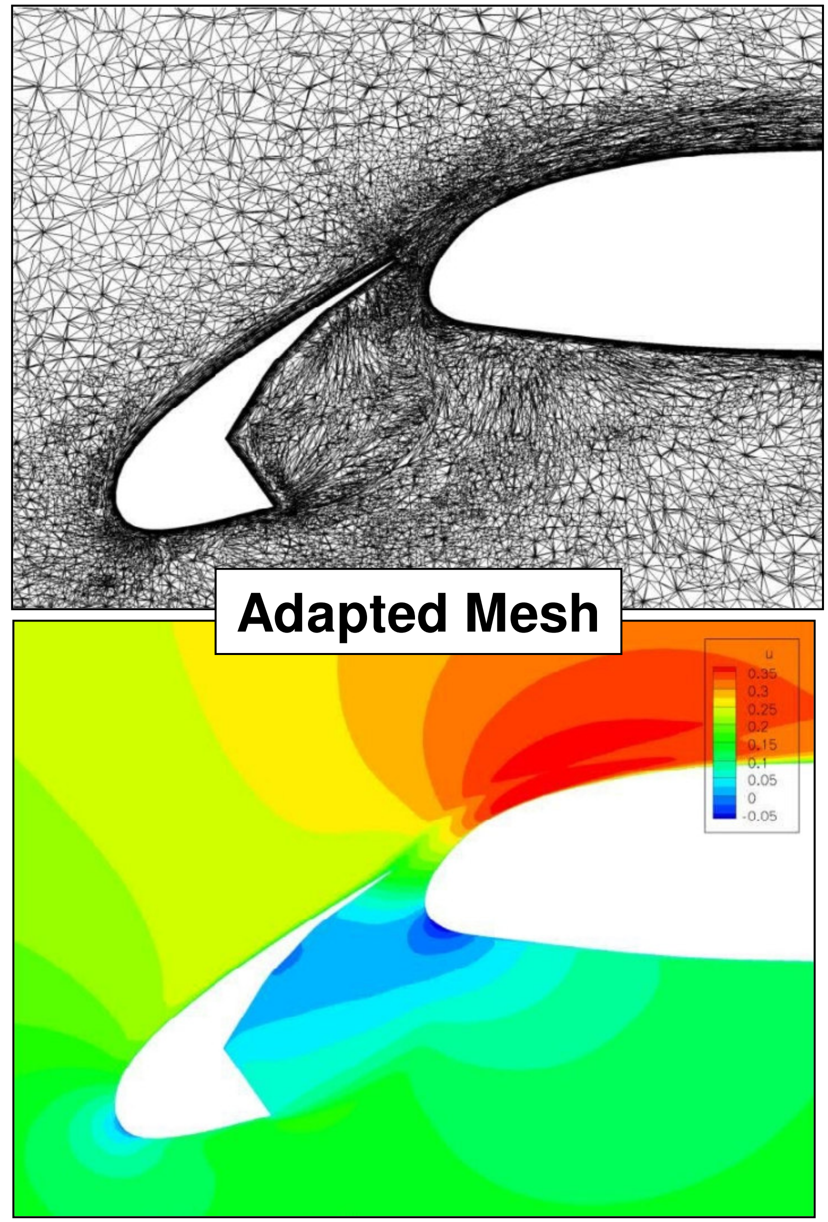
Mesh Adaptation for High-Lift Prediction Workshop





Mesh Adaptation for High-Lift Prediction Workshop





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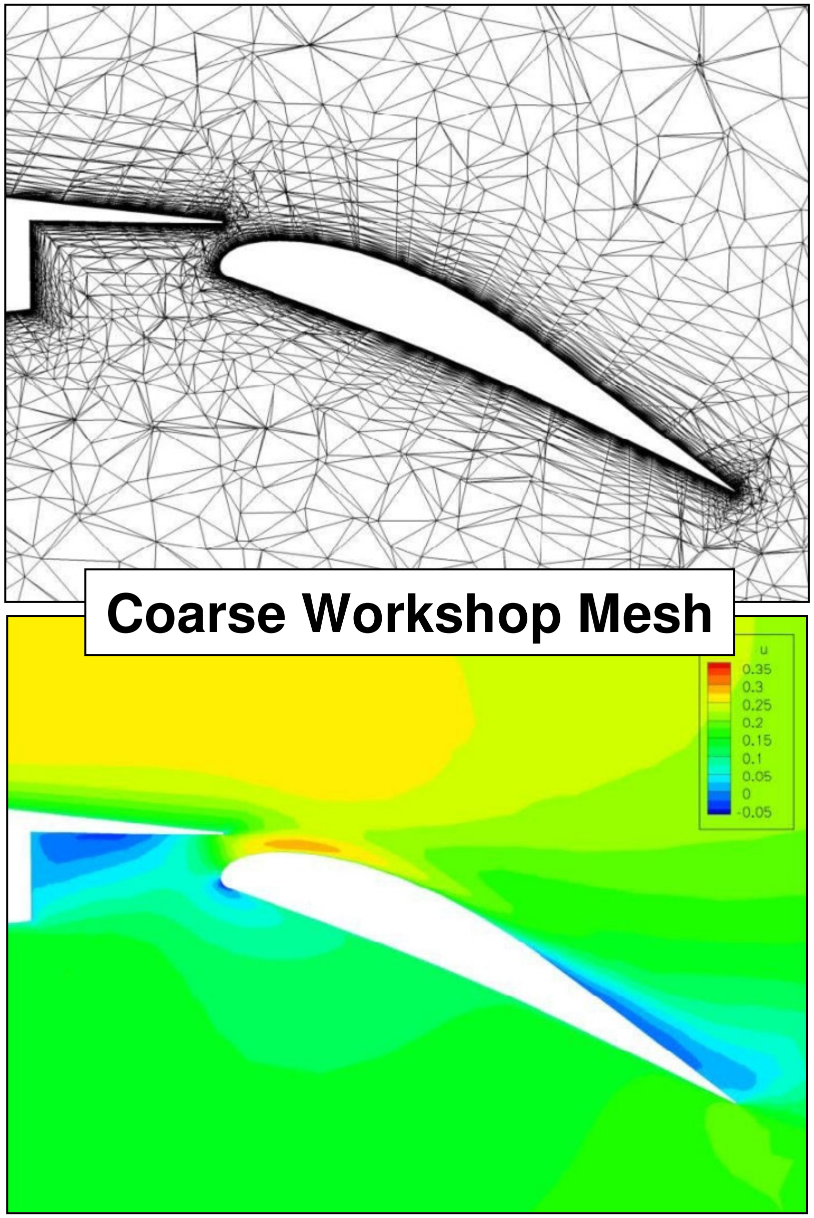

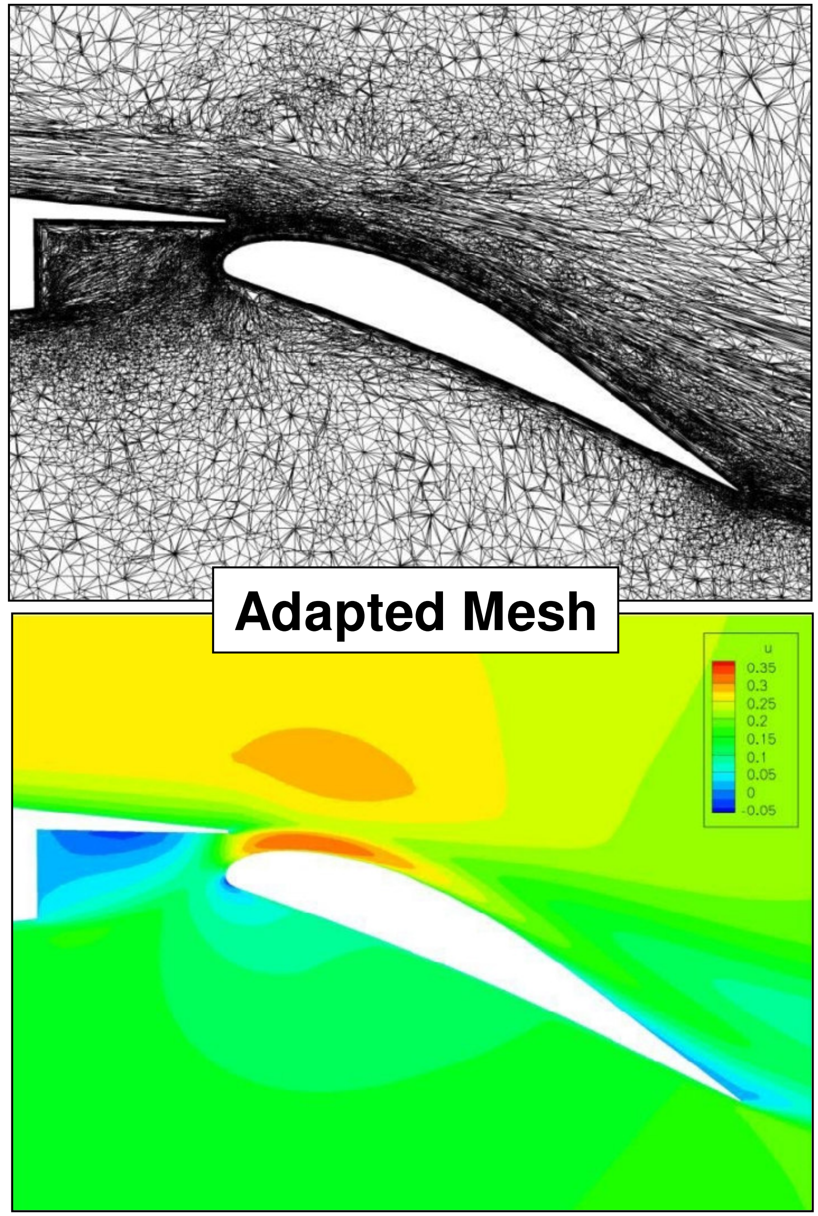

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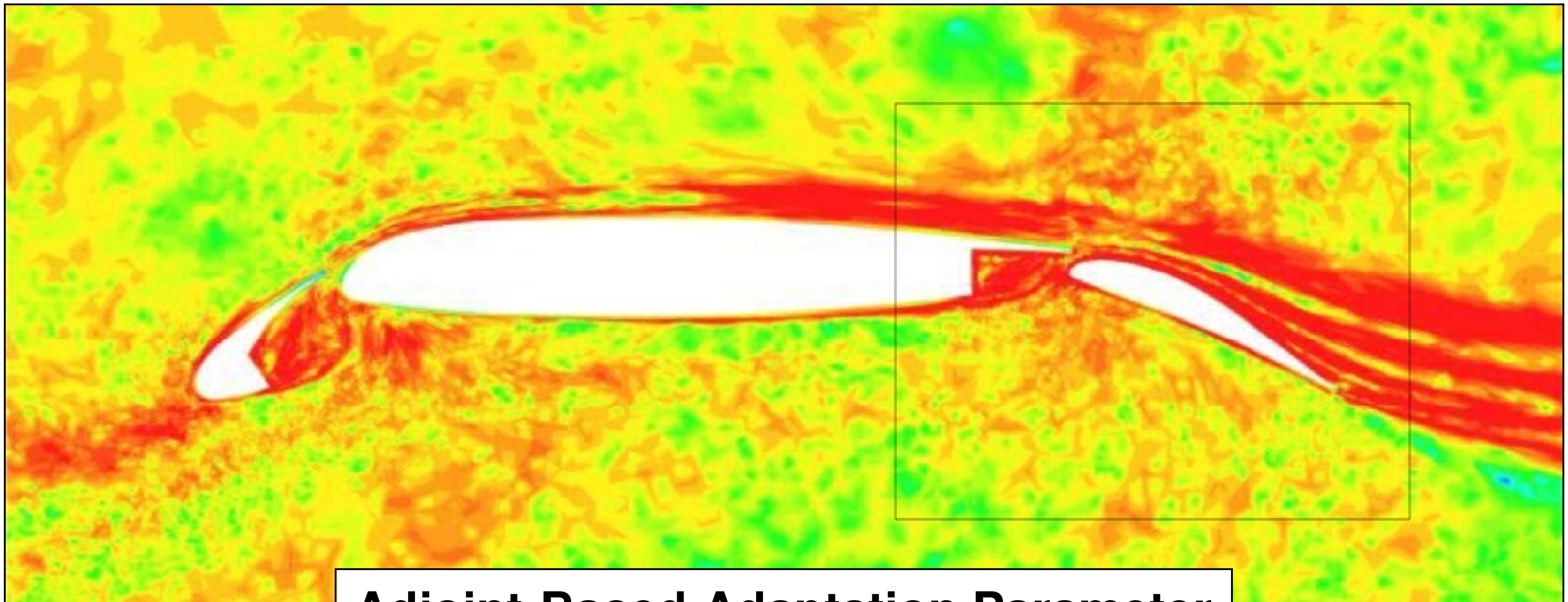
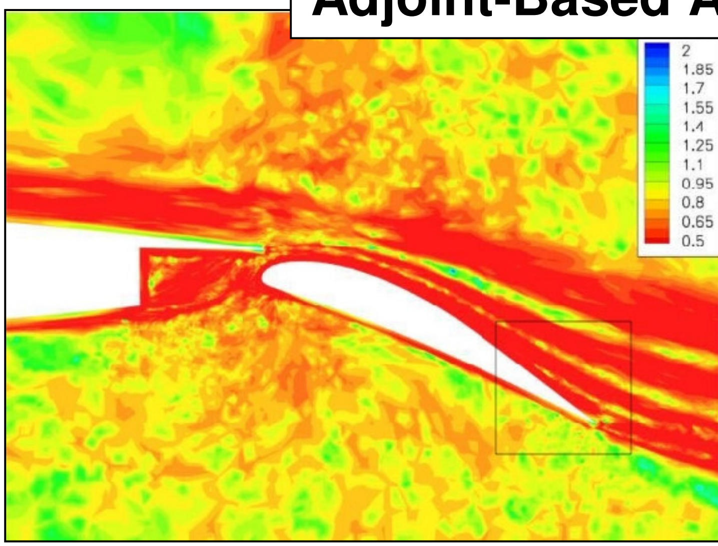
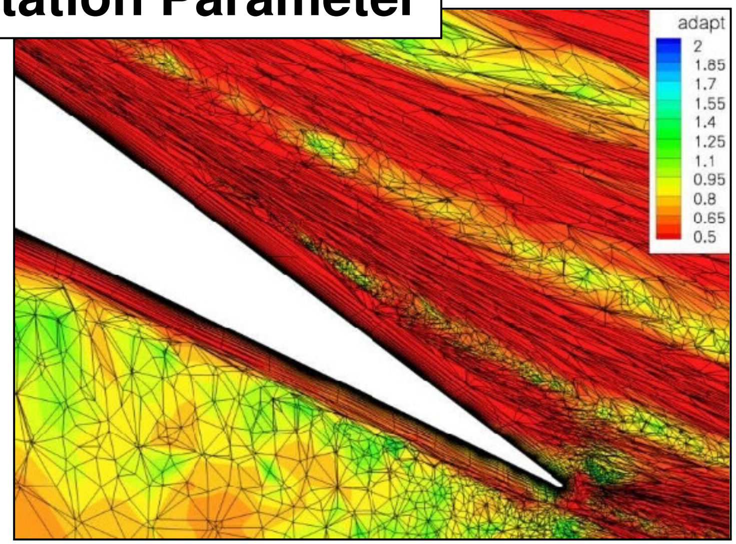


Adjoint-Based Adaptation Parameter





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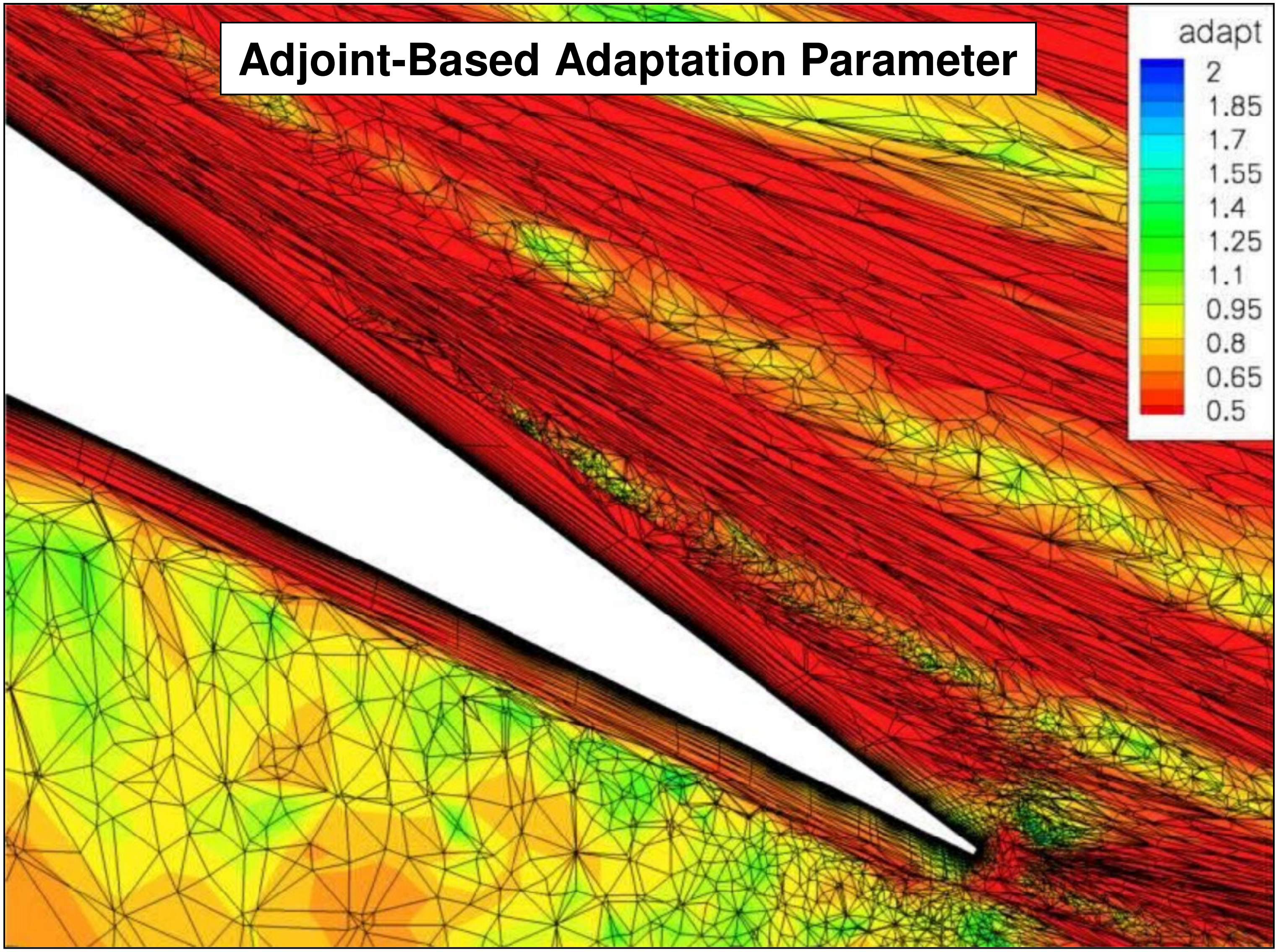
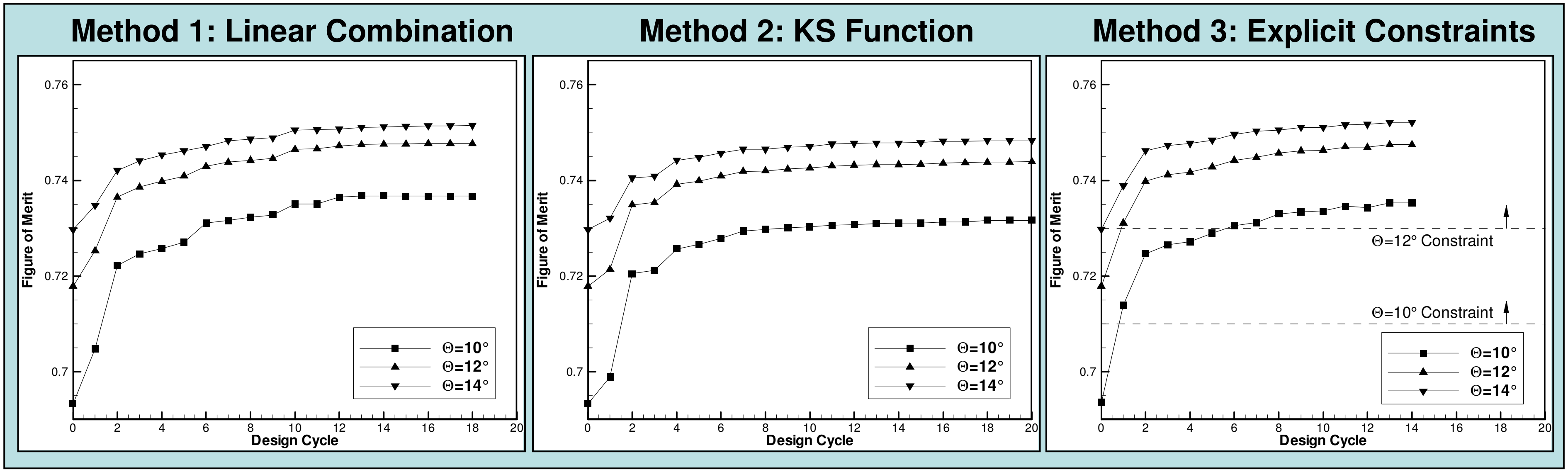
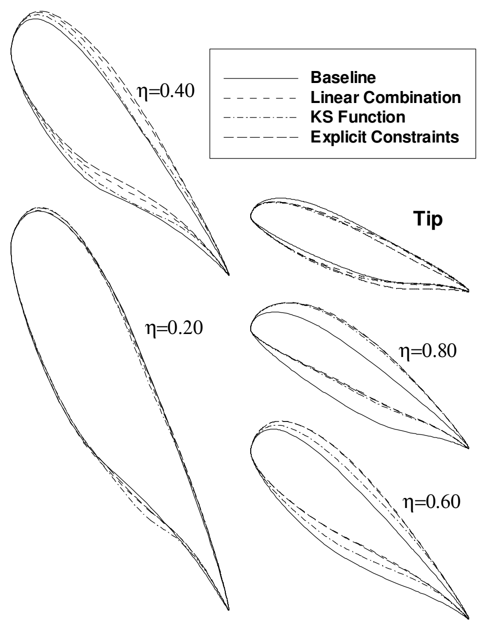
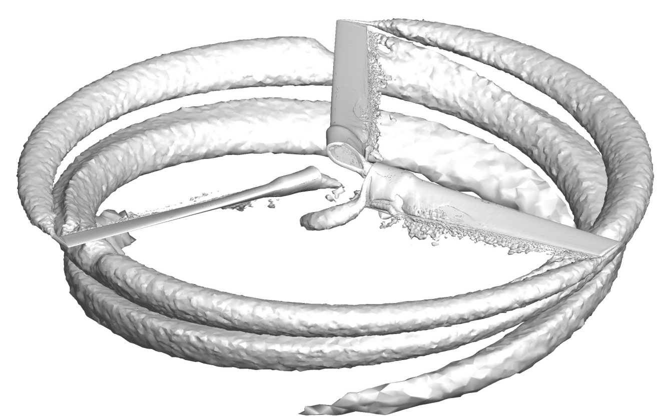


Adjoint-Based Design Optimization of Steady Flows



- Maximize rotorcraft Figure of Merit function for TRAM rotor in hover conditions (steady problem in noninertial frame)
- Multipoint optimization across 3 blade collective settings
- Each problem formulation yields roughly 6%, 4%, 3% improvement at each collective, but final geometries are very different



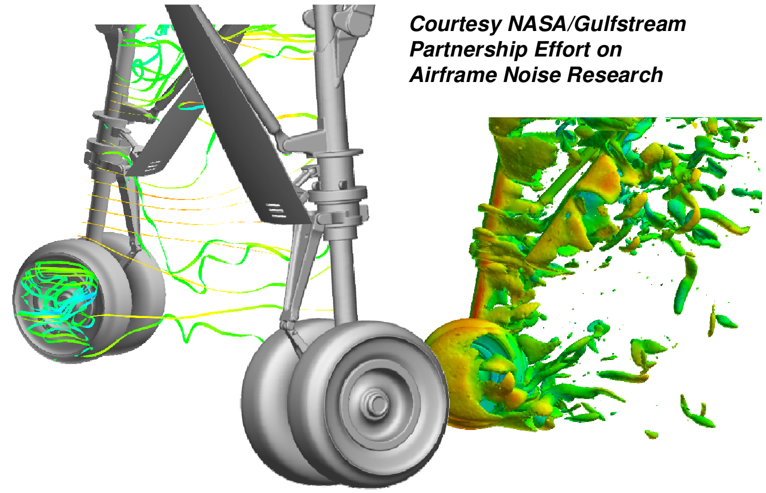


Isosurface of Q criterion for baseline Θ=14° case

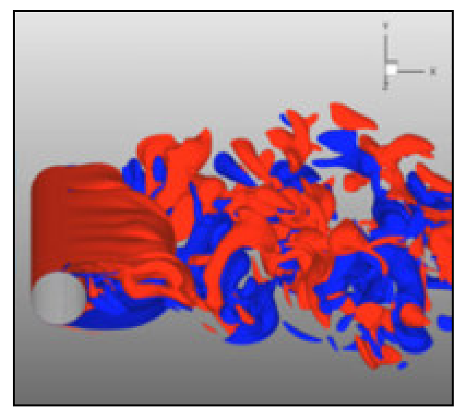
Adjoint Methods for Unsteady Flows

Goal: Develop and demonstrate an adjoint-based design capability for unsteady flows using the RANS equations on dynamic unstructured grids

- Adjoint methods provide very efficient and discretely consistent sensitivity analyses
- Long history of development/use in FUN3D for steady problems
- General unsteady formulation opens door to design of numerous configurations with unsteady features
  - Flow control devices
  - Aeroelastic problems
  - Maneuvering flight/6-DOF
  - Specified motion
  - Biologically-inspired: flapping wings, etc
- Enables mathematically rigorous mesh adaptation and error estimation to specified error bounds

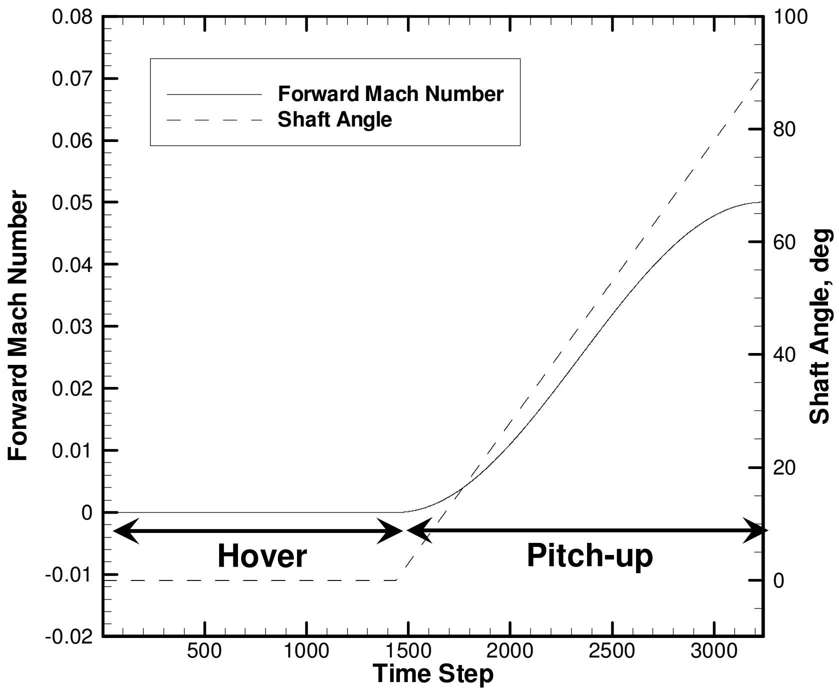


Courtesy NASA/Gulfstream Partnership Effort on Airframe Noise Research



Adjoint Methods for Unsteady Flows: Tiltrotor Example

- Geometry based on the three-blade Tilt Rotor Aeroacoustics Model (TRAM), similar to that used by the V-22
- Grid designed for Θ=14° blade collective setting; contains 5,048,727 nodes and 29,802,252 tetrahedral elements
- Rotational speed held constant such that $M_{tip}=0.62$ in hover, $Re_{tip}=2.1$ million
- Δt chosen according to 1° of rotor azimuth for 360 steps/rev
- $BDF2_{opt}$ used with 10 subiterations
- Rigid grid motion: 4 revs to quasi-steady hover condition, followed by 90° pitch-up maneuver with prescribed forward velocity over 5 additional revs

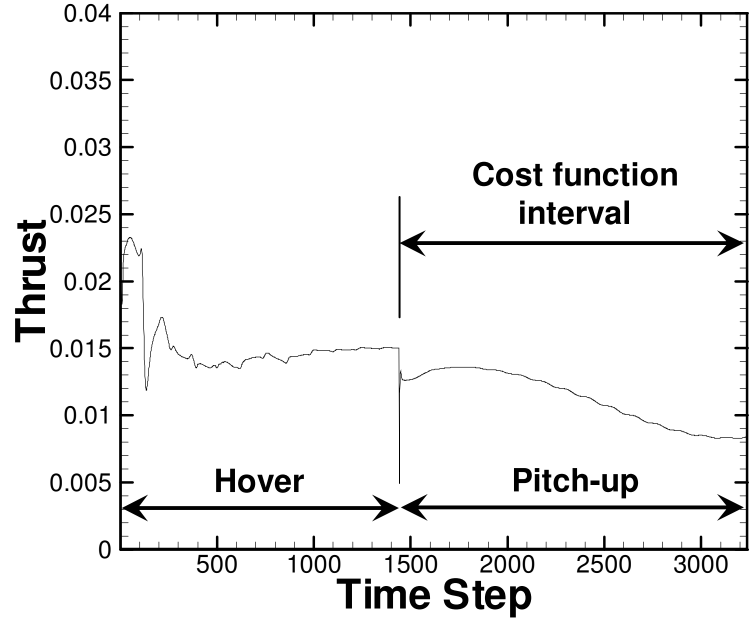


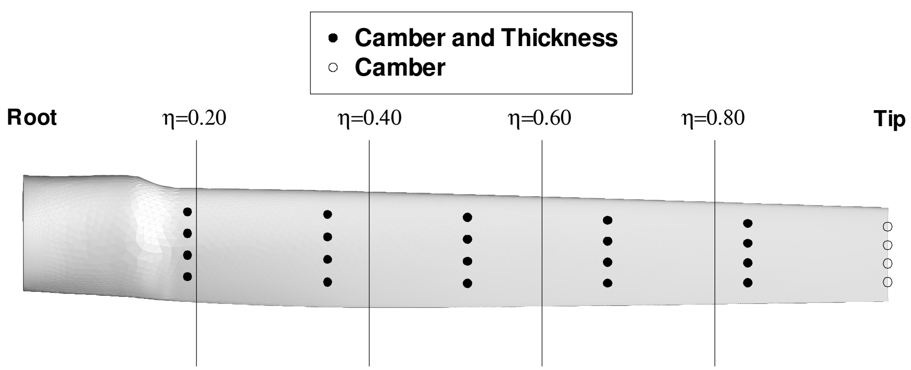
Adjoint Methods for Unsteady Flows: Tiltrotor Example

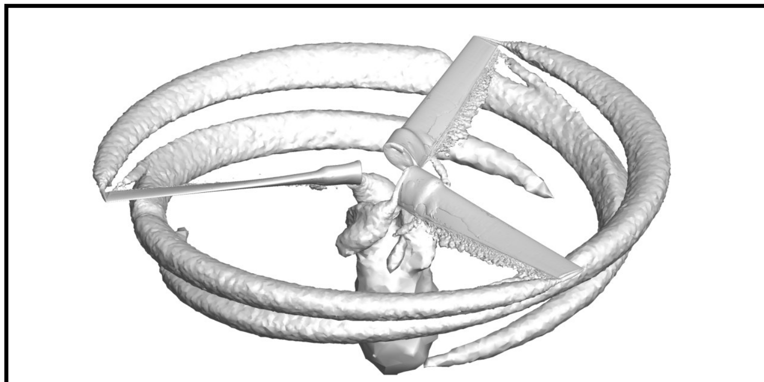
- Objective function is to maximize the thrust coefficient over the pitch-up maneuver:

$$f = \sum_{n=1441}^{3240} (C_T^n - 0.1)^2 \Delta t$$

- Blades parameterized as shown, no thinning allowed
- Blade twist also used to set the collective angle
- Total of 45 active design variables



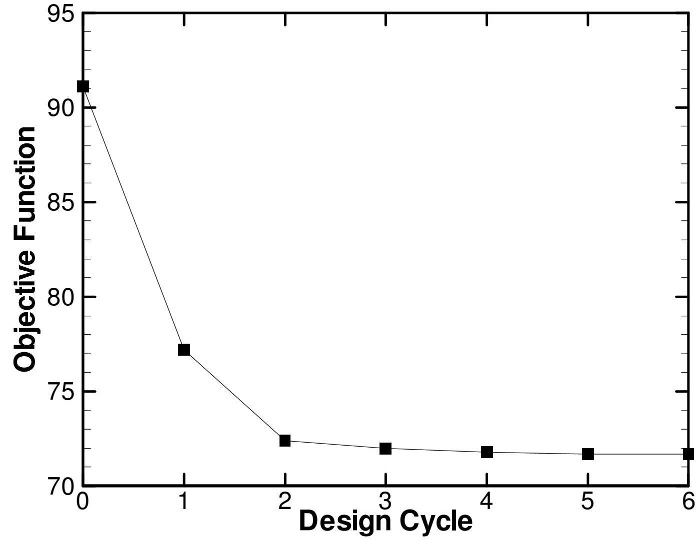


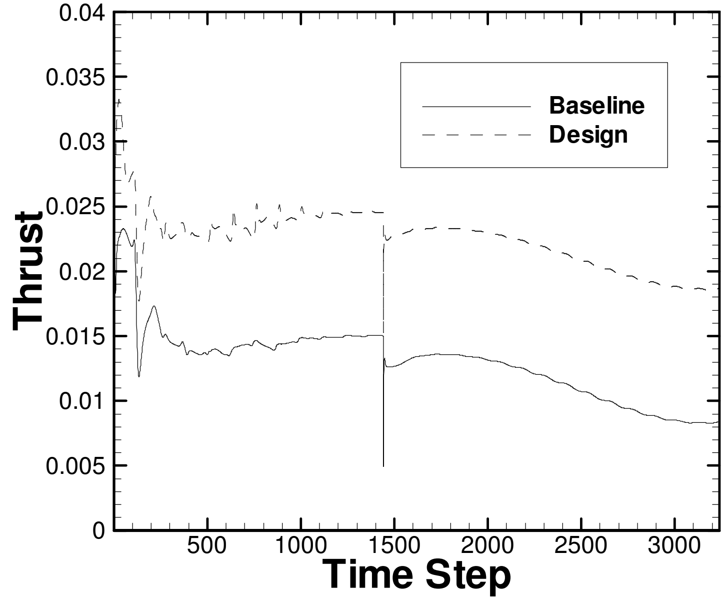


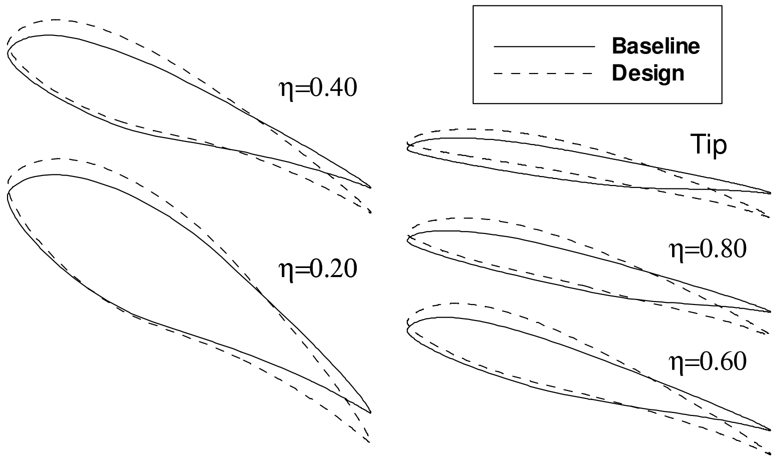
Isosurface of Q criterion after 4 revs

Adjoint Methods for Unsteady Flows: Tiltrotor Example

- Rapid reduction in cost function over first two design cycles; further improvements minimal
- Camber, collective angle have been increased across the blade; many variables have reached their bounds
- Single flow solution takes ~3.5 hours
- Single adjoint solution takes ~10.5 hours; varies w/ file system load due to heavy I/O
- Optimization requires 12 flow solutions and 6 adjoint solutions for total runtime of 4.5 days on 1024 cores or 110,000 CPU hours
- Disk storage for single unsteady flow solution is 1.5 terabytes

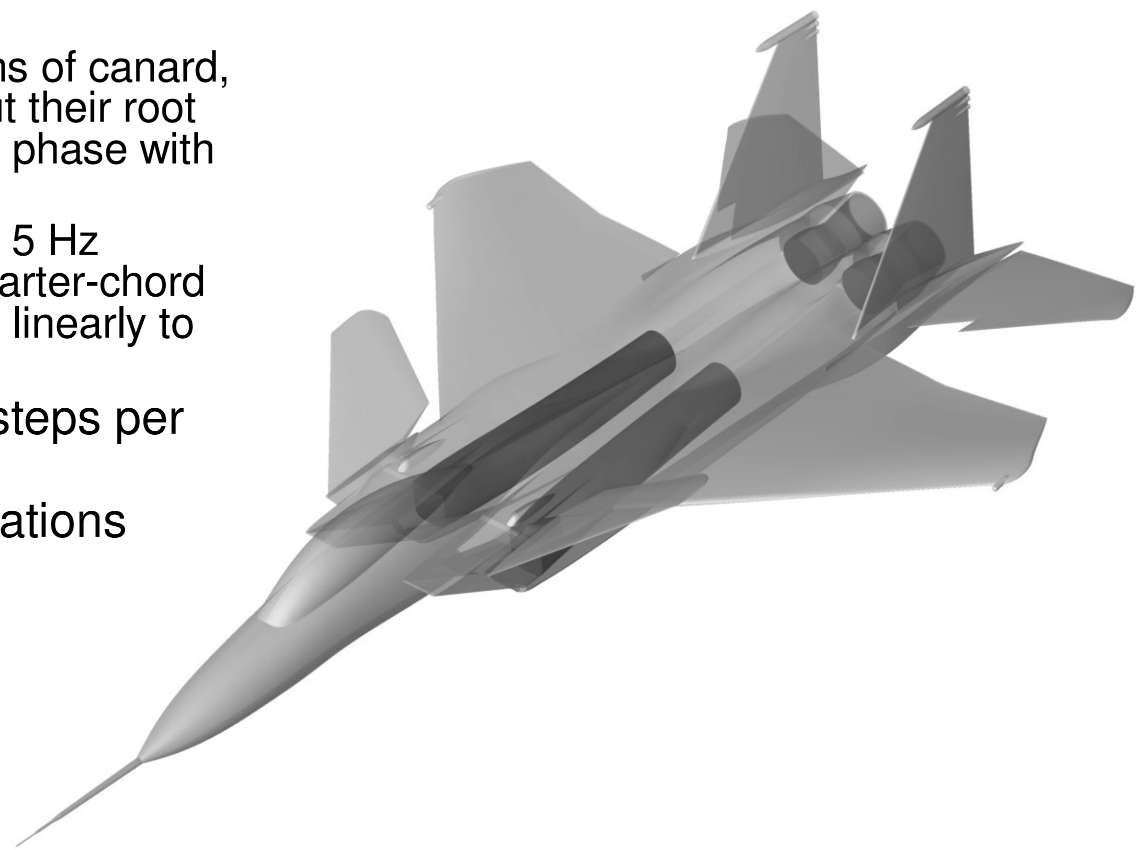






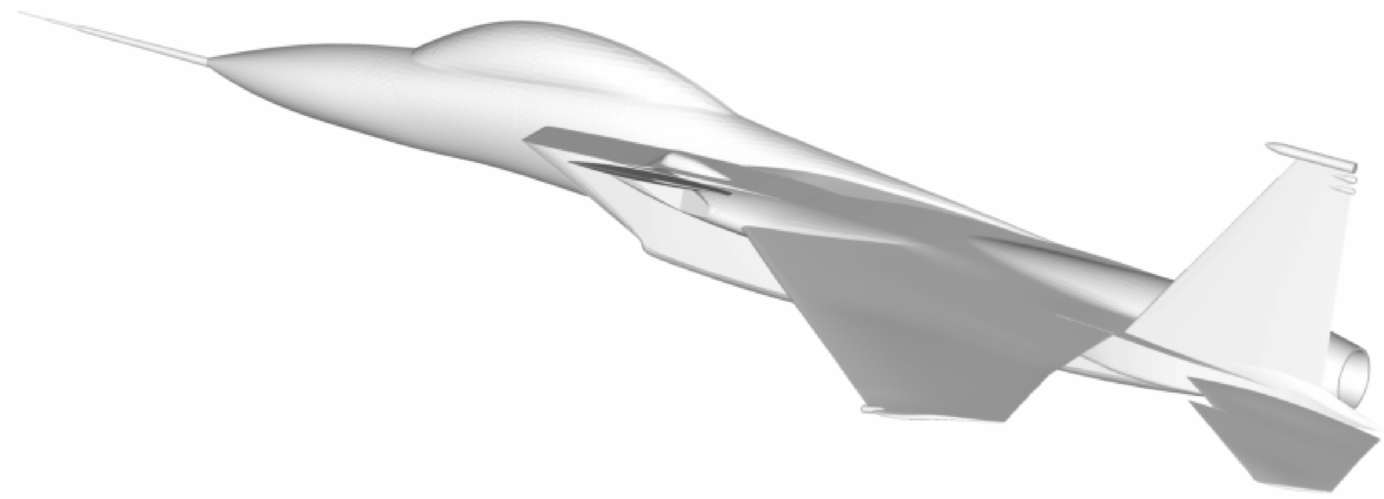
Adjoint Methods for Unsteady Flows: Fighter Jet Example

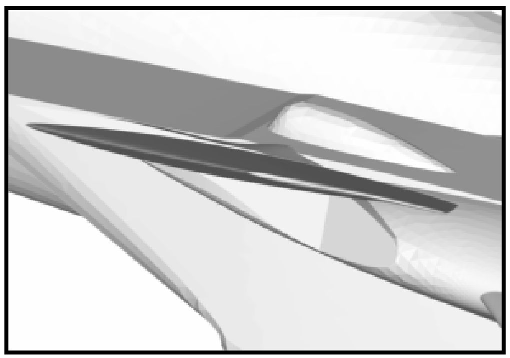
- Geometry based on a modified F-15 configuration with canards
- Grid consists of 4,715,852 nodes and 27,344,343 tetrahedral elements; half-plane symmetry assumed
- Model includes details of the external airframe as well as internal ducting upstream of engine fan face and plenum/nozzle downstream of turbine
- M_∞=0.90, α=0°, Re_{MAC}=1 million; p/p_∞=0.9 at fan face; $p_t/p_{t\infty}$=5.0 at plenum
- Deforming grid motion:
  - 5 Hz 0.3° oscillatory rotations of canard, wing, and tail surfaces about their root chordlines; wing 180° out of phase with canard and tail
  - Main wing also subjected to 5 Hz oscillatory twisting about quarter-chord line: 0.5° at the tip decaying linearly to 0° at the root
- Δt chosen according to 100 steps per cycle of grid motion
- $BDF2_{opt}$ used with 10 subiterations



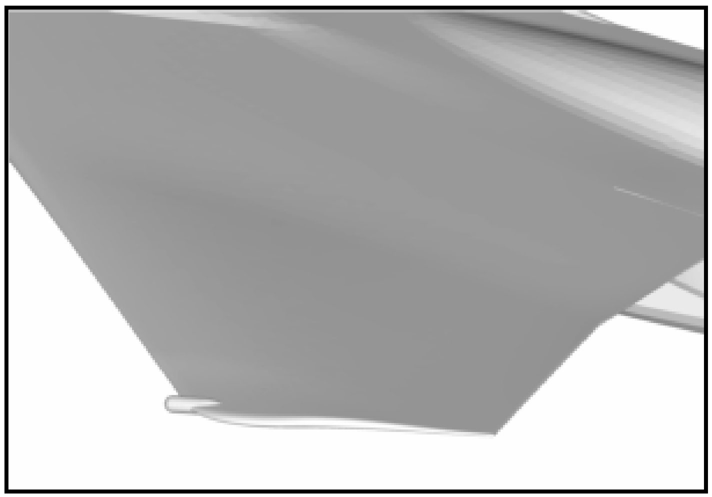
Adjoint Methods for Unsteady Flows: Fighter Jet Example

Prescribed Surface Deformations

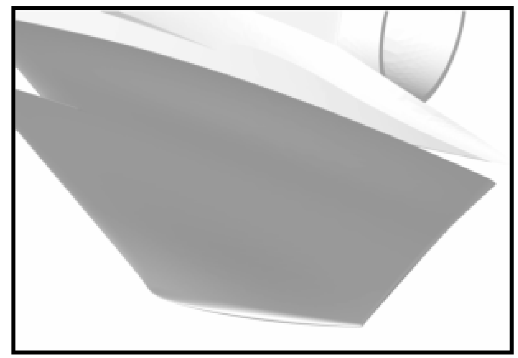




Canard Surface



Main Wing



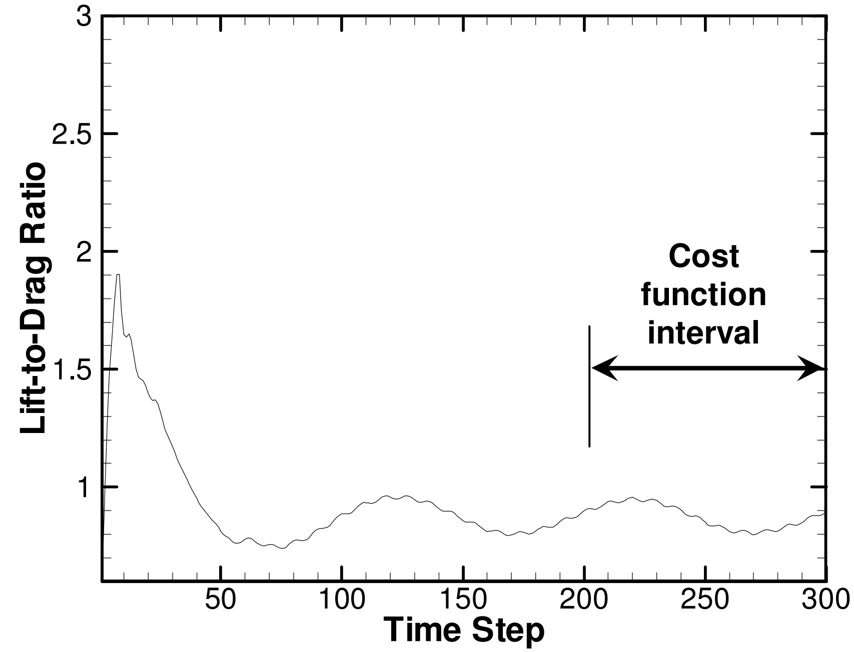
Tail Surface

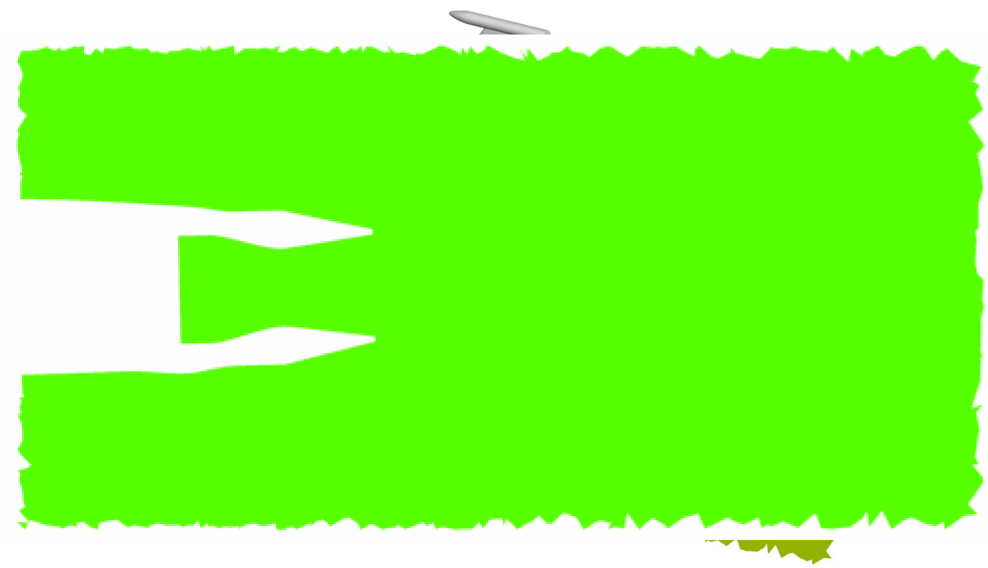
Adjoint Methods for Unsteady Flows: Fighter Jet Example

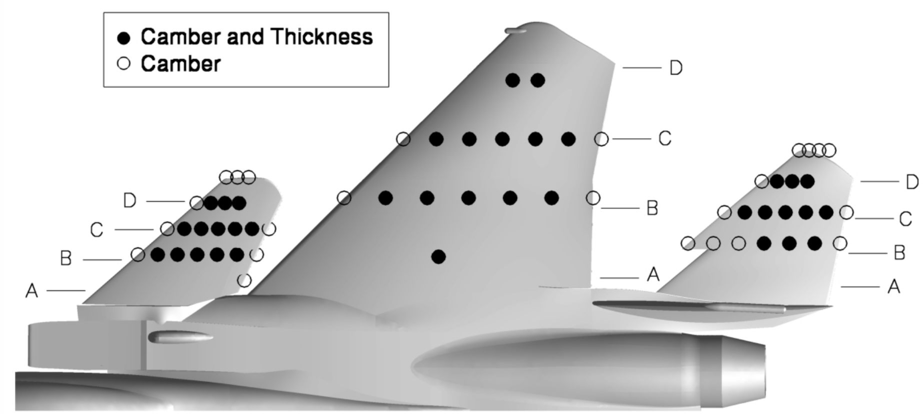
- High-frequency oscillations in L/D believed to be due to unsteady engine plume; also present in static grid simulation
- Objective function is to maximize L/D ratio over one period of motion:

$$f = \sum_{n=201}^{300} \left[(L/D)^n - 5.0 \right]^2 \Delta t$$

- Canard, wing, and tail surfaces parameterized as shown, no thinning allowed; total of 98 active design variables

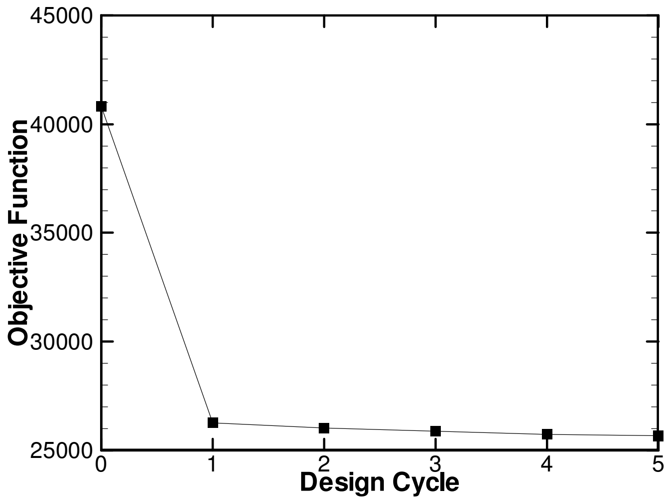


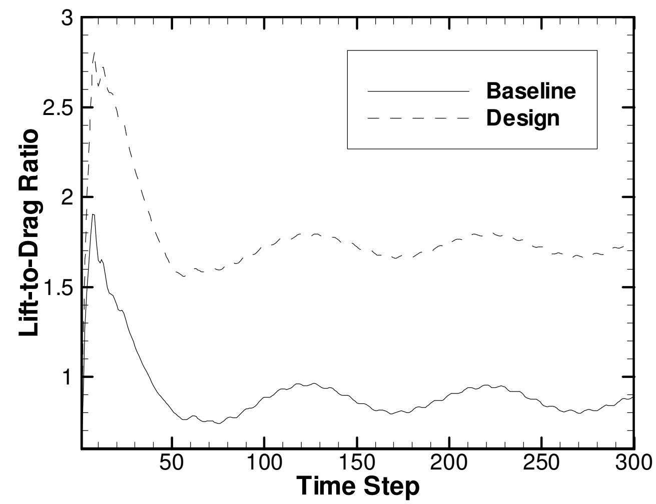


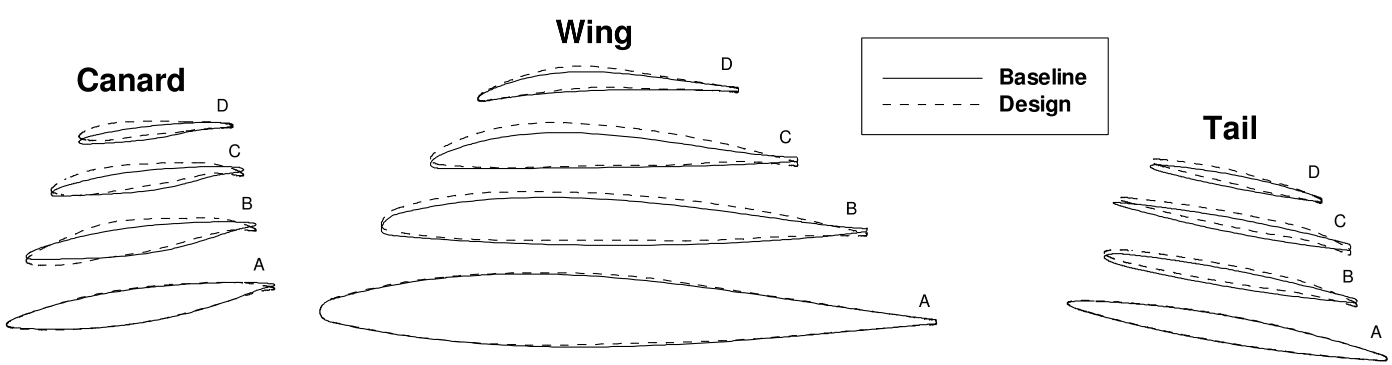


Adjoint Methods for Unsteady Flows: Fighter Jet Example

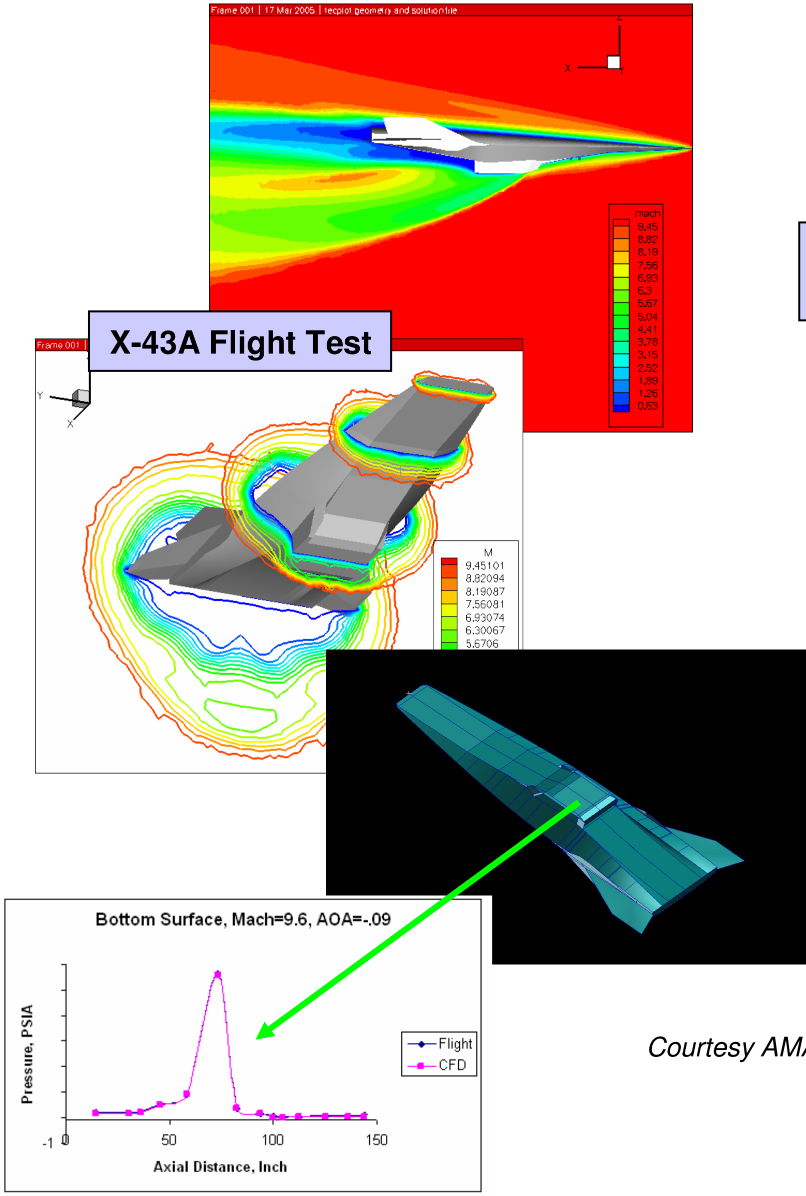
- Large initial reduction in cost function; many variables quickly reach their bounds
- Wing and canard thickness increased, camber increased on all three surfaces
- Downward deflection of all trailing edges
- Single flow solution takes 1 hr; single adjoint solution takes 1.5 hrs
- Optimizer requires 10 flow and 5 adjoint solutions: 18 hrs on 1024 cores (18,400 hrs)
- Single unsteady flow solution requires 136 GB of disk space





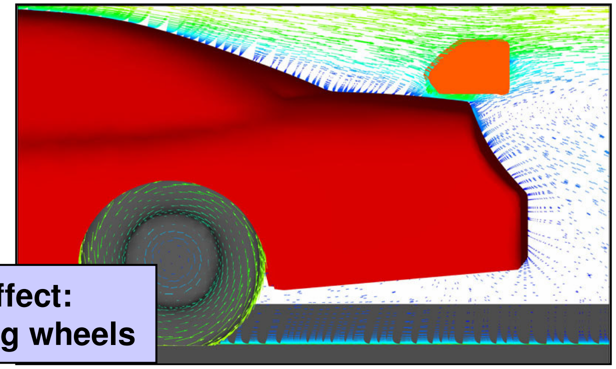


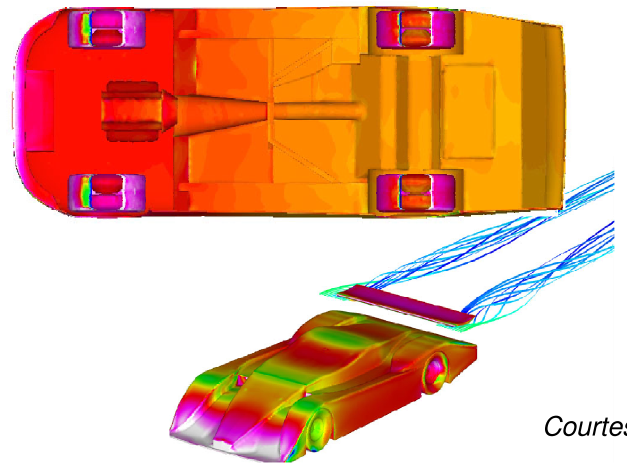
Customer Applications



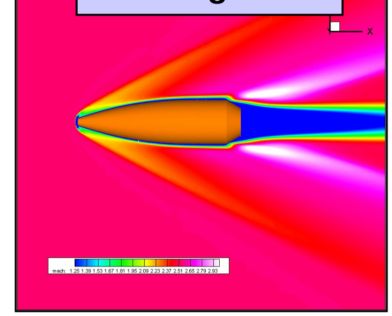
Courtesy AMA, Inc.

Vehicles in ground effect: moving roadway, spinning wheels



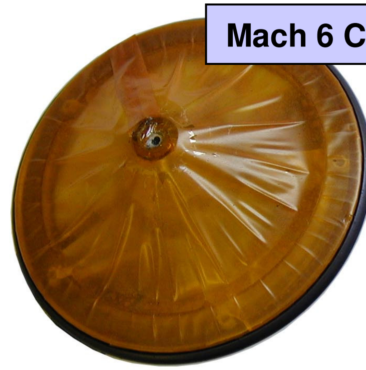


Rotating bullet

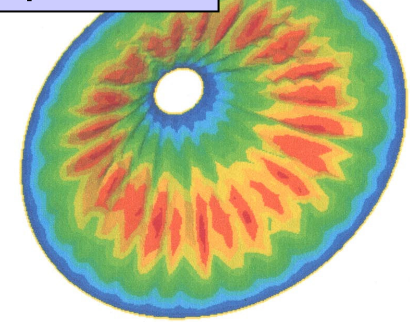


Courtesy BMI Corporation

Mach 6 Clamped Ballute



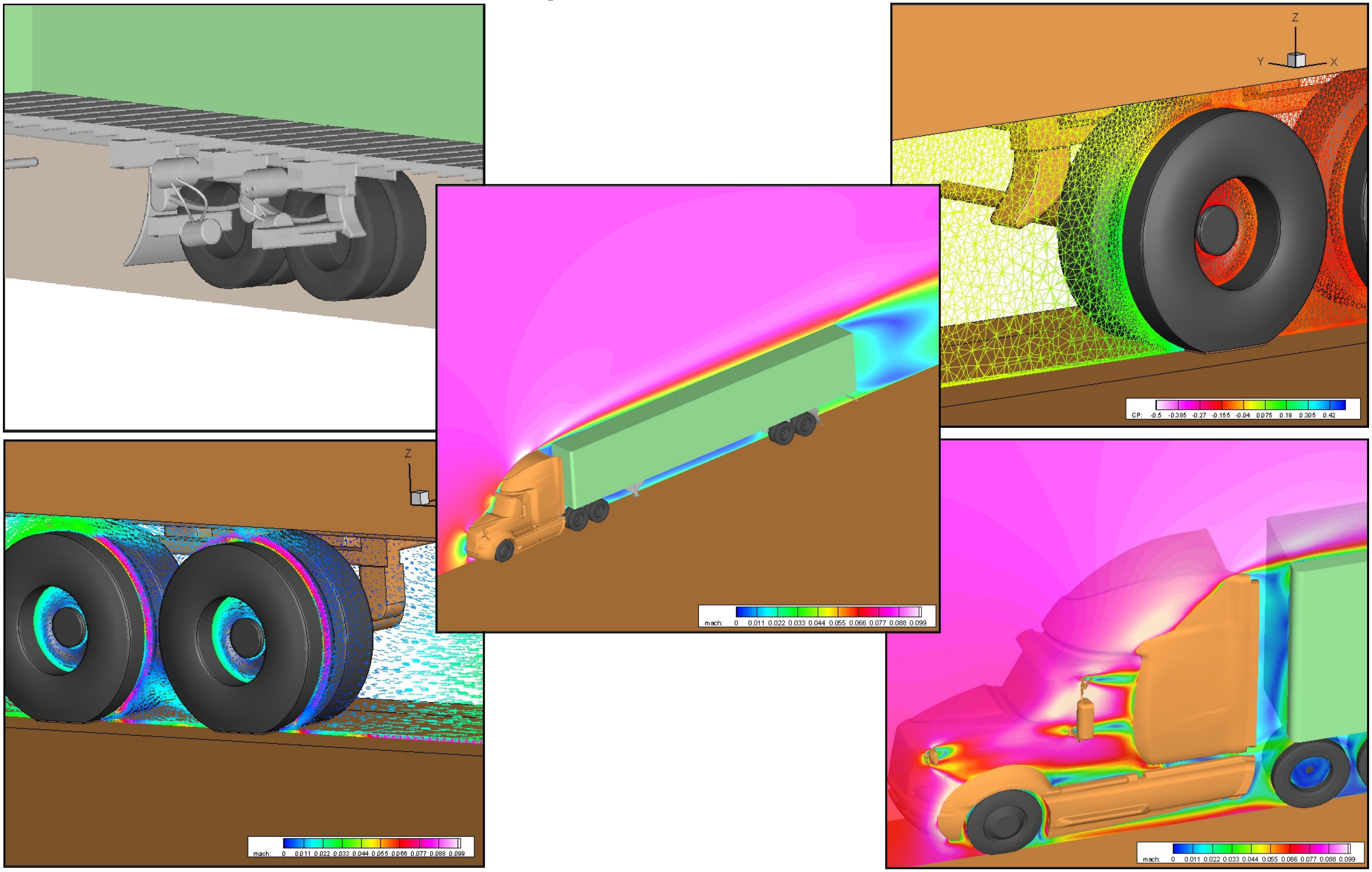
Test Article



FUN3D/NASTRAN

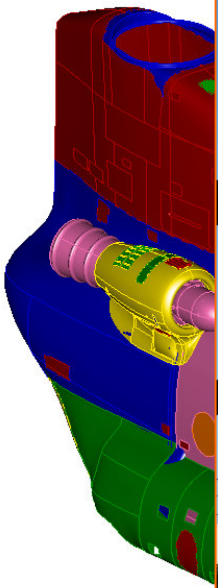
Customer Applications

BMI Corporation's *Smart Truck*

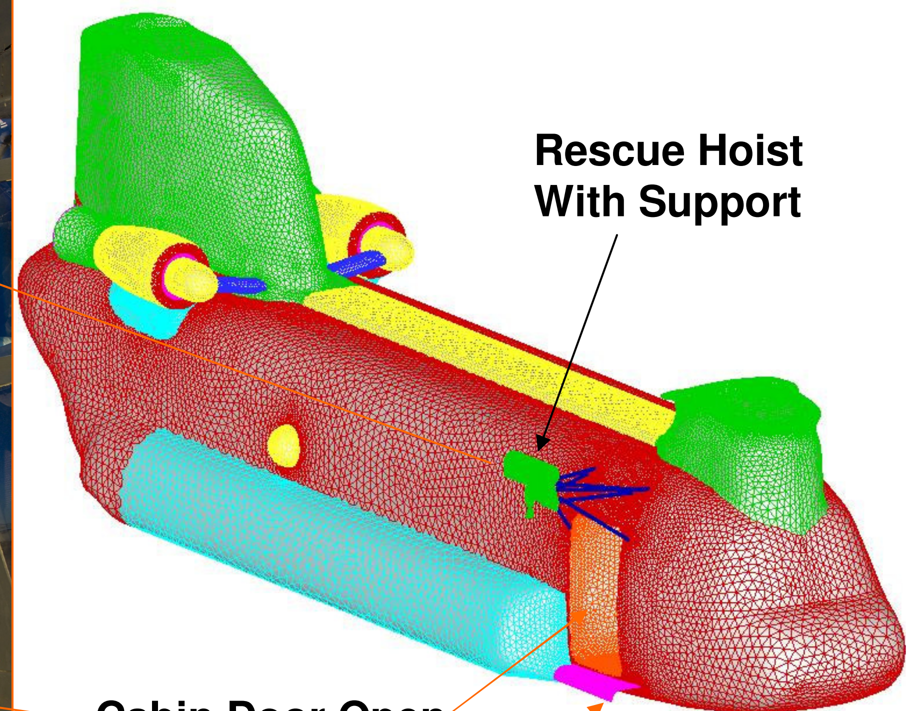


Rescue Hoist Drag Prediction for Chinook

C

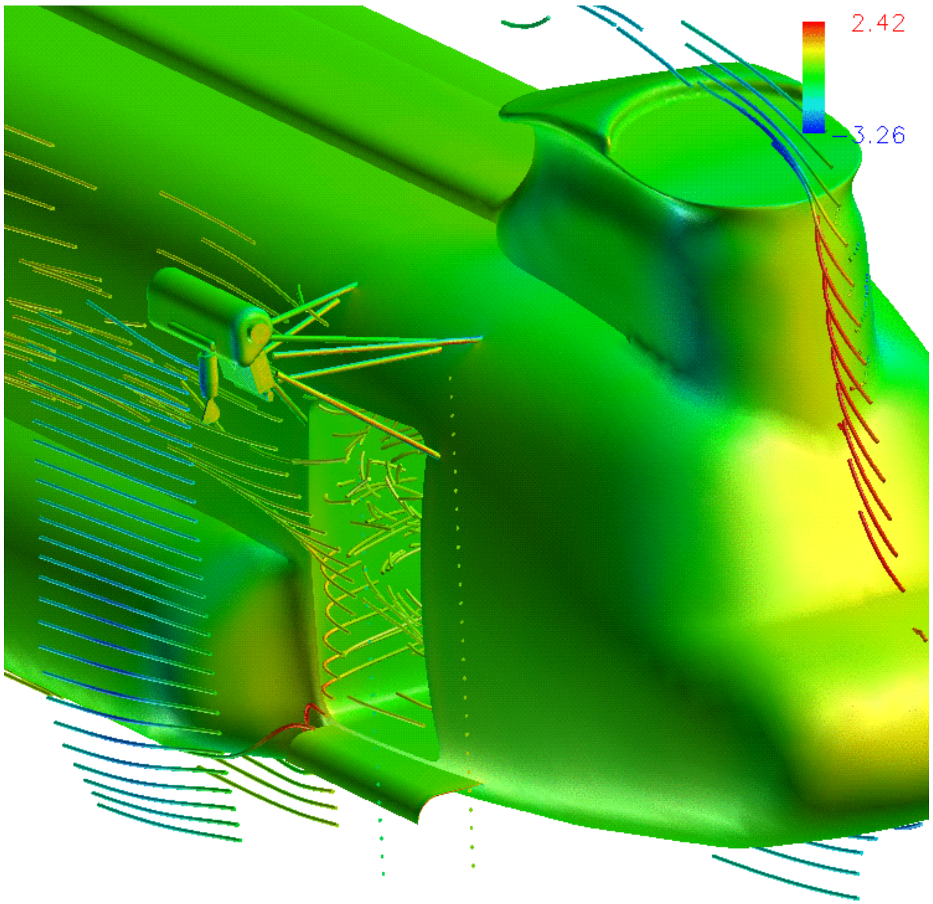


Updated CFD Surface Mesh

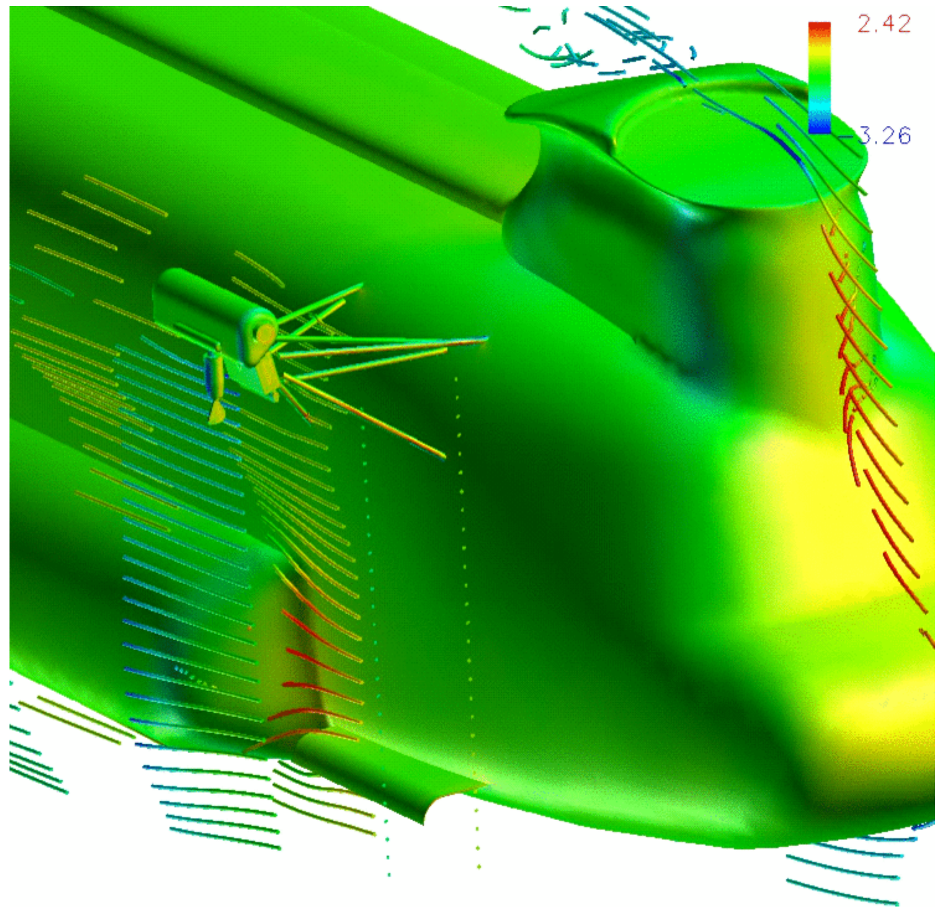


Rescue Hoist and Step Assembly were added to the CAD and CFD model has been updated

Particle Traces Colored with Surface-Pressure Coefficient in Forward Flight with and w/o Cabin Door at 0° yaw



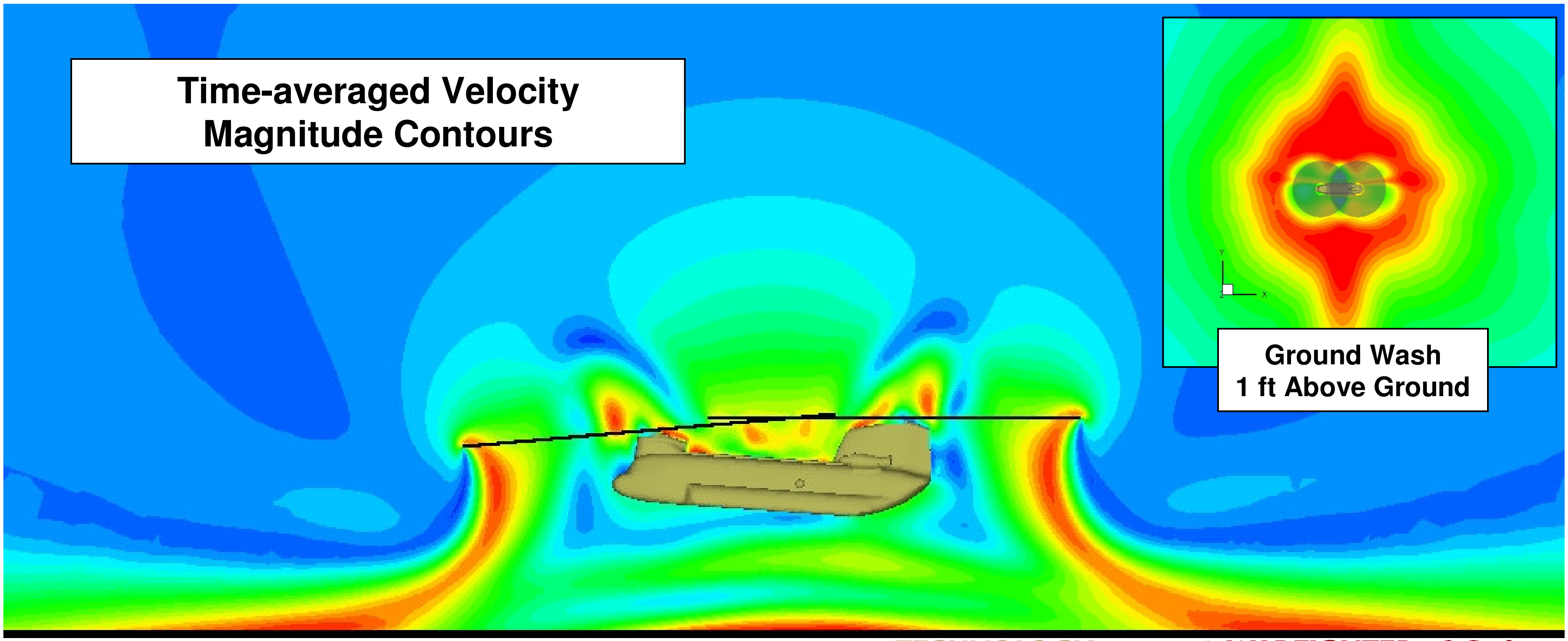
Cabin Door Open



Cabin Door Closed

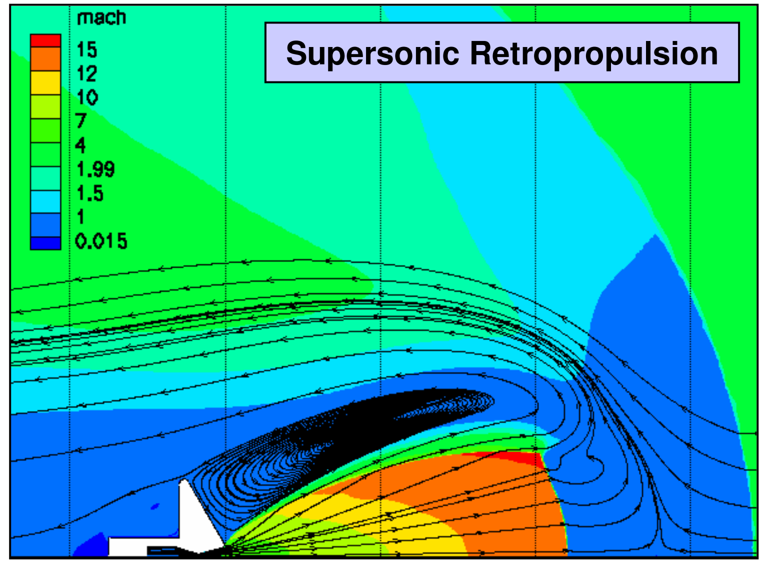
CH-47 Hover In Ground Effect

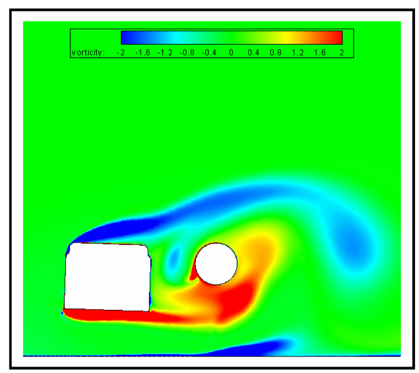
- **Objective**
  - Study the Rotor Wash of a CH-47 Hovering in Ground Effect
  - Determine the Cause of an Instability Observed in Flight Test
- **Methodology**
  - Unstructured Mesh CFD Flow Solver: FUN3D
  - Actuator Disk Approximation used for Rotor Modeling
- **Results**
  - Rotor Wash Visualization and Estimated Magnitude
- **Significance to DoD**
  - Safety of Personnel
  - Reduction in Flight Testing (Identify Root Cause without the Need for Further Test)
- **Recommendation**
  - Personnel should approach the helicopter from the front or rear of the aircraft



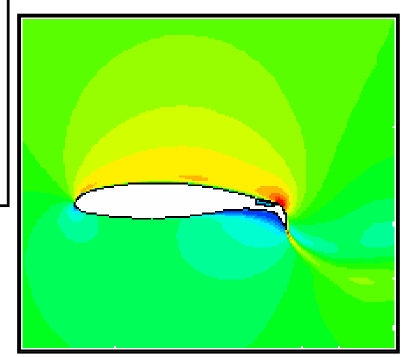
Other Active Areas

- Discretizations: node-centered vs cell-centered schemes
  - Accuracy/Robustness/Cost (CPU & memory)
- HPC Efforts
  - End-to-end parallelization
    - 105 million node / 600 million element grid preprocessed in ~5 minutes using 1,024 distributed processors (previously took two weeks using 800 GB shared-memory supercomputer)
    - Co-processing for visualization
  - Parallel I/O
  - GPU's
- Complex variable schemes
- Time-dependent algorithms
  - Temporal error controllers
- Drag Prediction/High-Lift Workshop activities
- Turbulence modeling activities
  - Extensive code-to-code verification
  - Public website resource with AIAA TC: *http://turbmodels.larc.nasa.gov*
  - URANS vs LES-type approaches
  - Compressibility, temperature, curvature effects
- Flow control
- Supersonic retro-propulsion





Unsteady Flows



Flow Control