USM3D-ME Simulations for DPW-VII: Expanding the Envelope

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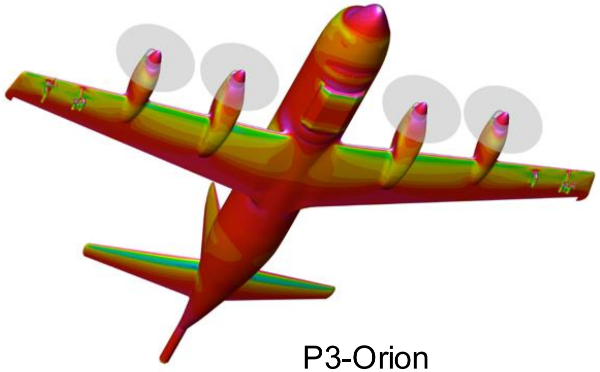
Outline

- **USM3D-ME Overview**
- **Grids and Computational Methodology**
- **Selected Cases**
  - – Case 1a: Grid Convergence Study for Re=20 million
  - – Case 2a: Alpha Sweep for Re=20 million
  - – Case 3: Reynolds Number Sweep

USM3D-ME (TetrUSS Flow Solver)

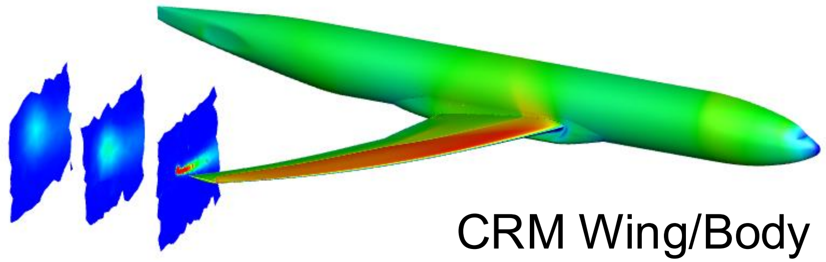
- **Builds on rich legacy of USM3D tetrahedral grid flow solver**
- **Cell-centered, finite-volume, mixed-element, unstructured-grid flow solver**
  - Euler and RANS equations with second-order spatial accuracy
  - Spalart-Allmaras (SA) turbulence model (standard, negative, RC, and QCR2000)
- **Upwind spatial discretization for mean flow inviscid flux**
  - Cell gradients using Green-Gauss method and nodal solutions
  - Options for flux functions: FDS, HLLC, LDFSS, FVS, HLLE, etc.
  - Cell- and face-based gradient limiters: Barth-Jespersen, Venkat, van Albada
- **Second-order diffusion; face-gradients based on Mitchell’s method**



P3-Orion
Courtesy Craig Hunter (NASA LaRC)

USM3D-ME (TetrUSS Flow Solver)

- **Standard and specialized boundary conditions**
- **Force-term approach for simulation of propellers and other applications**
- **Time integration**
  - Steady state with local time-stepping
  - Second-order BDF2 for temporal accuracy
- **Rigid-body 6-DoF motion support**
- **Parallelized using MPI paradigm; excellent scalability**
- **Nonlinear iteration methods**
  - Preconditioner-Alone (PA); baseline solver technology
  - Hierarchical Adaptive Nonlinear Iteration Method (HANIM); stronger solver for improved robustness and efficiency; automatic update of CFL



CRM Wing/Body

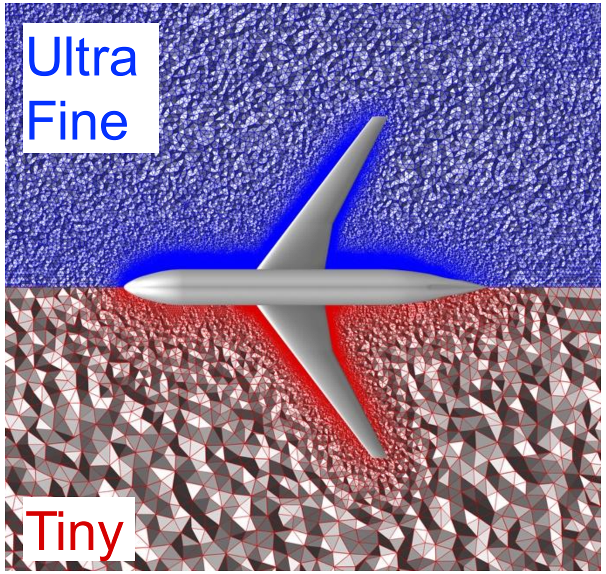
AIAA 2013-2541, *AIAA Journal*, 54(9) 2016, *AIAA Journal*, 55(10) 2017, AIAA 2019-2333, *AIAA Journal*, 59(8) 2021, *AIAA Journal*, 59(11) 2021

Compute Resources

- **NASA Advanced Supercomputing (NAS) facility**
- **Located at NASA Ames Research Center**
  - More than 11,000 nodes and 241,000 compute cores
  - Intel and AMD chips
  - TOSS3 operating system
- **Resource usage for DPW-VII**
  - IvyBridge (Intel) chips
  - Between 600 and 2,500 processors
  - Medium cases run on 600 processors
  - Walltime totaled a few hours, depending on the grid and convergence criteria

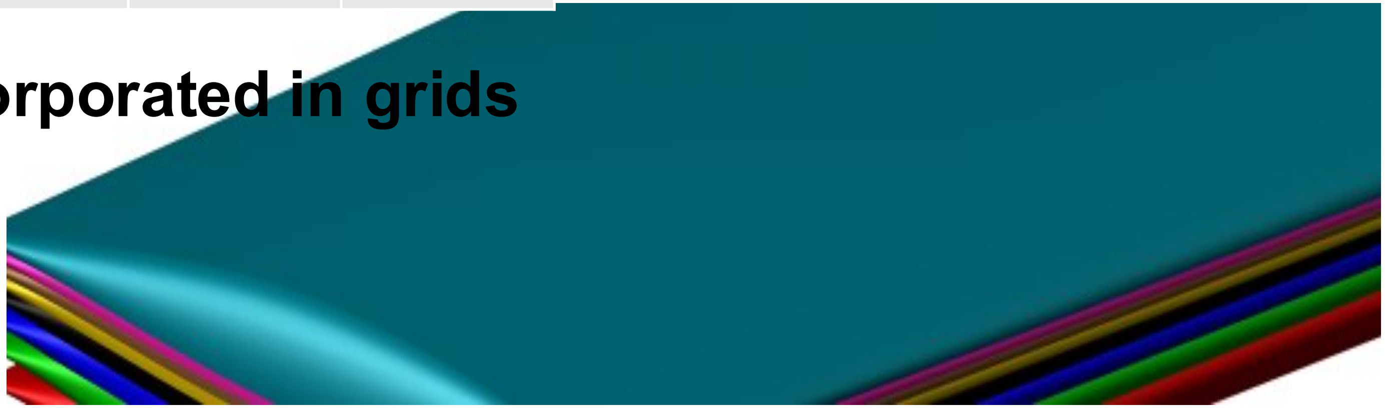
Grids

- **Used mixed-element JAXA-supplied grids**
  - Grid convergence study performed on all six grids
  - Majority of work executed on medium-density grid
  - Nondimensionalized by mean aerodynamic chord



	Tiny	Coarse	Medium	Fine	Extra Fine	Ultra Fine
Level	L1	L2	L3	L4	L5	L6
Approximate Cell Count (Millions)	8.7	26.9	60.2	111.8	184.1	291.2

- **Aeroelastic deformations incorporated in grids**

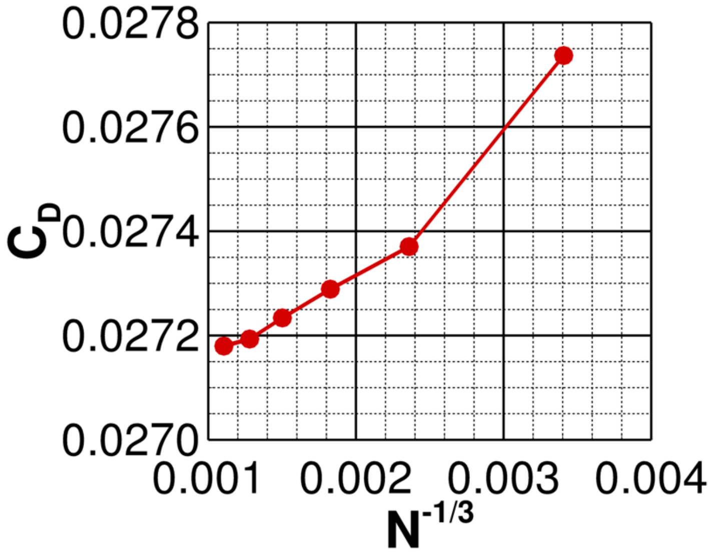


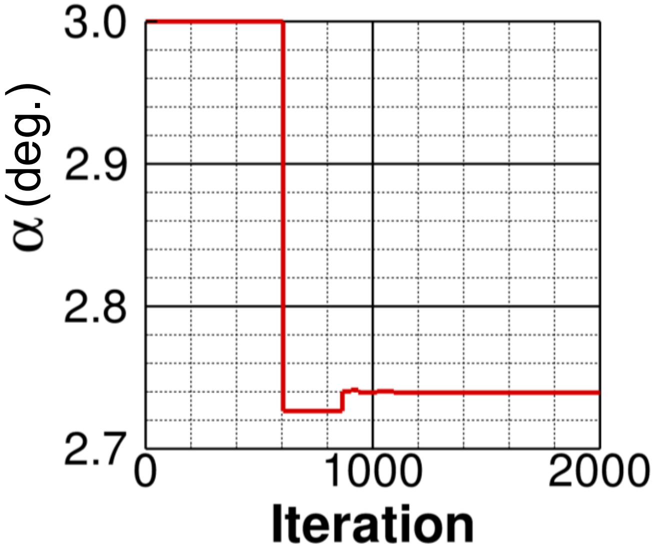
Computational Approach

- **RANS scheme for all simulations**
- **Turbulence model**
  - SA-neg QCR-2000
  - RC not utilized as best practices have not yet been established
  - First-order advection term
- **Inviscid flux for meanflow equations**
  - Second-order
  - Roe’s flux different splitting scheme without gradient limiters

Case 1a: Grid Convergence

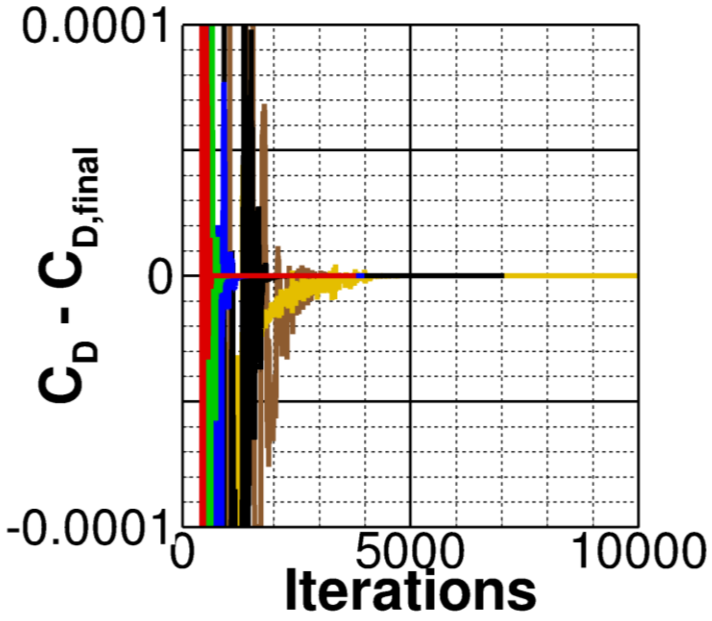
- **Simulations performed on all six grids**
  - Rapid iterative convergence from HANIM methodology
  - Solution residuals reduced below 1.0E-13
- **Solution value taken at final iteration**
- **Simulations performed in C_L-matching mode**
  - Tolerance for C_L set at committee-specified +- 0.0001
  - Angle of attack perturbed automatically to match prescribed C_L within the tolerance limits
  - Angle of attack adjusted after residuals are reduced 1.5 orders of magnitude below the initial freestream state

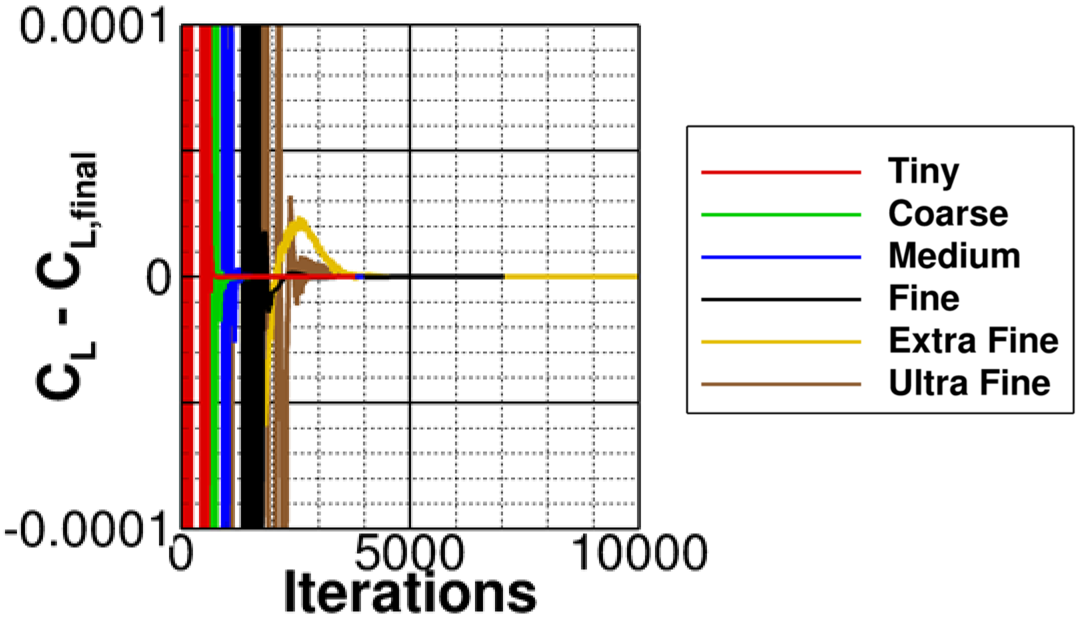




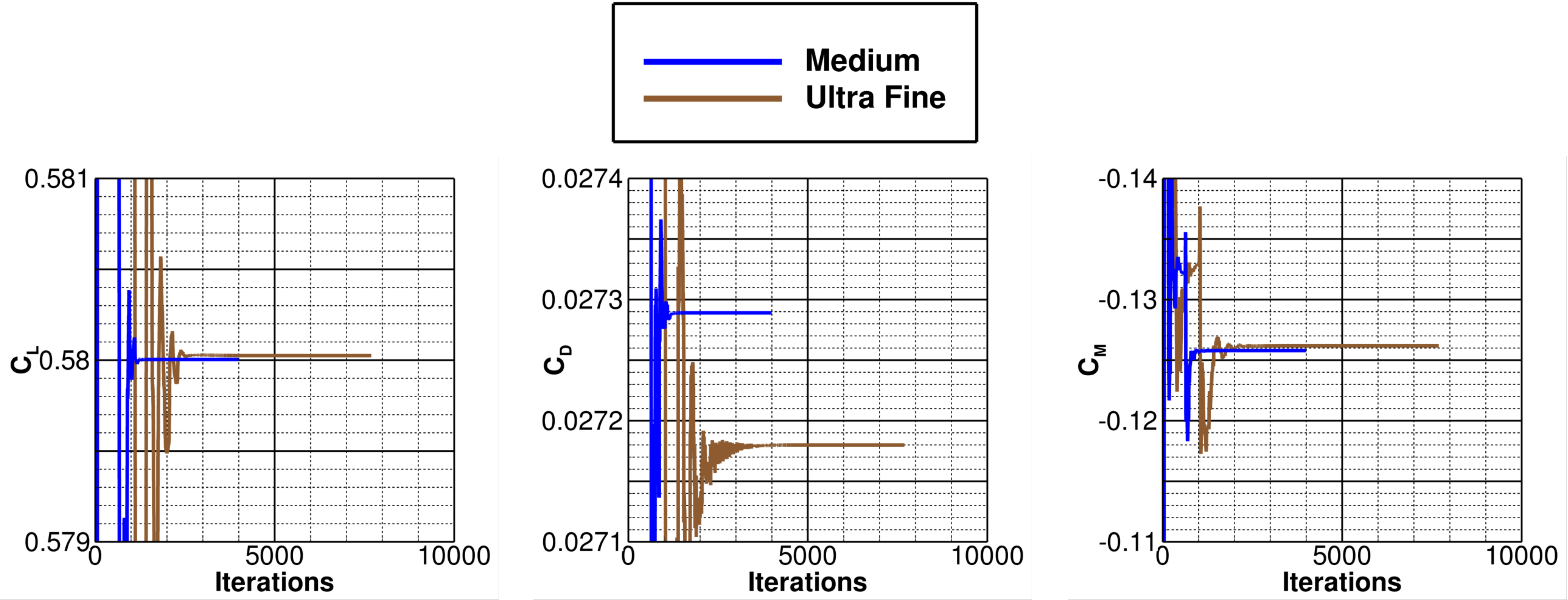
Case 1a: Convergence History

- Convergence history monitored and stopped by the user
- Drag has converged within six significant digits for all cases



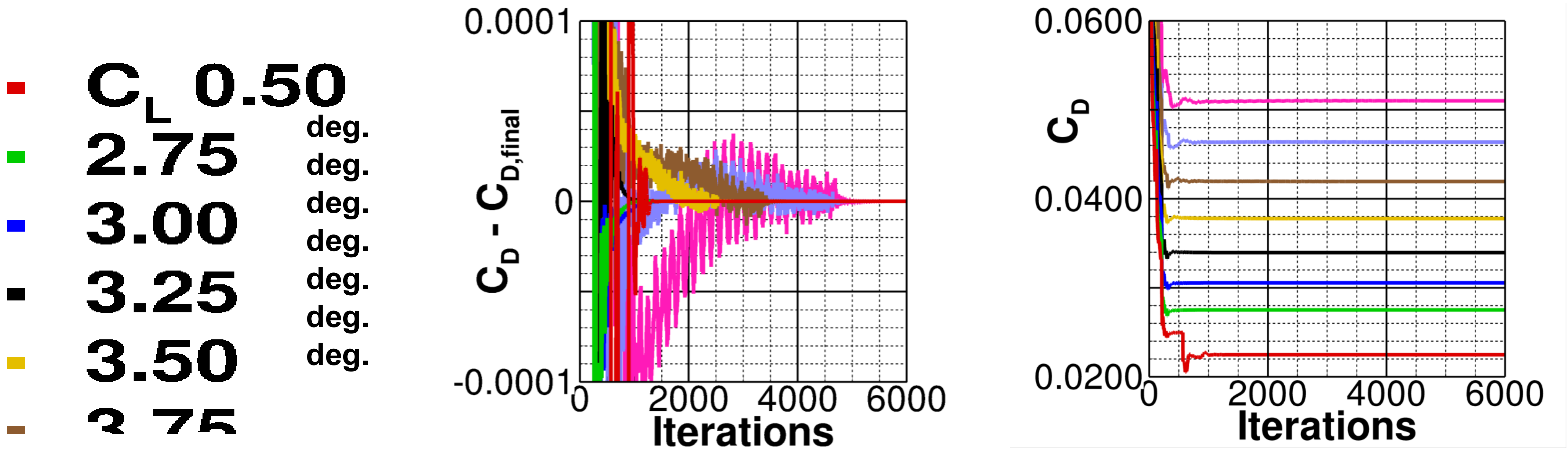


Case 1a: Medium and Ultra Fine Grids



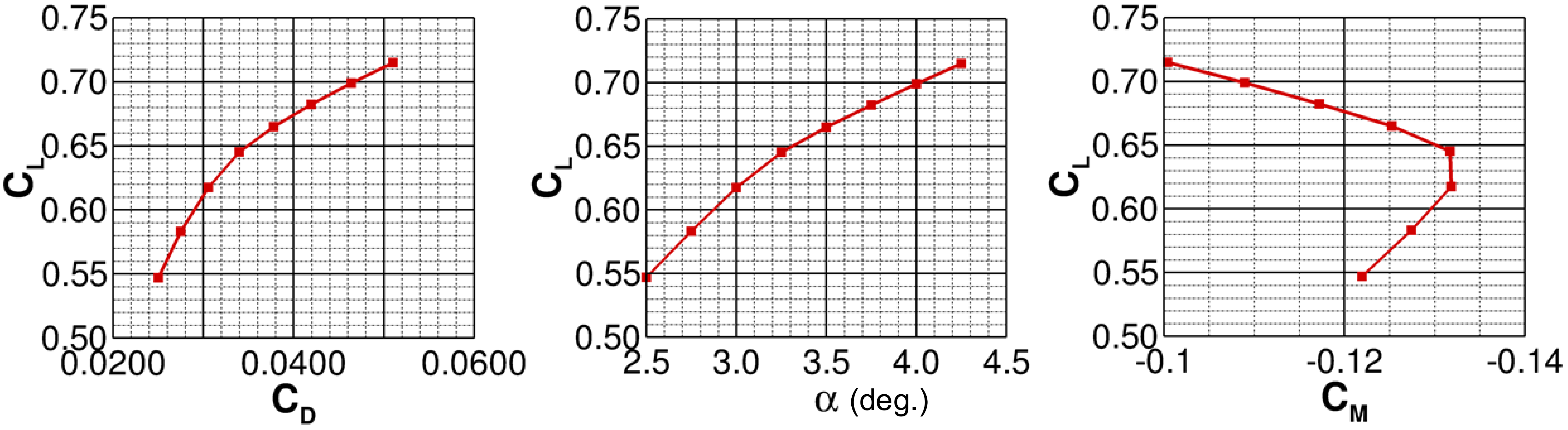
Case 2a: Iterative Convergence

- Solution residuals reduced below 1.0E-13
- Low-alpha cases converged in ~1k iterations
- Converged solutions observed after 5k iterations for all simulations



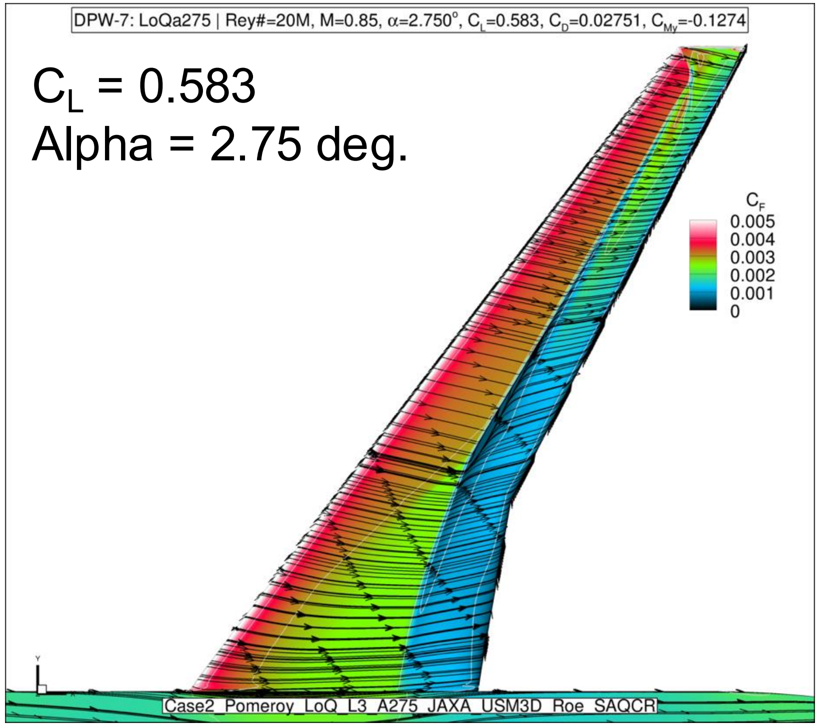
Case 2a: Aerodynamic Performance

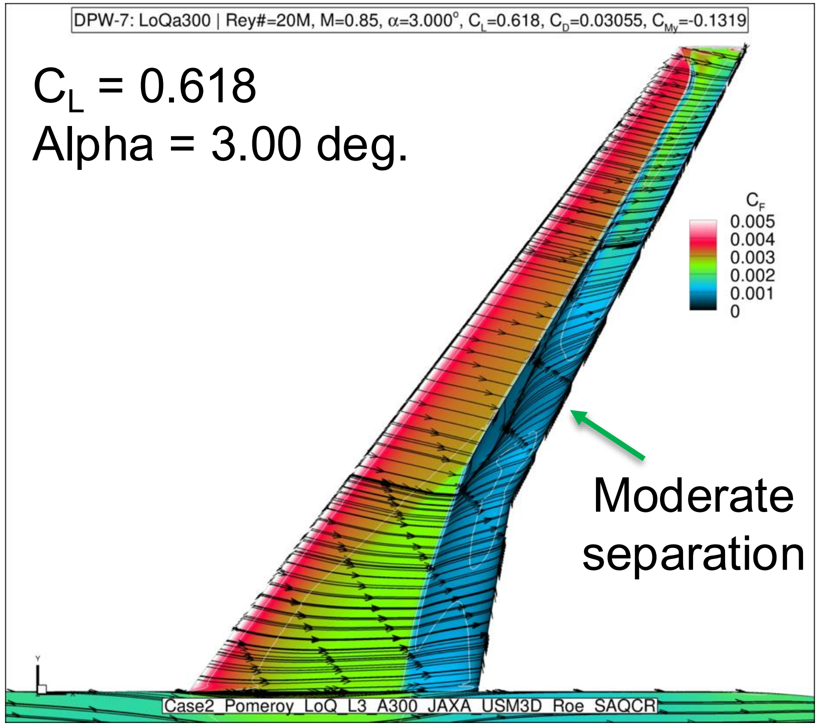
- Pitch break observed between C_L of ~0.62 and ~0.65 (3 to 3.25 deg.)
- Bucket of pitching moment curve at C_M of about –0.133

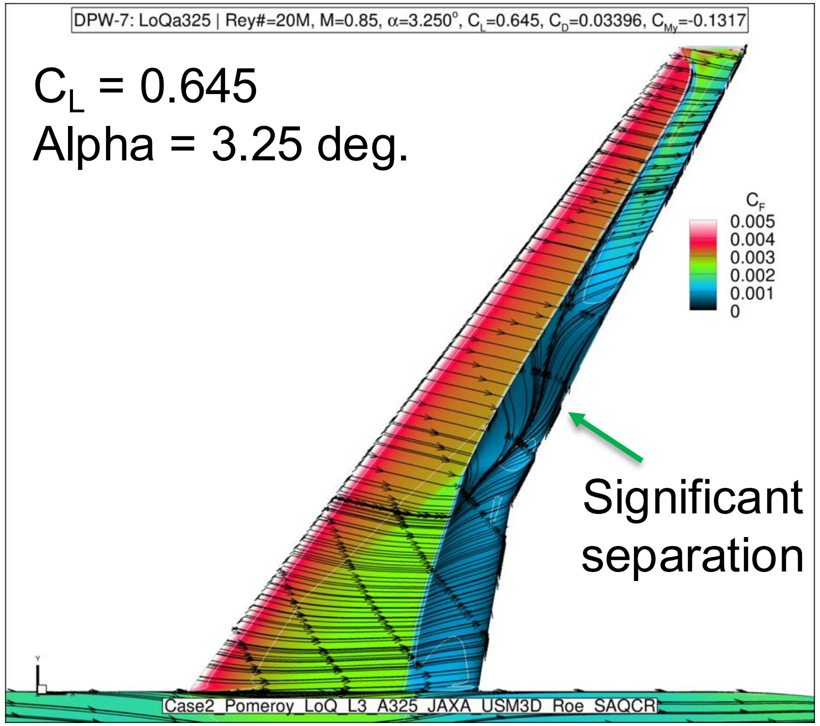


Case 2a: Surface Separation Behavior

- **Surface contours of C_F with streamlines**
- **Shock-induced separation observed at 3.00 deg.**
- **Midspan separation seen at 3.25 deg. (consistent with pitch break)**

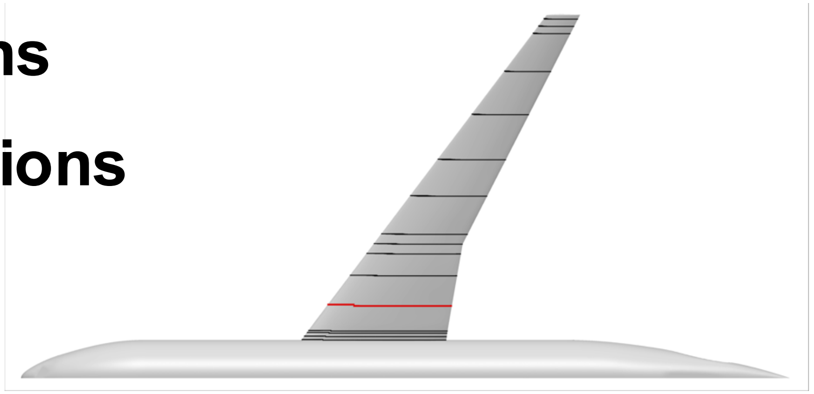


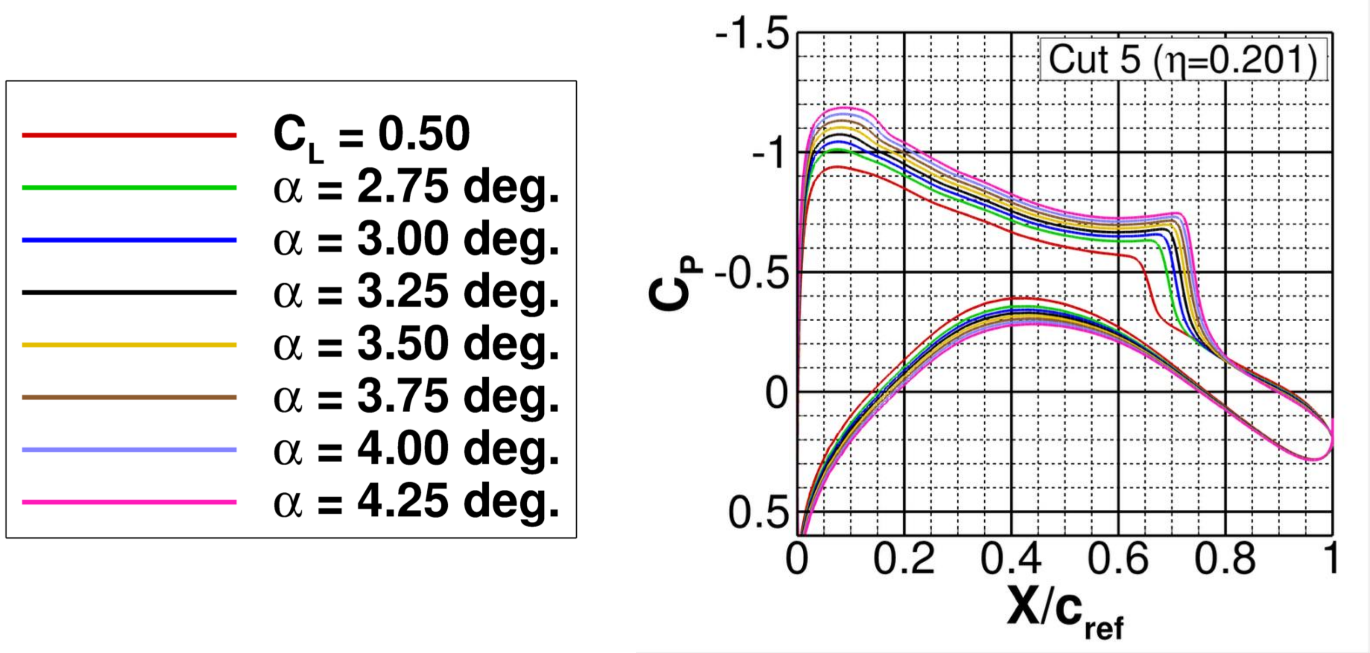


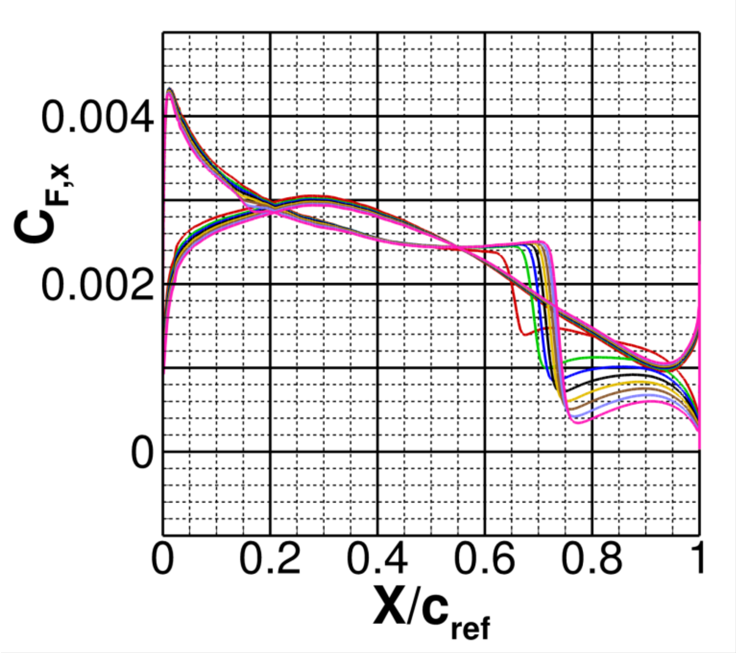


Case 2a: Inboard Surface Cuts

- Cuts shown for the fixed-alpha conditions
- Attached flow present across all simulations
- Consistent with previous contour plots

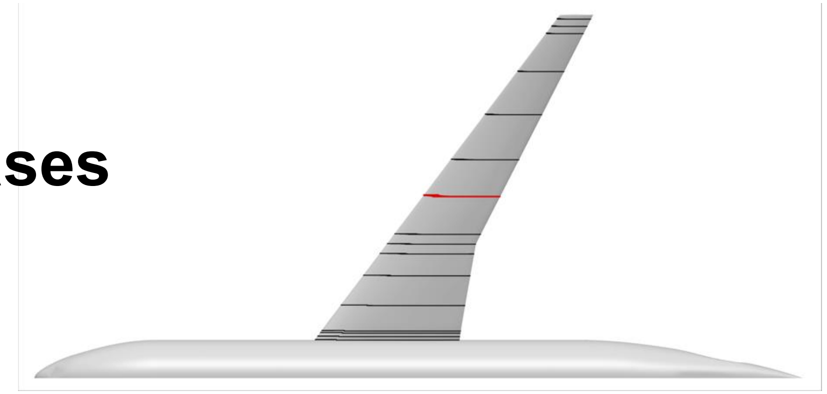




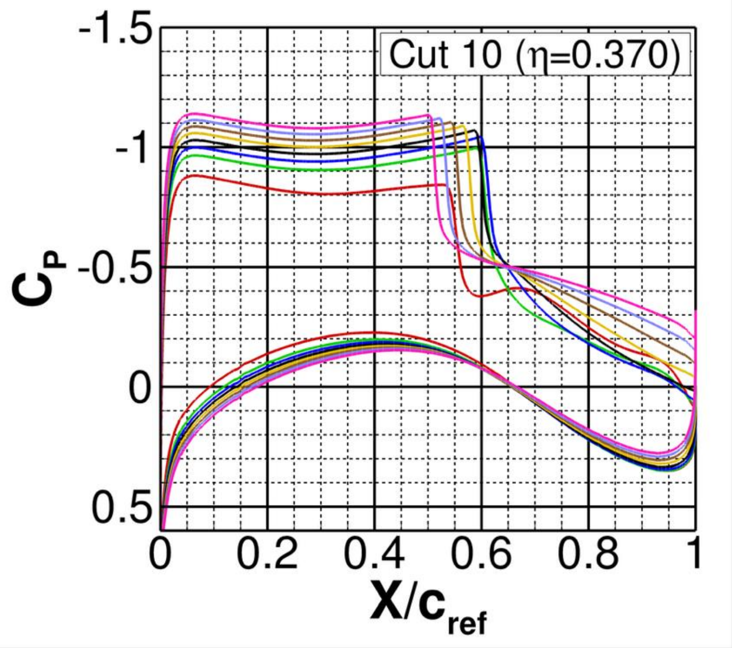


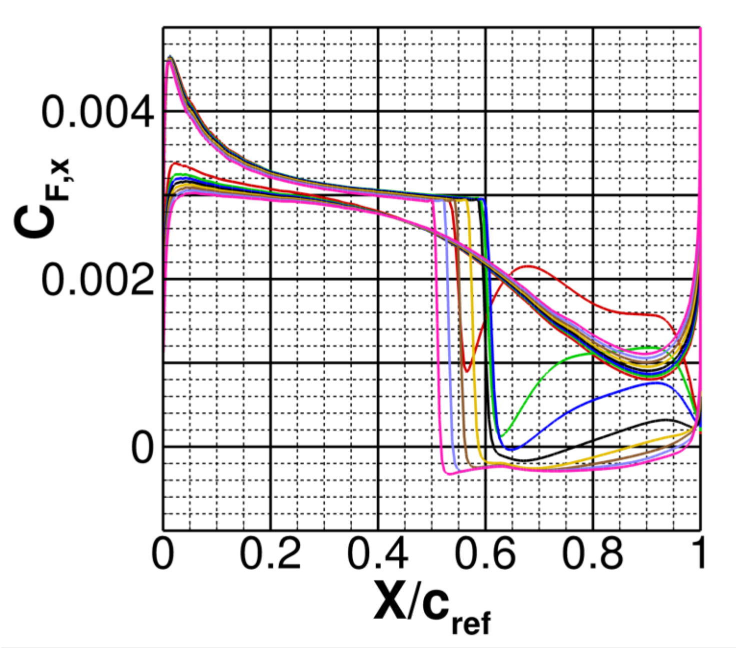
Case 2a: Mid-Span Surface Cuts

- **Region of earliest separation**
- **Extent of downstream separation increases with larger alphas**
- **Trailing edge flow separation for alpha above 3.00 deg.**



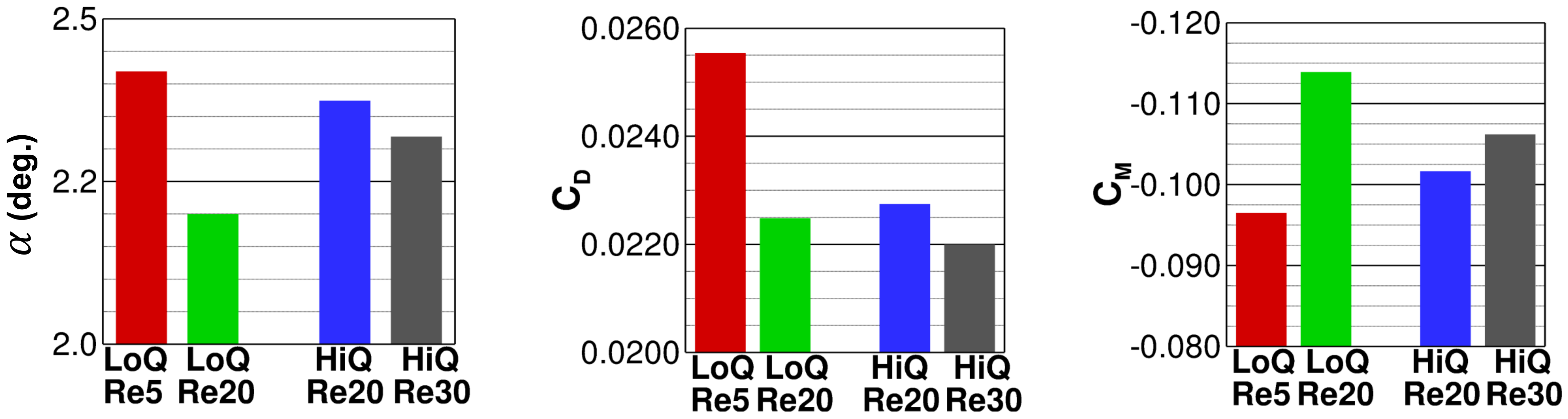
$C_L = 0.50$
α = 2.75 deg.
α = 3.00 deg.
α = 3.25 deg.
α = 3.50 deg.
α = 3.75 deg.
α = 4.00 deg.
α = 4.25 deg.





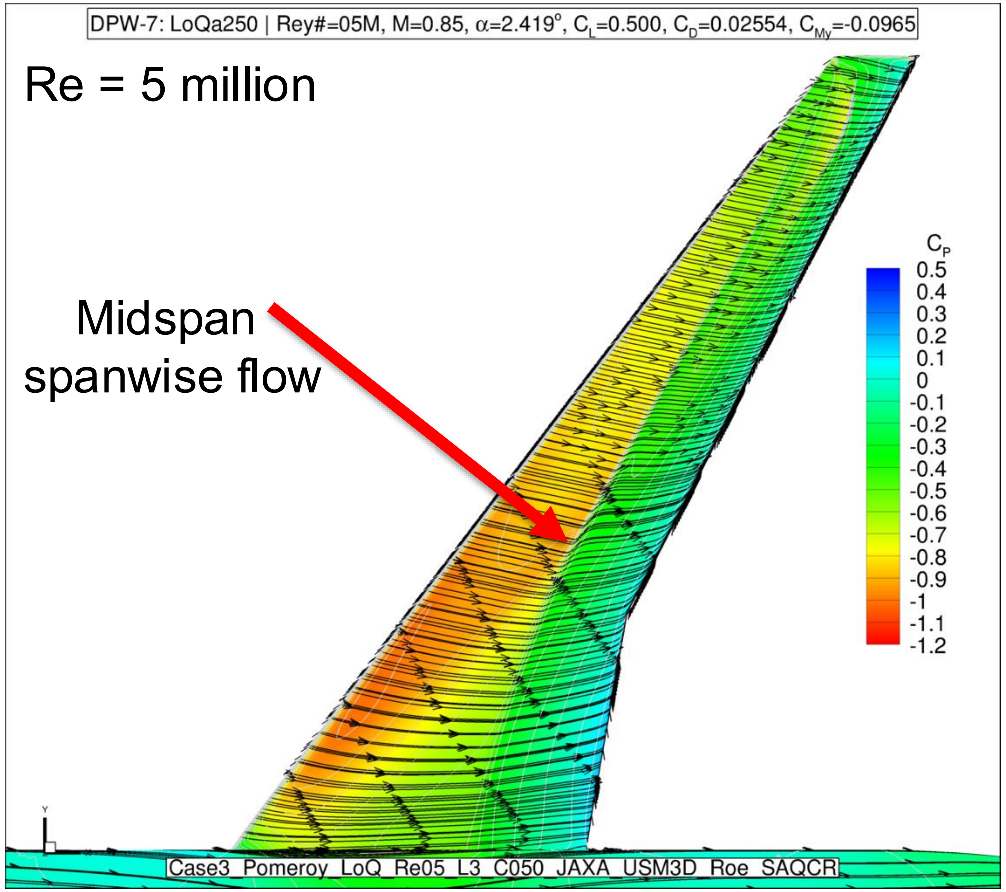
Case 3: Reynolds Number Sweep

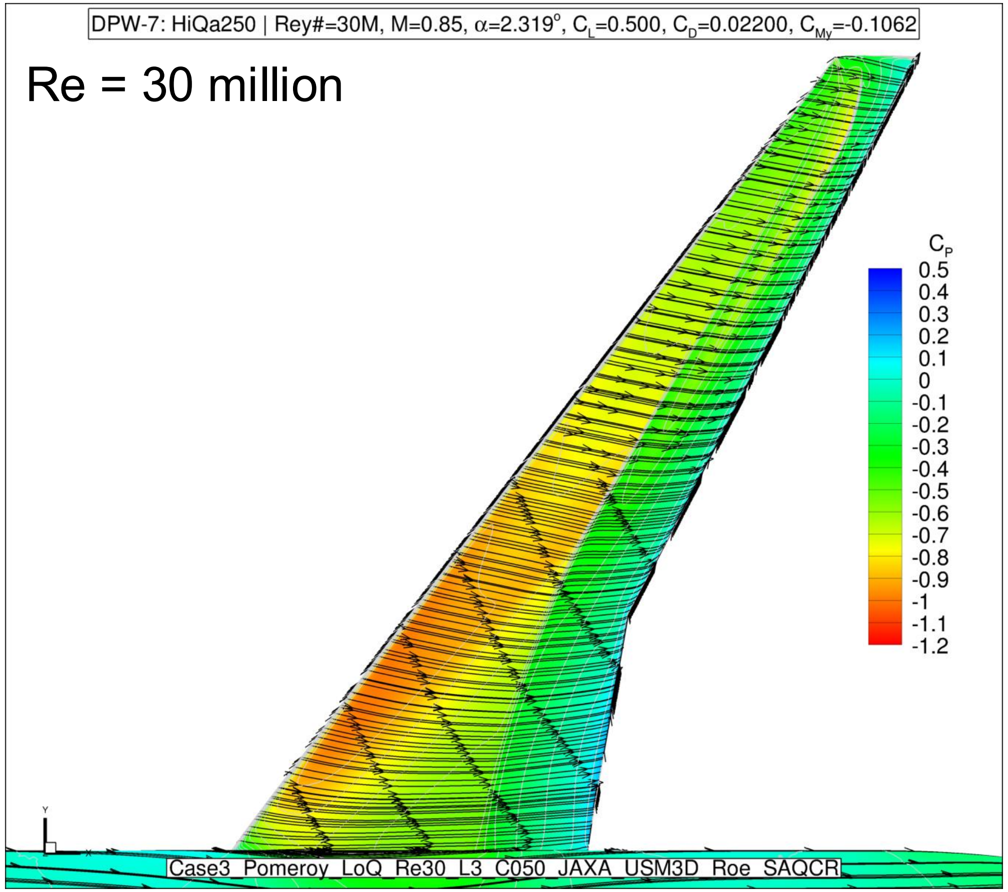
- Significant increase in drag for decreasing Reynolds number as the wing moves off design
- Deviations in C_M ~0.016 between two 20 million cases (different conditions and lofts)



Case 3: Surface Pressure Comparison

- **Spanwise flow observed for low-Reynolds number case**





Conclusions

- USM3D-ME results for cases 1a, 2a, and 3 presented
- Rapid convergence to machine-zero residuals achieved (less than 1,000 iterations for some cases)
- Strong grid convergence across all six JAXA grids
- Pitch break at C_L ~0.62 (alpha ~3.15 deg.)
- Committee-required data files previously provided

Acknowledgments

- NAS for compute facilities
- Appreciation extended to the DPW-7 workshop committee for providing grids, the data format, and data reduction scripts