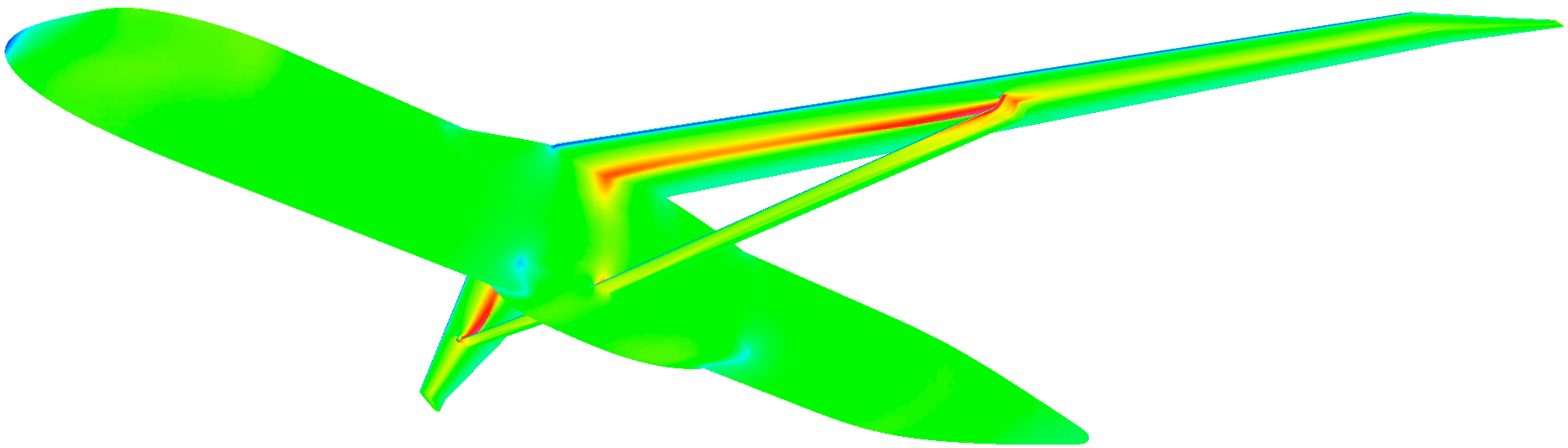
Application of Passive Drag Reduction Methods to a Generic Strut-Braced Wing



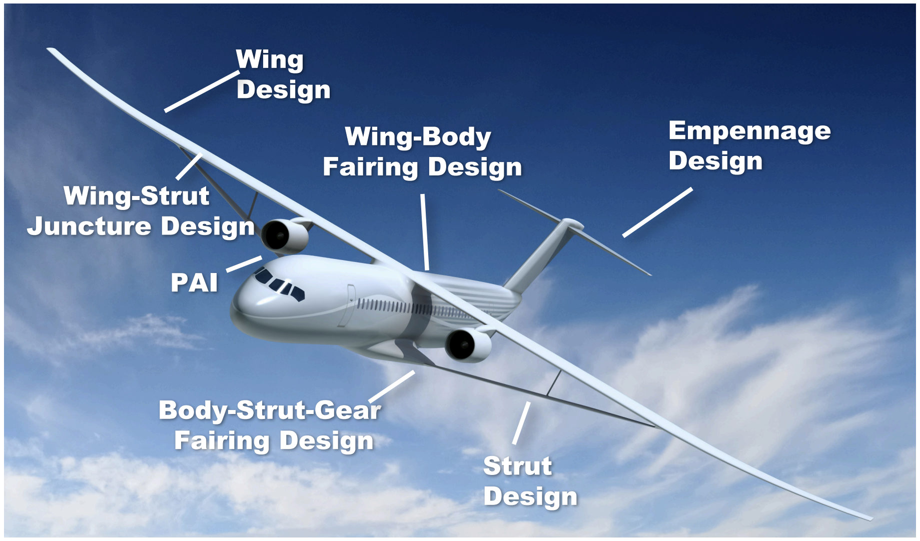
Richard L. Campbell
Sally A. Viken
Michelle N. Lynde

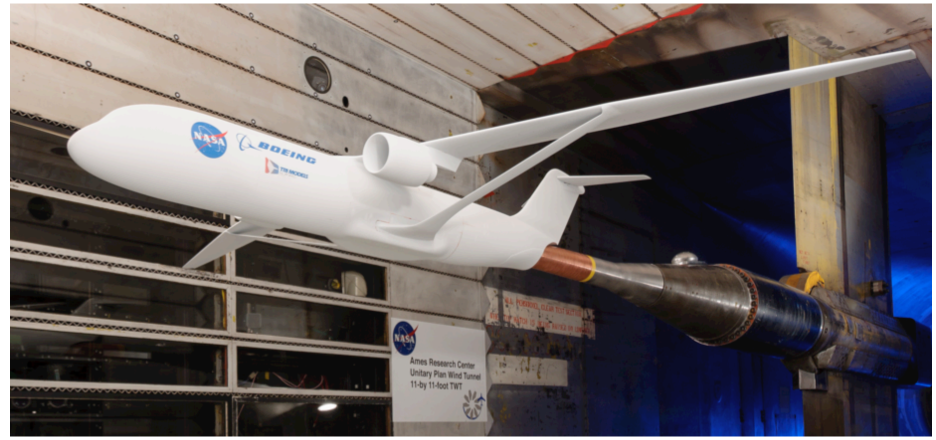
Presented at the PADRI Workshop, Barcelona, Spain
November 29 – December 1, 2017

Outline

- Introduction
- Baseline Evaluation
- Approaches to Drag Reduction
  - Aerodynamic Design (CDISC)
  - Passive Porosity (PASSPORT)
  - Comparison of CDISC and PASSPORT Results
- Concluding Remarks

Introduction



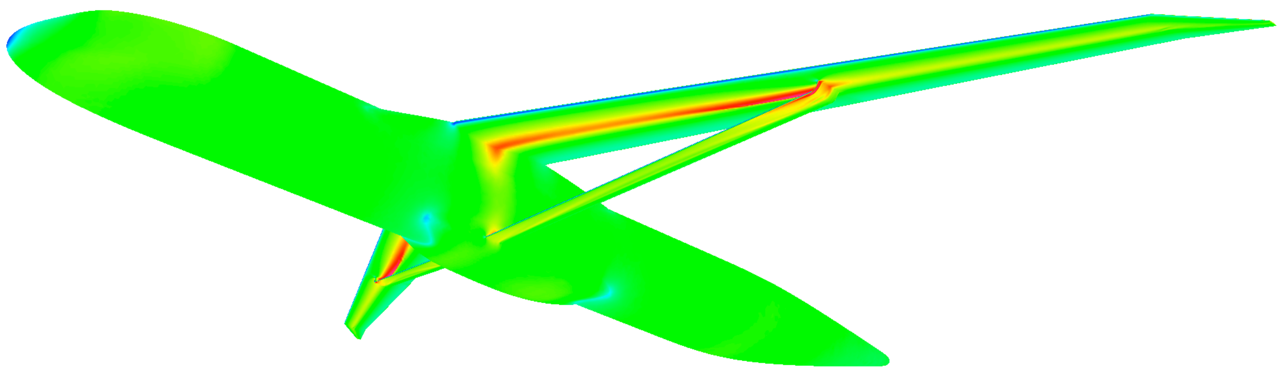


Boeing/NASA 4.5%-Scaled Truss-Braced Wing Model in NASA Ames 11-Foot Transonic Tunnel

Why Strut-Braced Wings?

- Increasing wing aspect ratio reduces lift-induced drag and can lead to significant fuel savings
- Aspect ratio can be increased to 20 or more if supported by strut or truss
- NASA is investigating strut-braced wing configurations to meet its N+3 goals of reducing fuel burn by 60%

Introduction



Challenges with Strut-Braced Wings

- Wing-strut aerodynamic coupling has tendency for shock to develop in juncture region at transonic conditions
- Shock in juncture region increases drag and can lead to separation

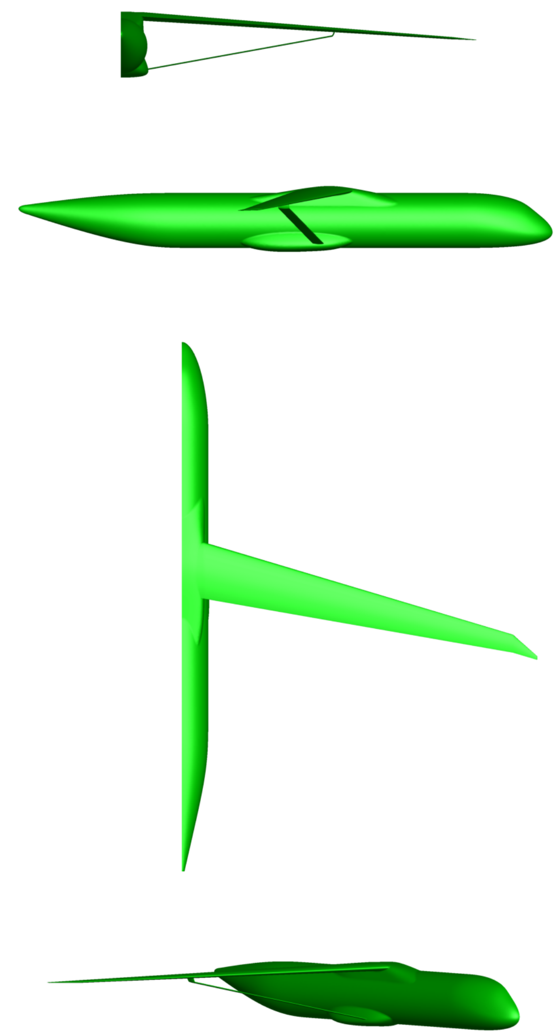
PADRI Workshop

Goal of Workshop:

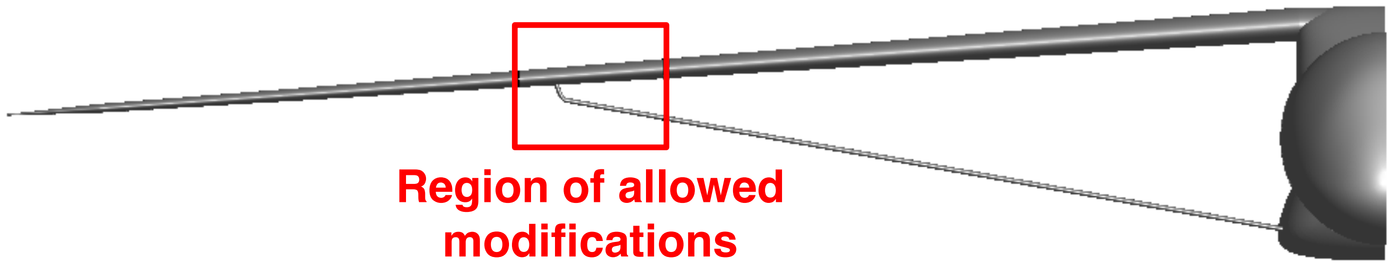
- Explore candidate flow control technologies and optimization strategies to minimize shock wave and interference drag in wing-strut juncture region
- Apply and evaluate drag reduction strategies to simplified strut-braced wing configuration at transonic conditions

Flight Conditions:

- Mach = 0.72, α = 1 deg., altitude = 30,000 ft.
- Adjust angle of attack of configuration with drag reduction mechanism to maintain initial total lift



PADRI Workshop Constraints



Wing:

- Can only alter between spanwise region of 14.5 m < Y < 17.5 m
- Cannot be modified: upper surface, twist, chord length
- Original lower surface cannot be penetrated

Strut:

- Can only alter between spanwise region of 14.5 m < Y < 17.5 m
- Cannot be modified: maximum thickness, chord, spanwise wing attachment location, length of vertical portion

Baseline Evaluation

- Introduction
- **Baseline Evaluation**
- Approaches to Drag Reduction
  - Aerodynamic Design (CDISC)
  - Passive Porosity (PASSPORT)
  - Comparison of CDISC and PASSPORT Results
- Concluding Remarks

Analysis Tools

Unstructured grid generation: *VGRID*

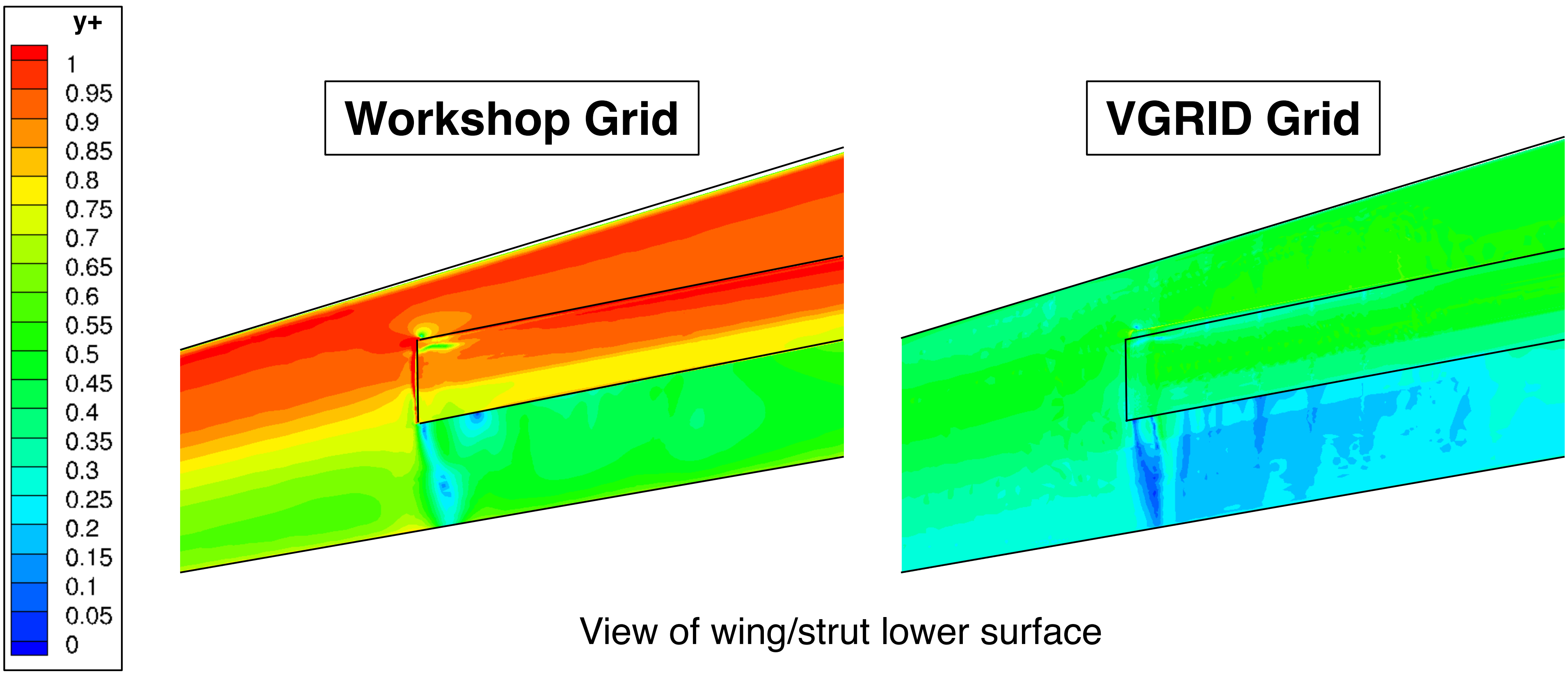
- Triangulated surface grid, tetrahedral volume cells
- Advanced layers in viscous regions, advancing front in outer flow
- Grid clustering control via line and volume sources

Navier-Stokes flow solver: *USM3D*

- Unstructured tetrahedral volume grid
- Cell-centered upwind scheme, no limited used
- Spalart-Allmaras (SA) turbulence model
- Passive or active porous surface boundary conditions available

Baseline Grid Comparison

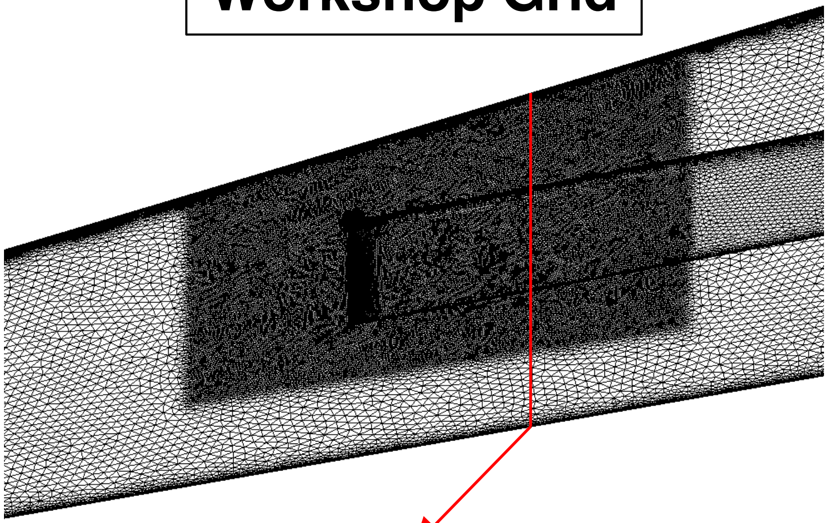
Grid	Flow Solver	Turbulence Model	Total Elements
Workshop	TAU	SA	59.3 million
VGRID	USM3D	SA	31.0 million

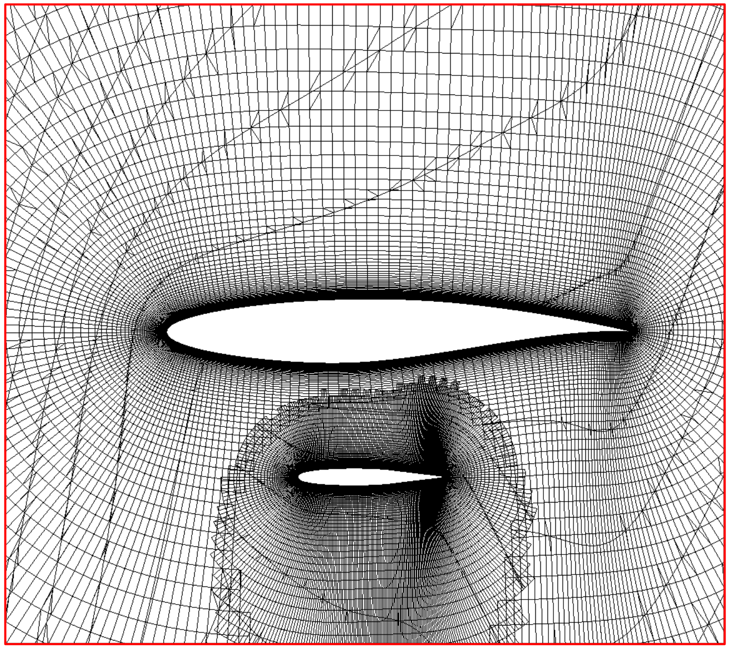


View of wing/strut lower surface

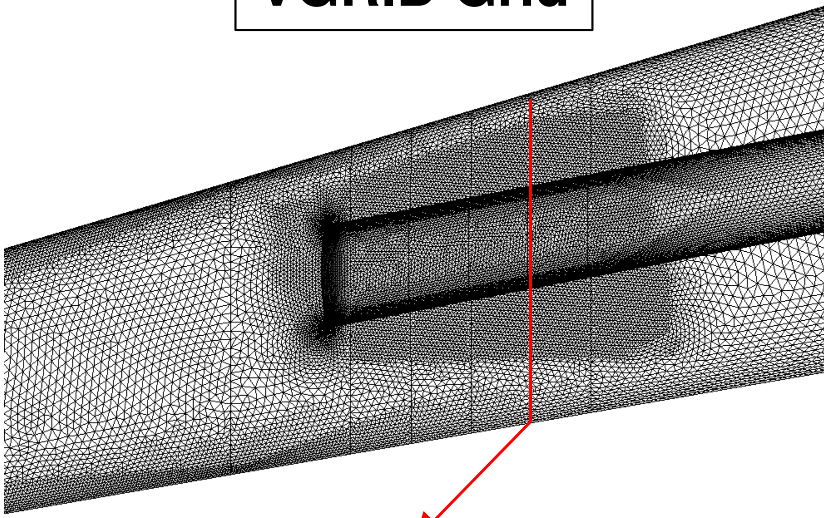
Baseline Grid Comparison

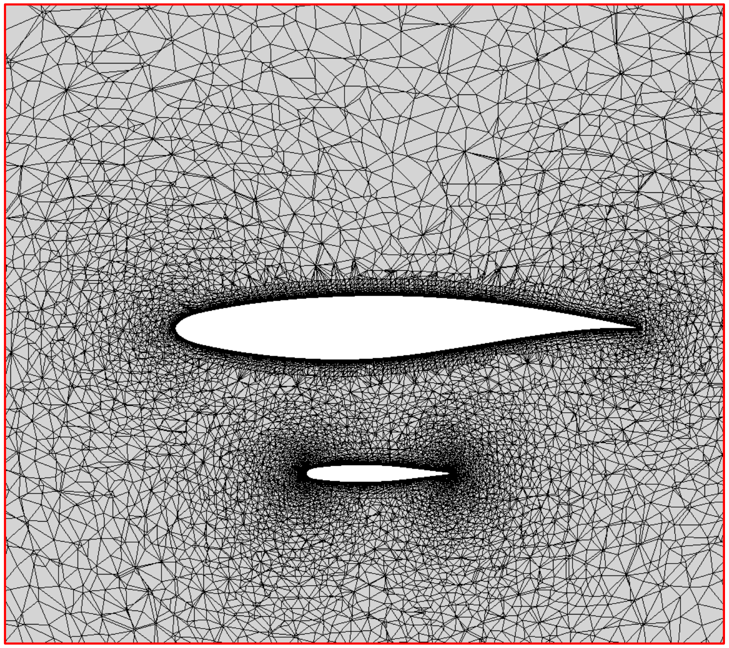
Workshop Grid





VGRID Grid

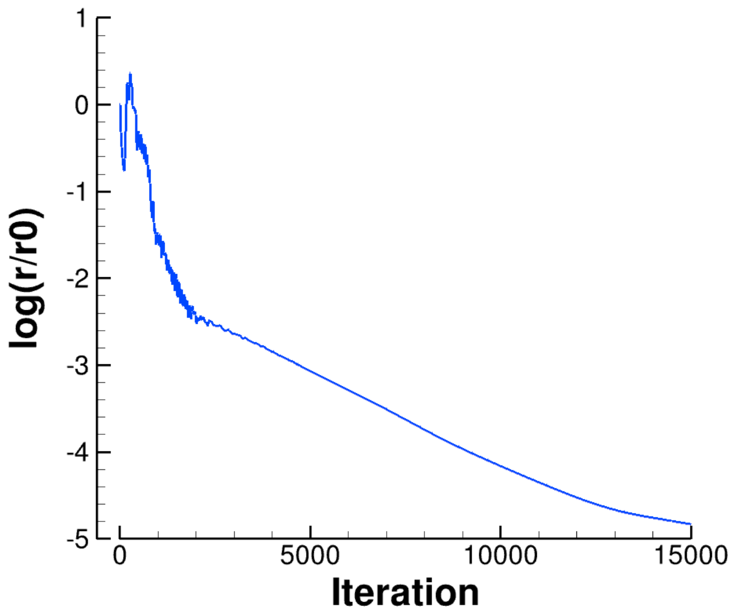


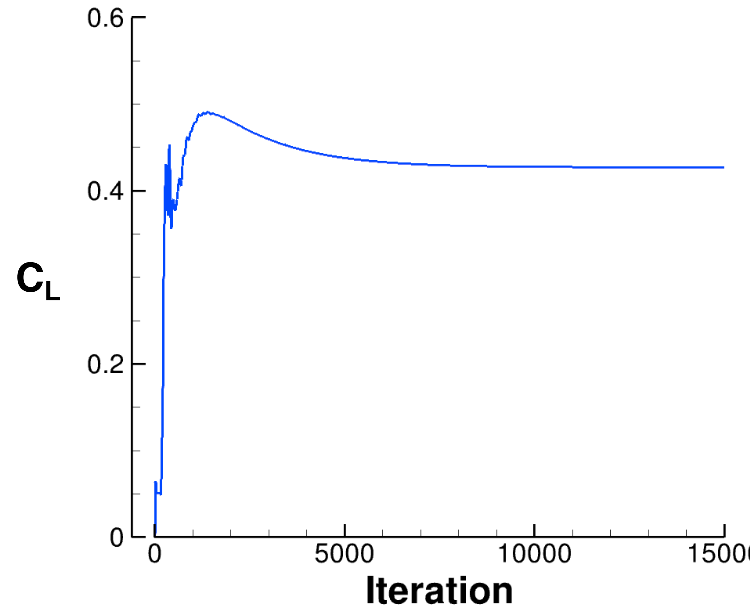


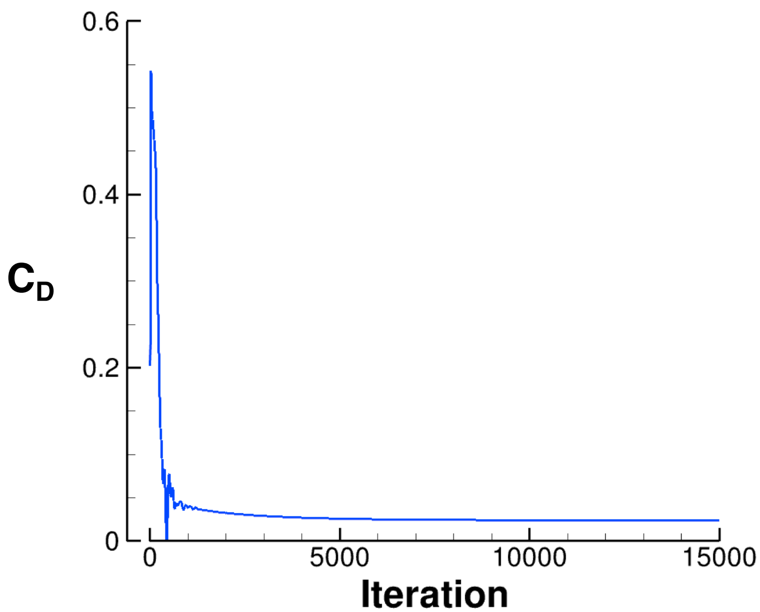
Surface mesh view of wing/strut lower surface

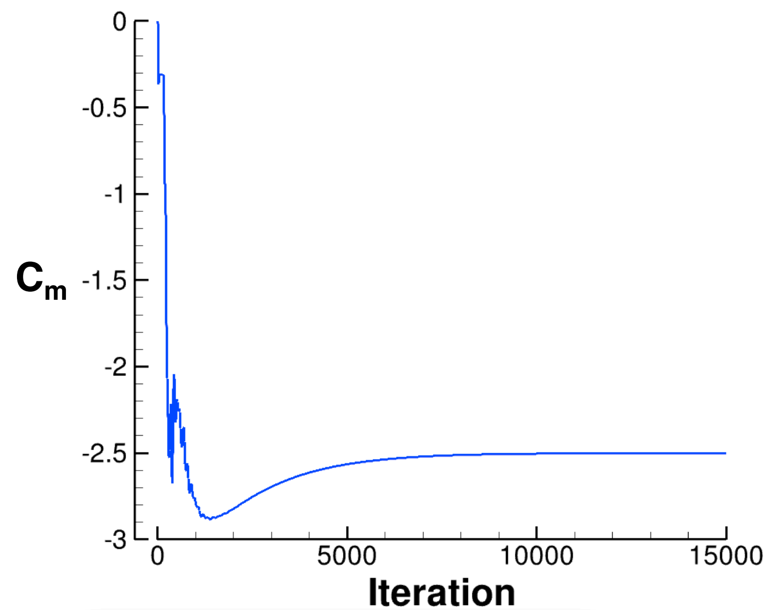
Volume mesh view of wing/strut slice at Y = 15.0 m

Baseline USM3D Solution Convergence







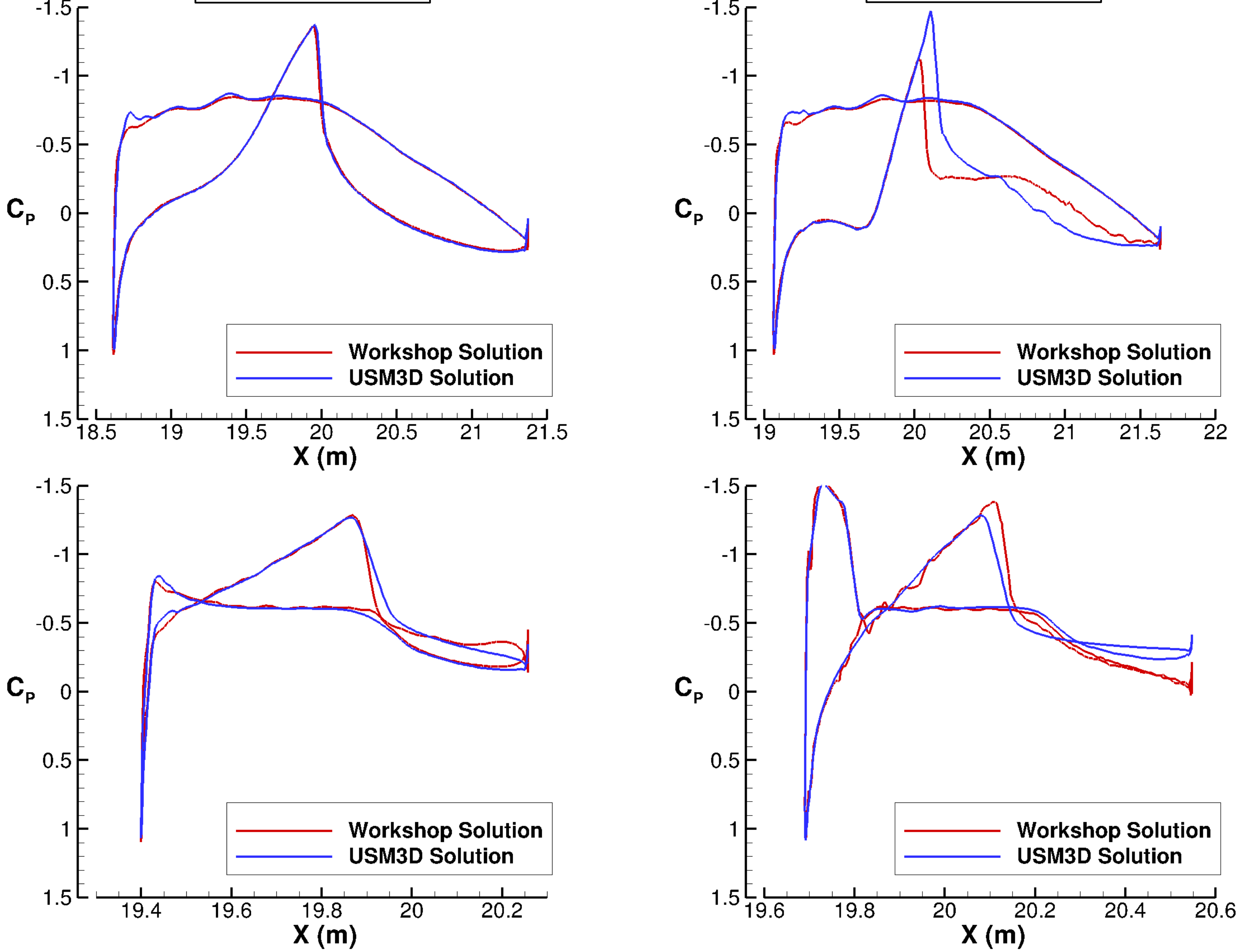


Baseline Solution Comparison: Pressure

Y = 15.0 m | **Y = 16.5 m**

Wing

Strut

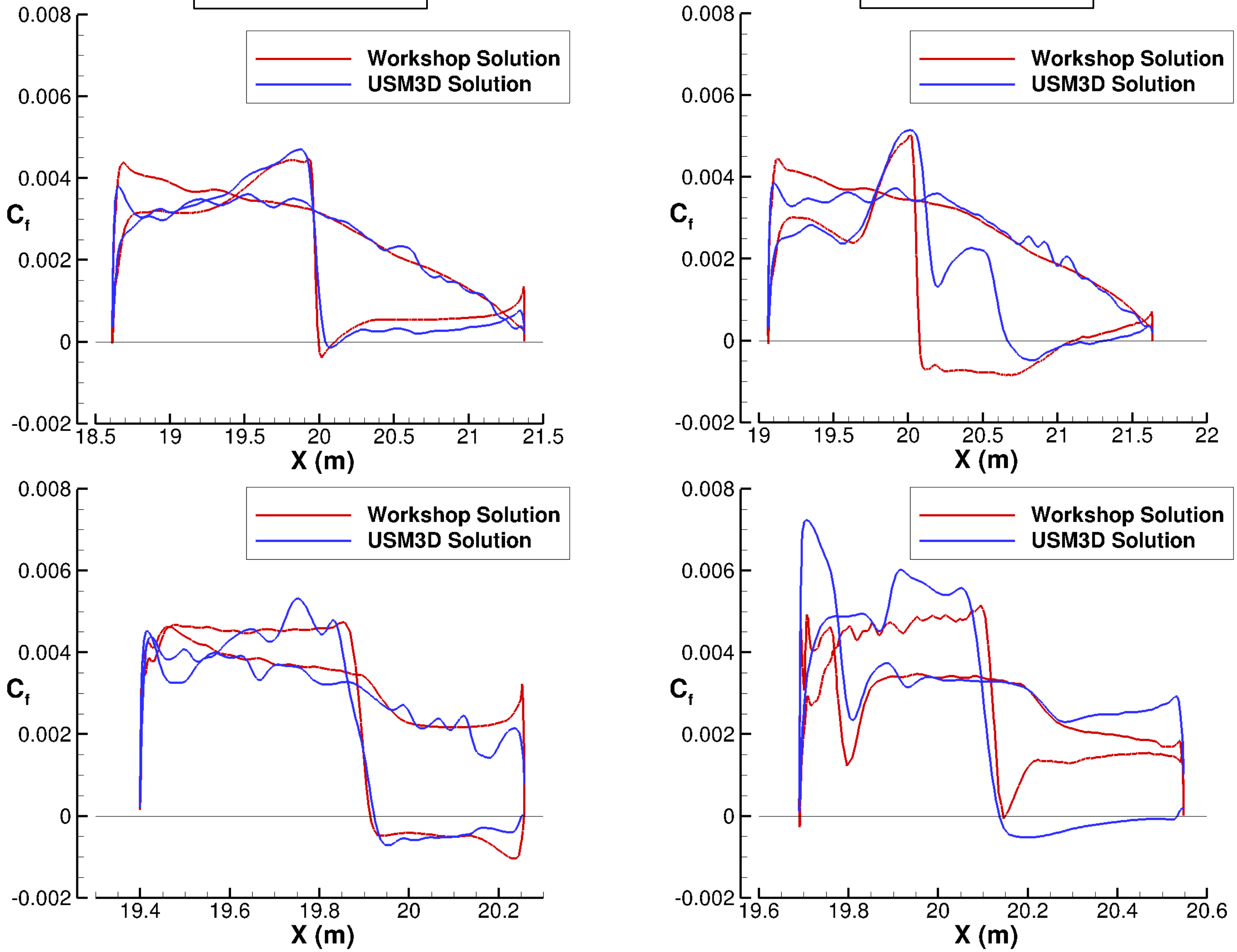


Baseline Solution Comparison: Skin Friction

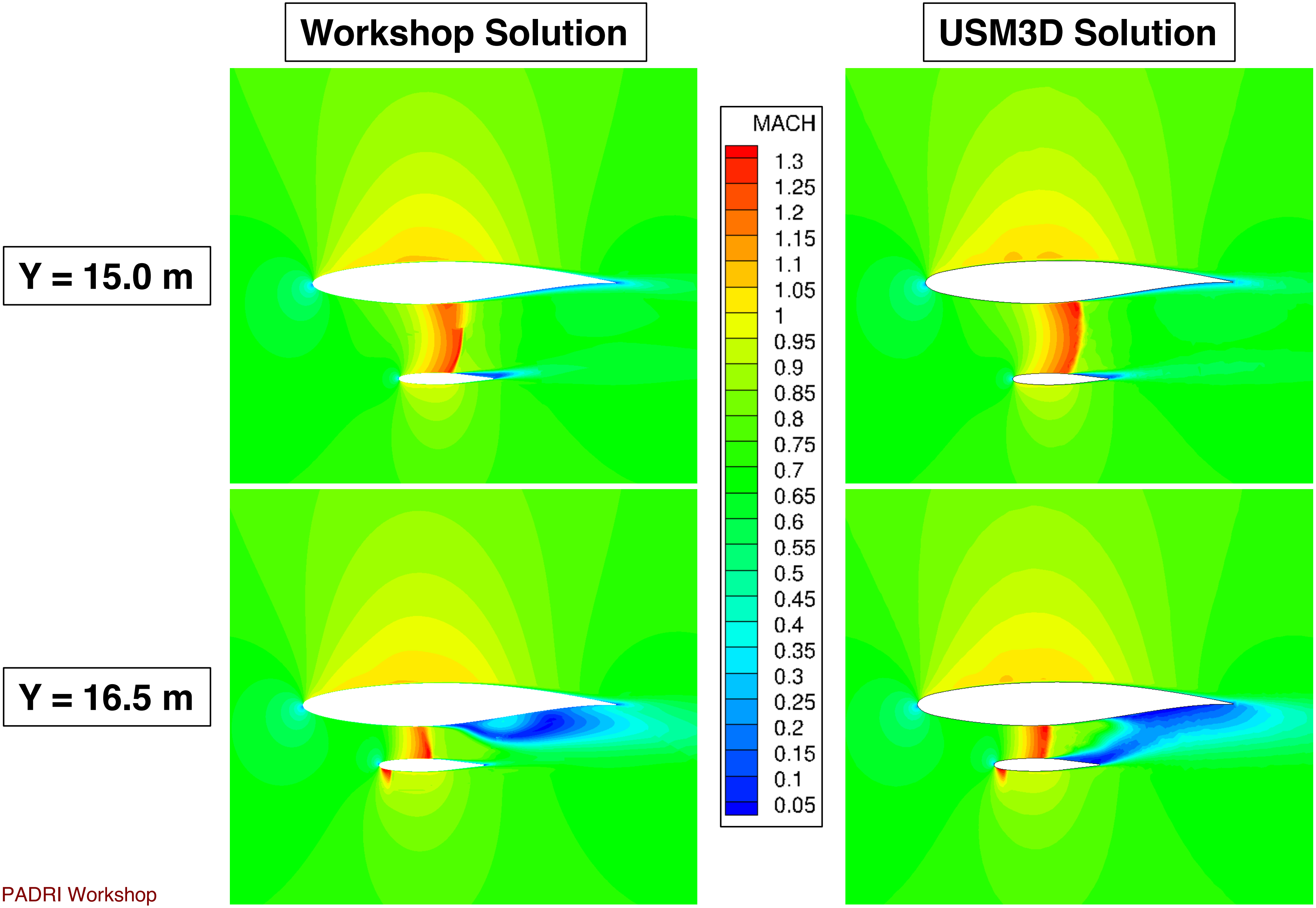
Y = 15.0 m | Y = 16.5 m

Wing

Strut



Baseline Solution Comparison: Mach Contour



Baseline Solution Comparison Summary

- USM3D and Workshop baseline solutions are generally in good agreement
- Results at Y = 16.5 m show some difference in shock strength and separation extent, not enough information on Workshop solution to assess cause of differences
- Initial studies with USM3D using multiple grids and grid generators showed similar differences with Workshop solution at Y = 16.5 m
- Final grid for design studies chosen based on reasonable size and stronger shock (conservative)

Approaches to Drag Reduction

- Introduction
- Baseline Evaluation
- **Approaches to Drag Reduction**
  - **Aerodynamic Design (CDISC)**
  - Passive Porosity (PASSPORT)
  - Comparison of CDISC and PASSPORT Results
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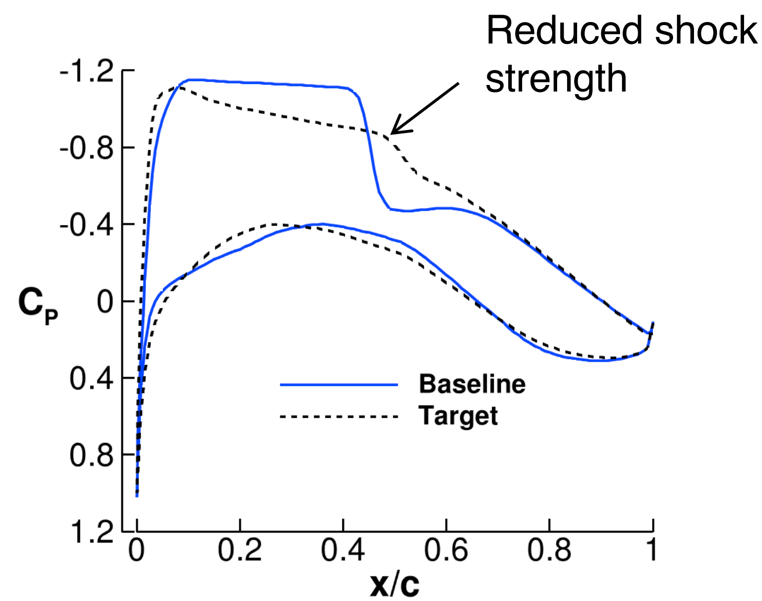
CDISC Design Method

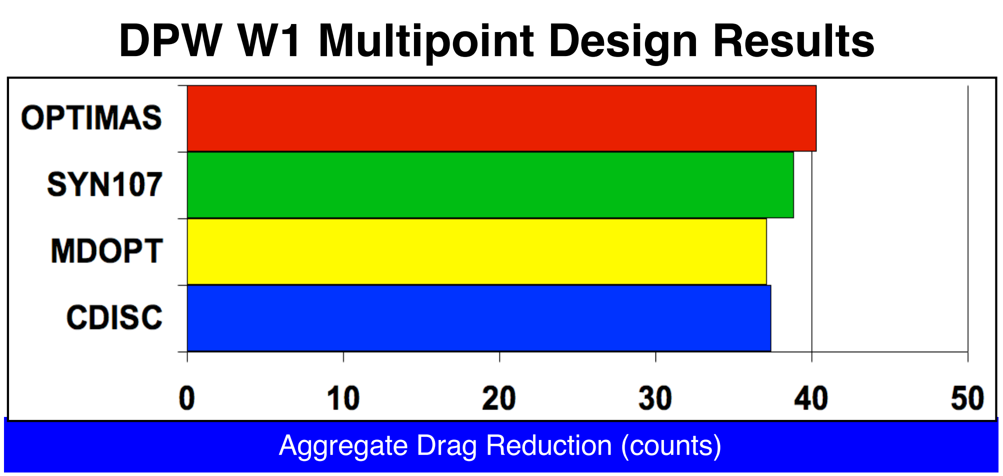
- Knowledge-based design uses prescribed flow/geometry sensitivity derivatives
- Flow constraints automatically generate target pressure distributions from current analysis pressures
- Geometry constraints incorporate multidisciplinary influences
- Modular Linux script approach allows easy coupling of CDISC with a wide range of flow solvers (USM3D, CART3D, MSES, OVERFLOW, CFL3D, PMARK, FUN3D, etc.)

- Design time ≈ analysis time (1-3 orders of magnitude faster than optimization)
- Allows use of same level of geometric and flow physics fidelity in design and analysis

CDISC Applications for Drag Reduction

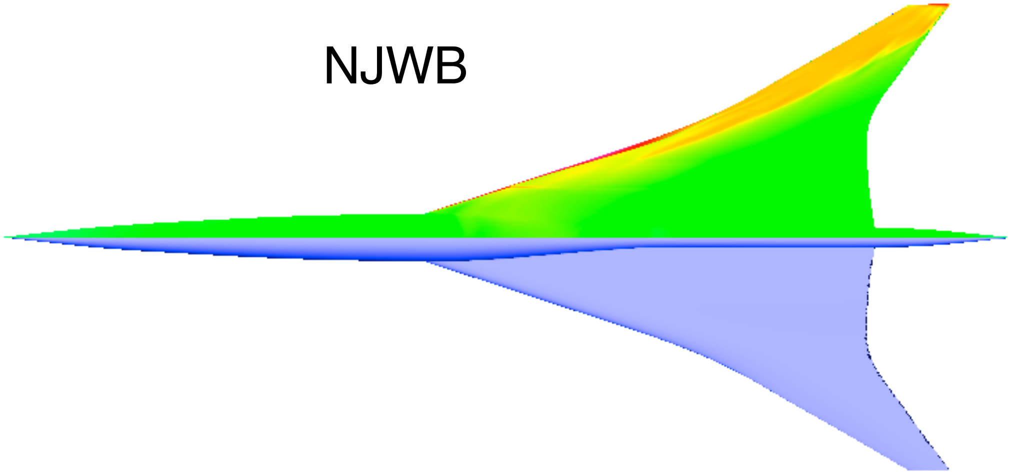
- Drag Prediction Workshop (DPW) W1 Wing
- Gulfstream G650
- FAST-MAC National Transonic Facility model
- D8 “Double Bubble”
- Truss-Braced Wing
- Lockheed Martin Advanced Hybrid Wing Body
- Boeing High Speed Slotted Wing



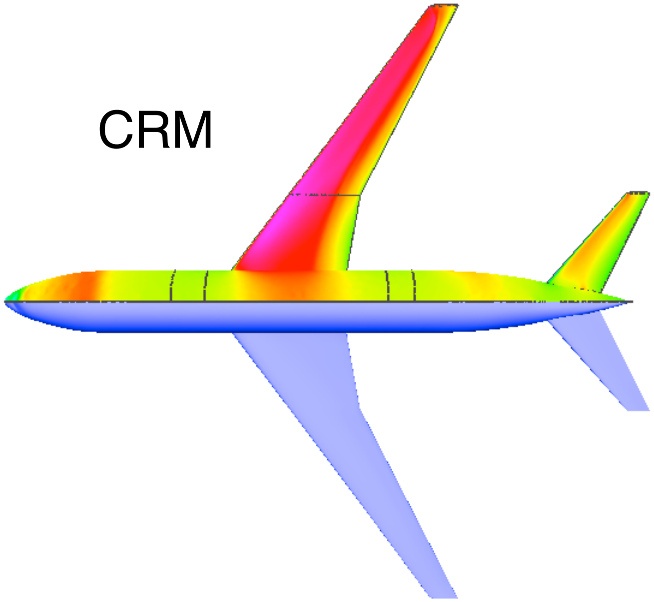


CDISC Applications for Laminar Flow

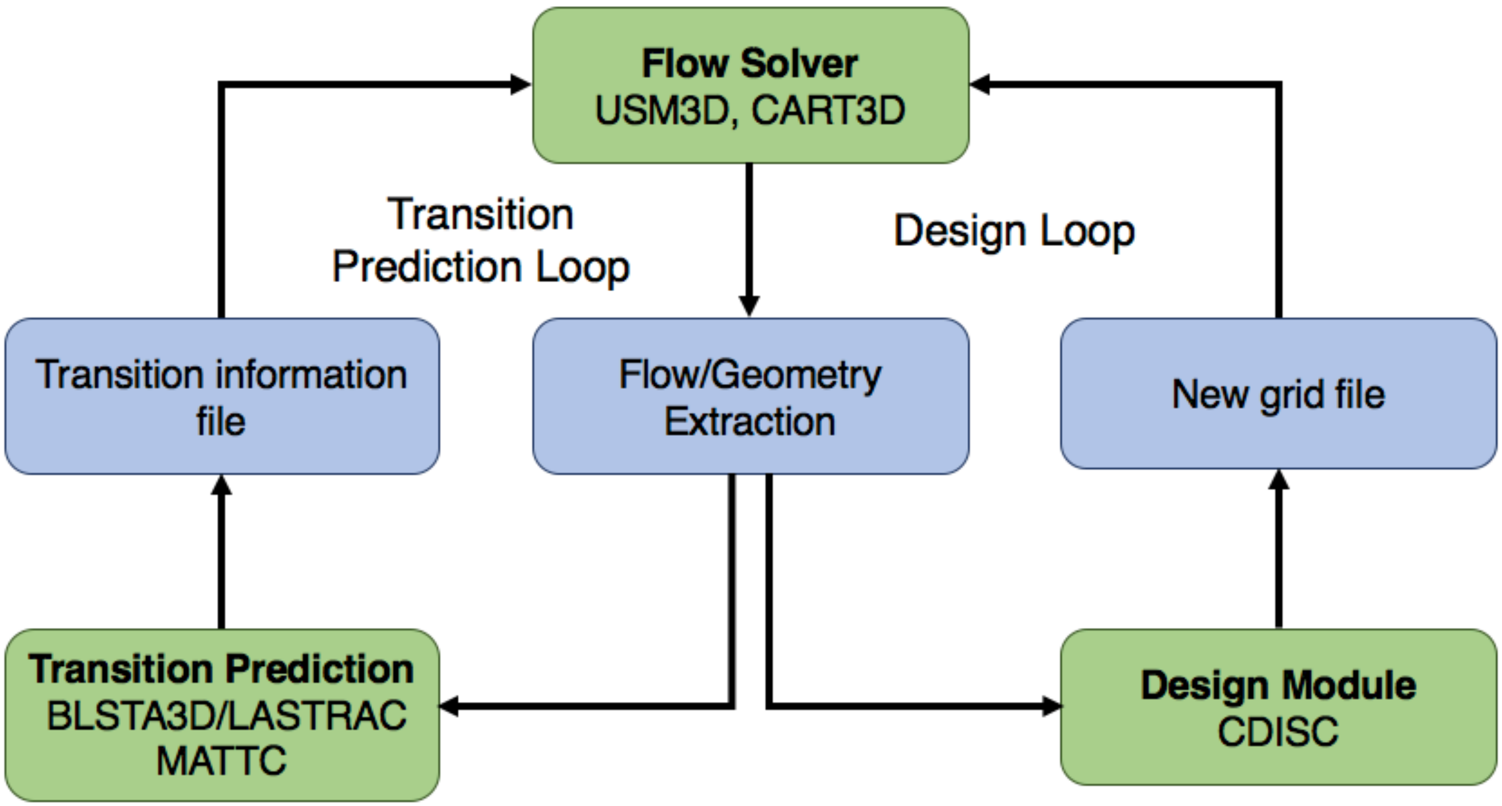
NJWB



CRM



CDISC Flow Chart



CDISC Constraints Used in SBW Design

Flow Constraints:

- Mach levels limits
  - $M_{shock} < 1.0$ on wing
  - $M_{shock} < 1.1$ on strut
- Modified Uniform Distribution (MUD) to unload strut
- C_P smoothing

Geometry Constraints:

- Section $(t/c)_{max}$ and leading-edge radius fixed
- Curvature limits, surface and twist smoothing for realistic geometry
- "Hard surface" restriction applied to wing lower surface

$$c_{d,wave} = \frac{0.49}{k} * (M_{shock} - 1)^{4.39}$$

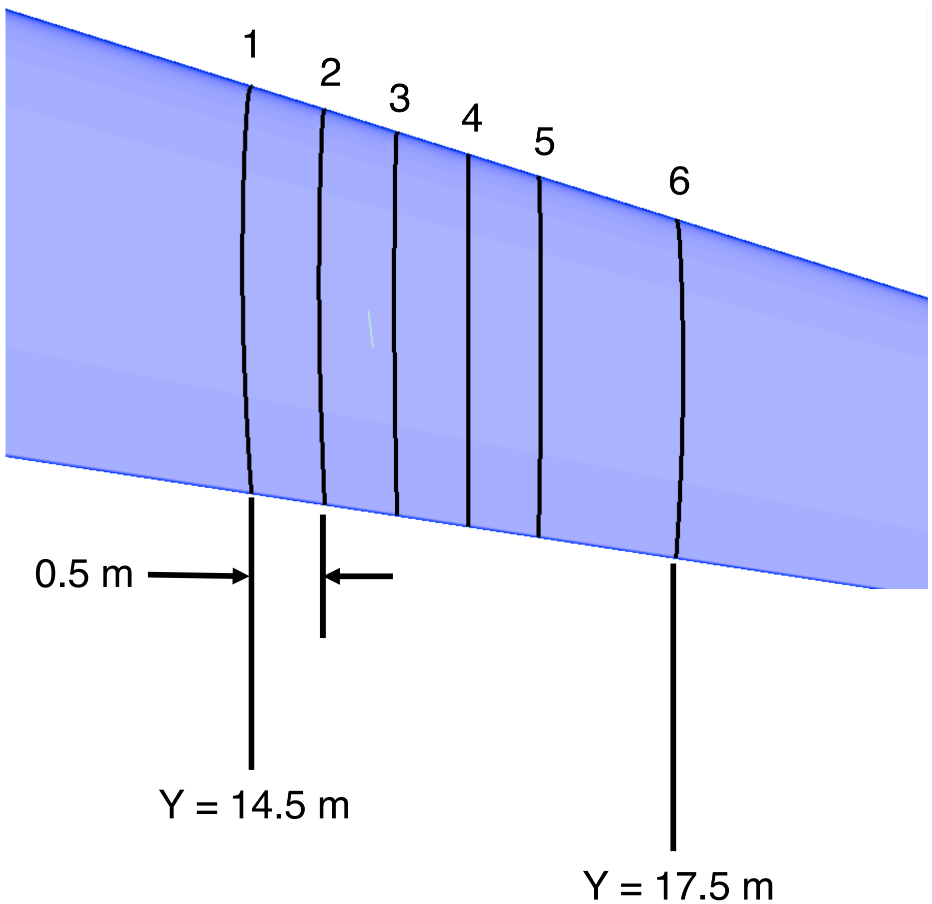
where k is surface curvature, shows that

M_{shock} < 1.1 produces less than 1 count of wave drag

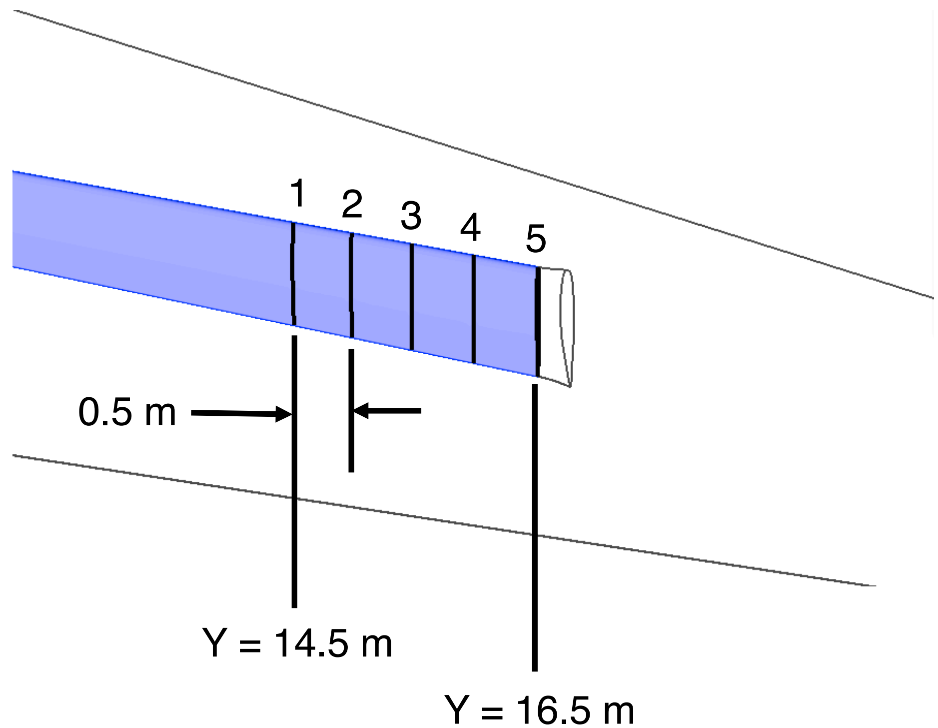
(AIAA 2011-3527)

CDISC Design Station Layout

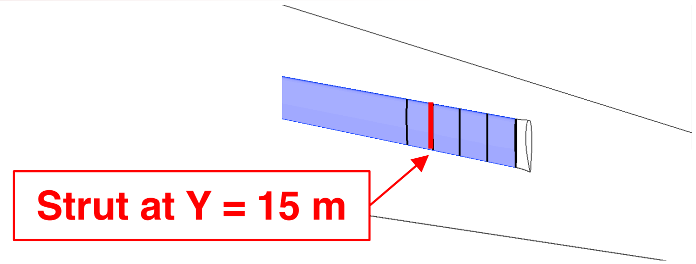
Wing

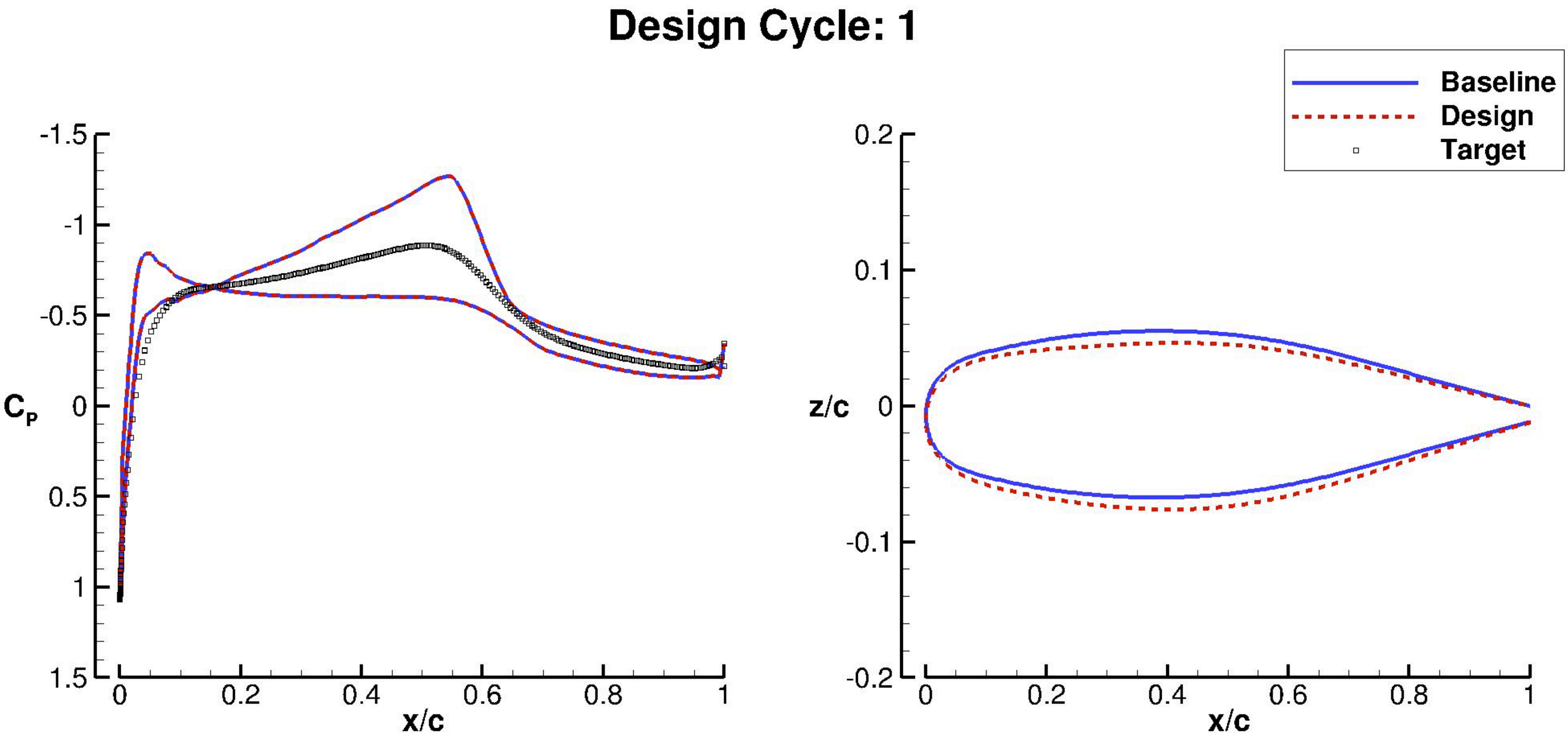


Strut

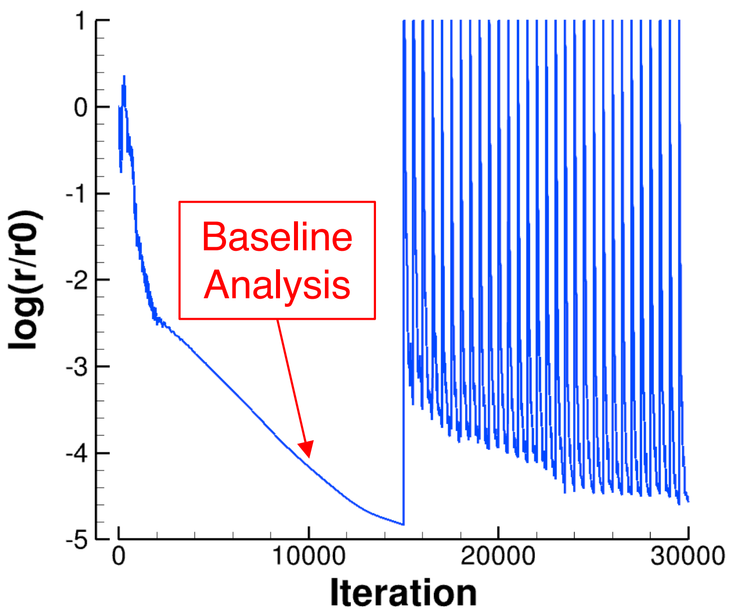


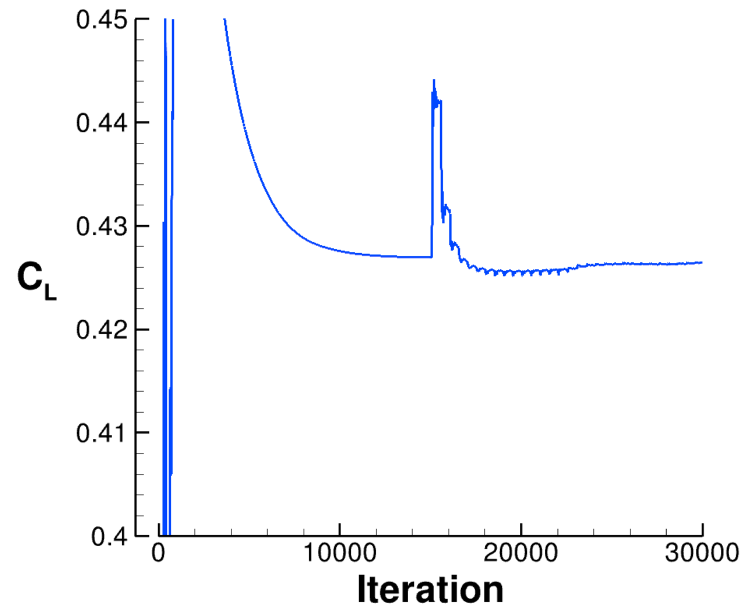
Example of CDISC Design Process

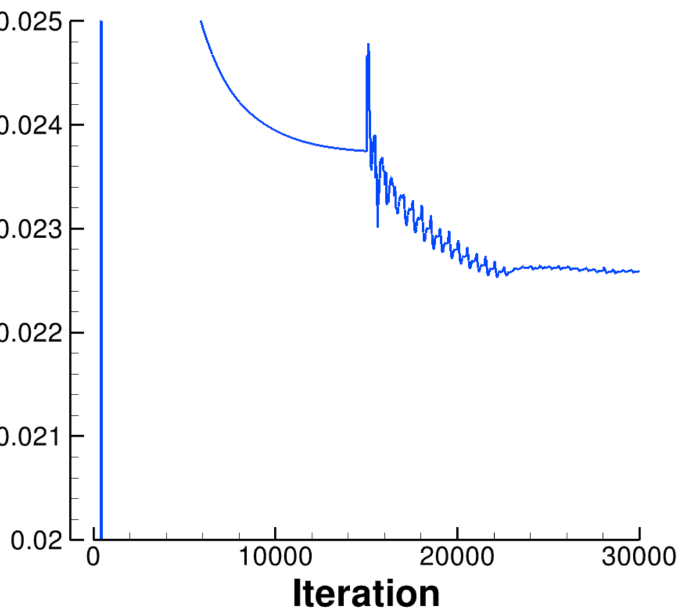


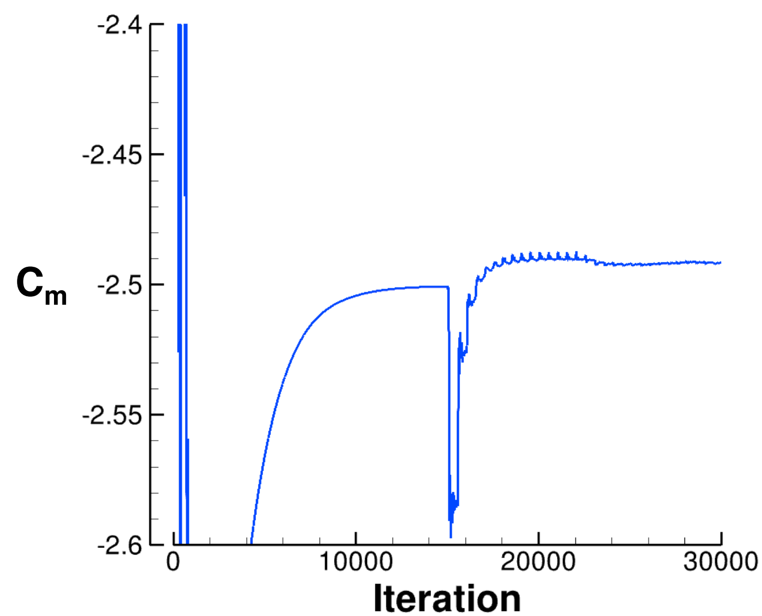


USM3D Convergence for CDISC Design

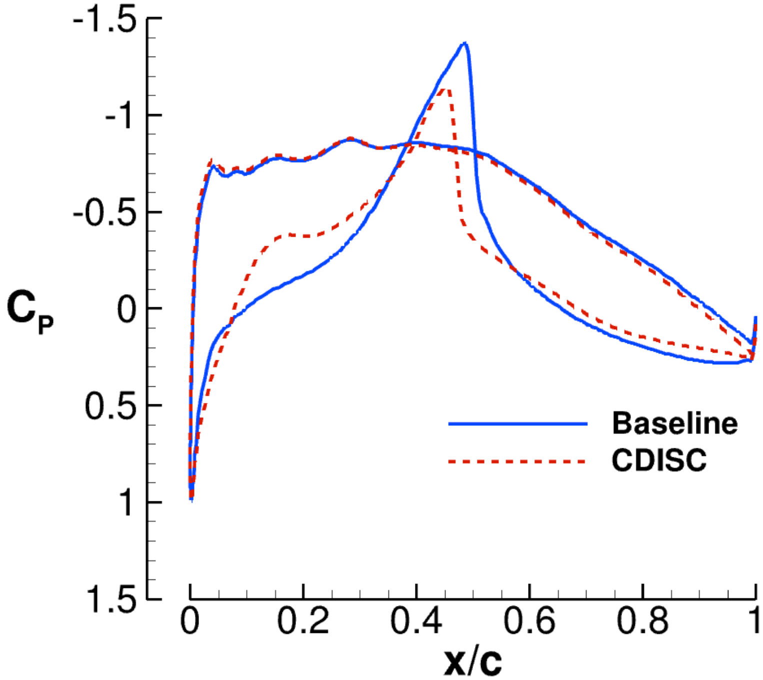


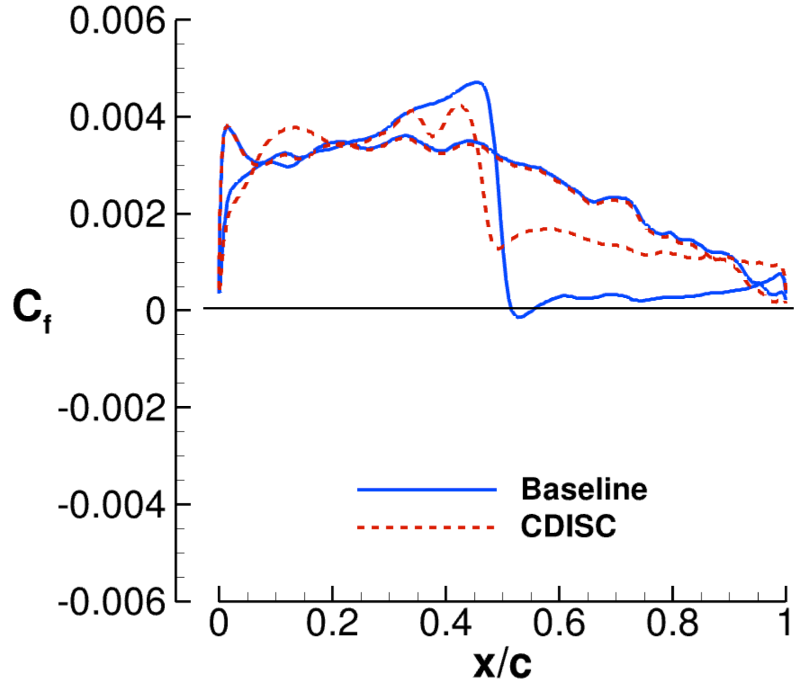


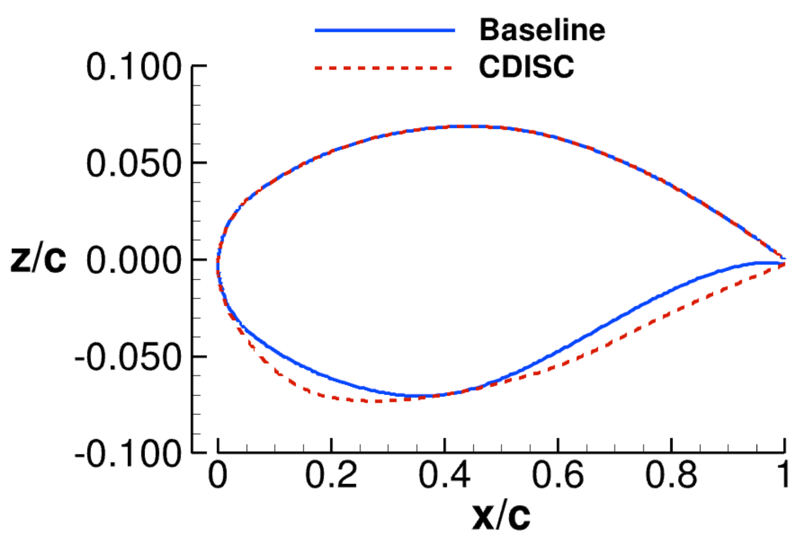




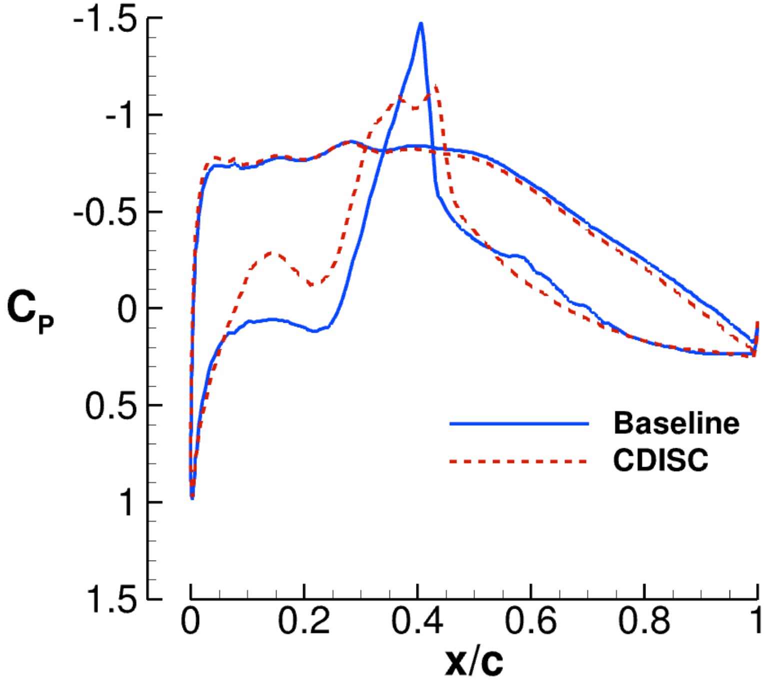
CDISC Results: Wing at Y = 15.0 m

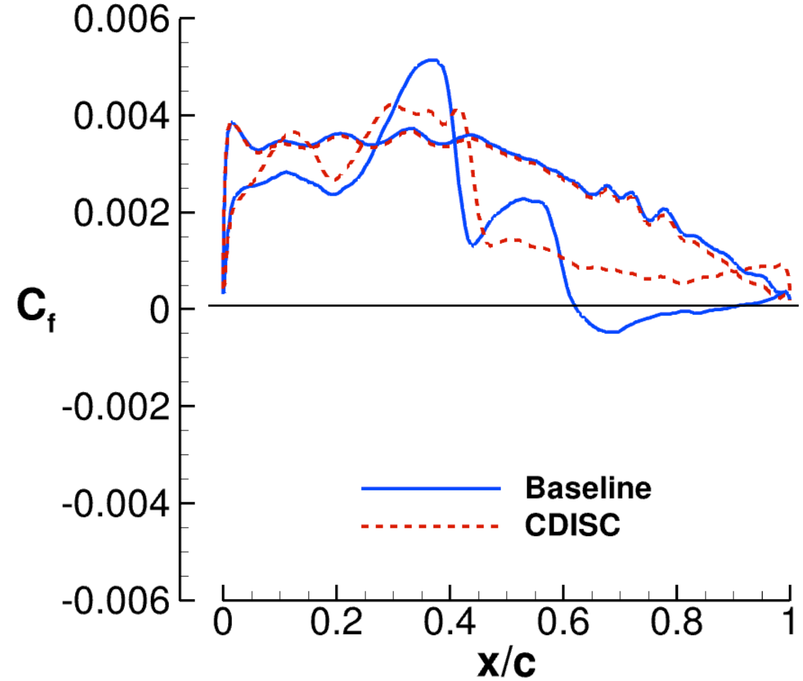


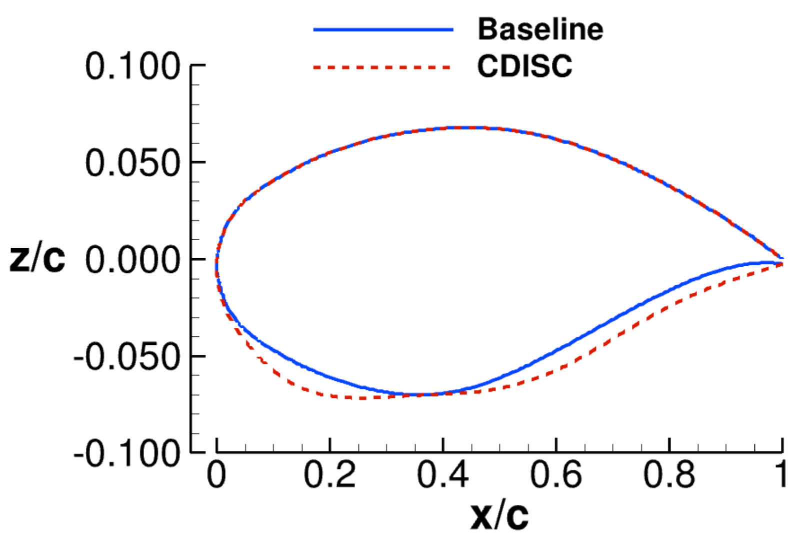




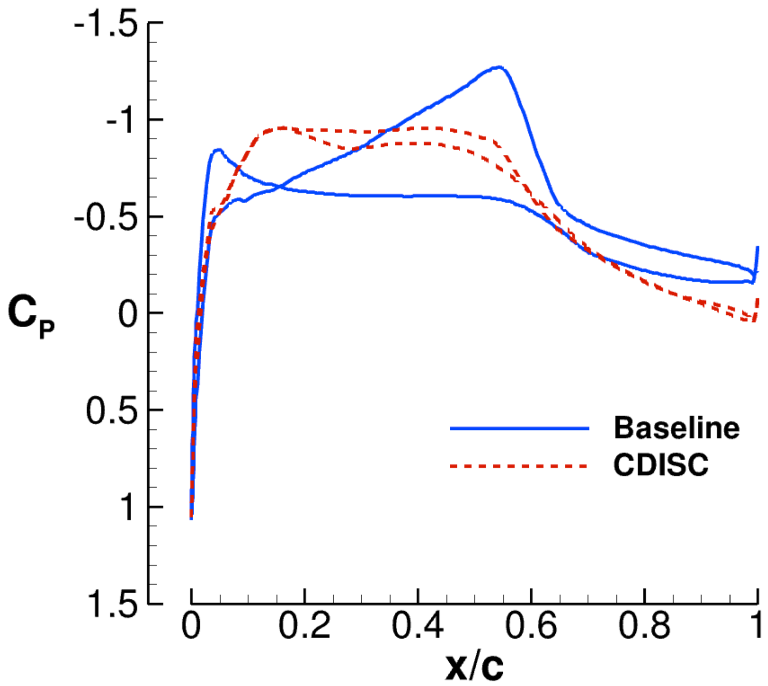
CDISC Results: Wing at Y = 16.5 m

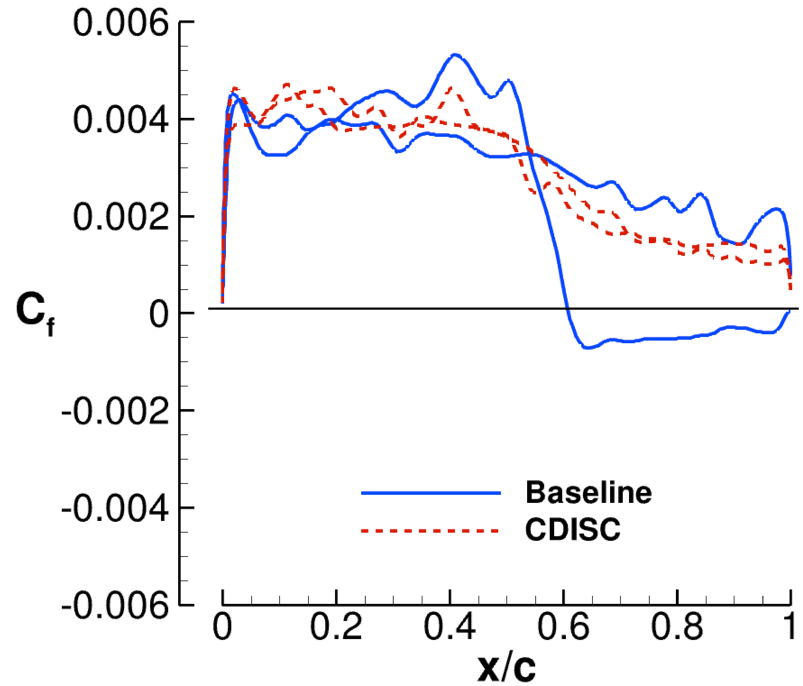


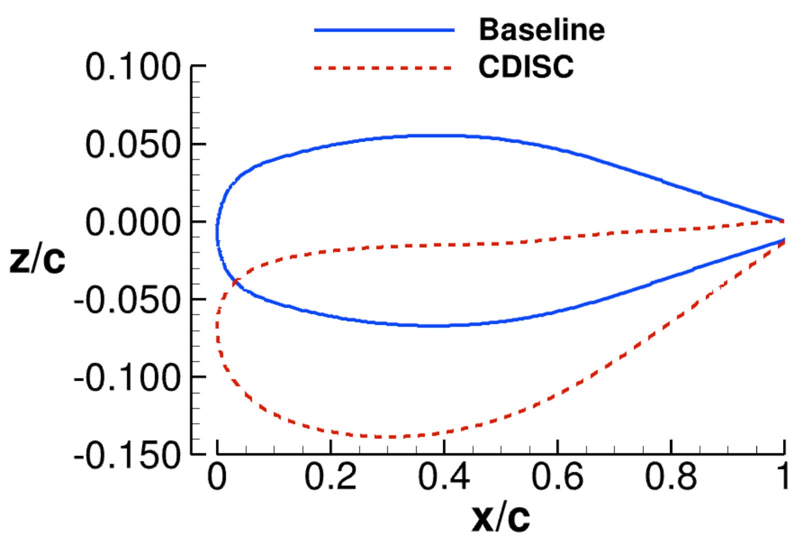




CDISC Results: Strut at Y = 15.0 m







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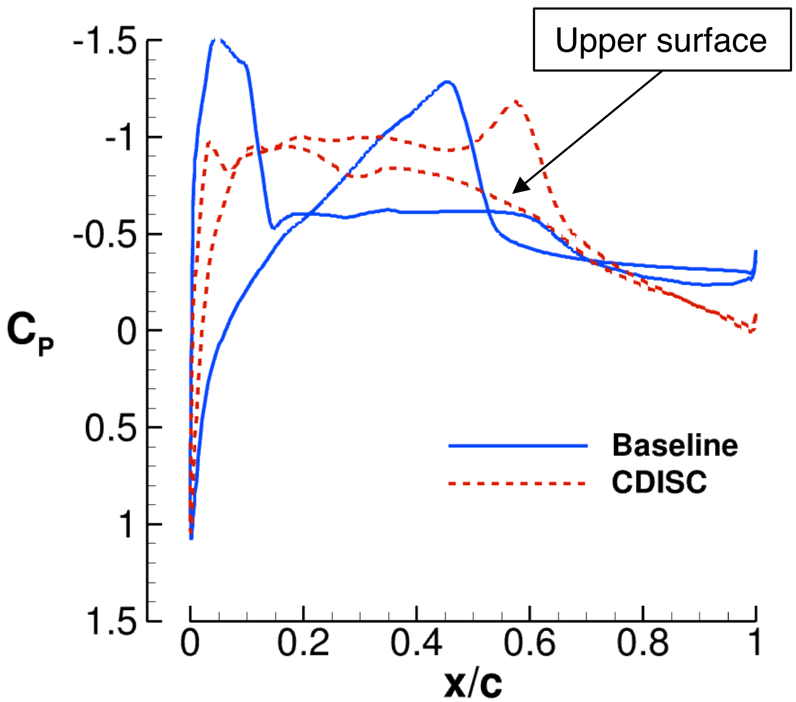
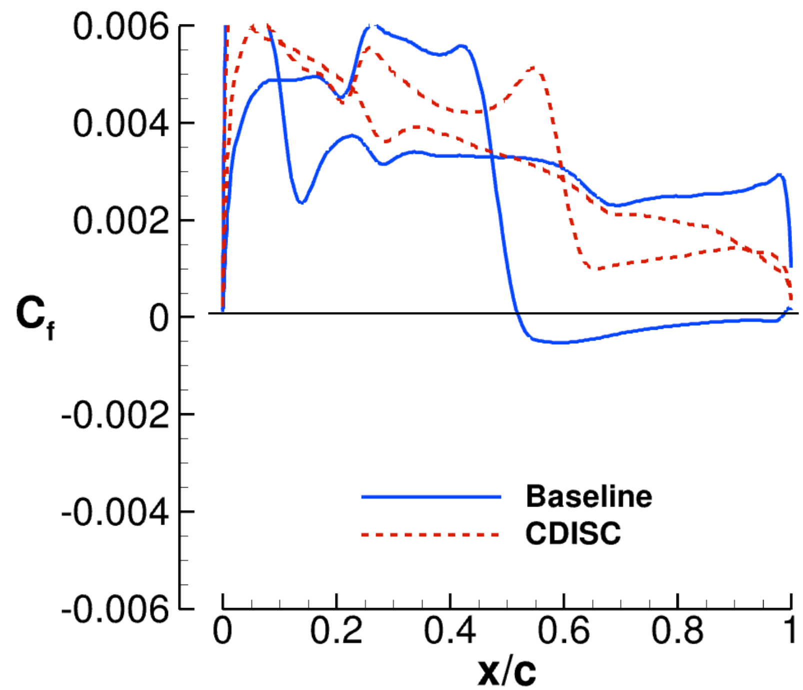
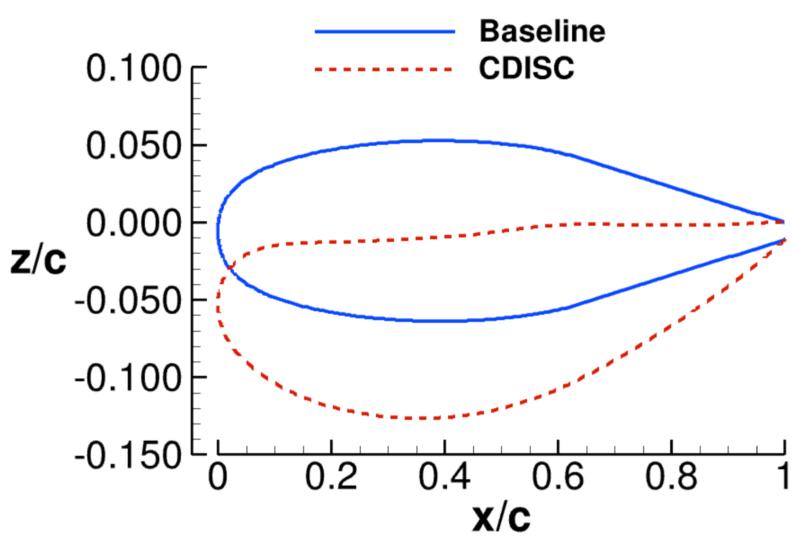




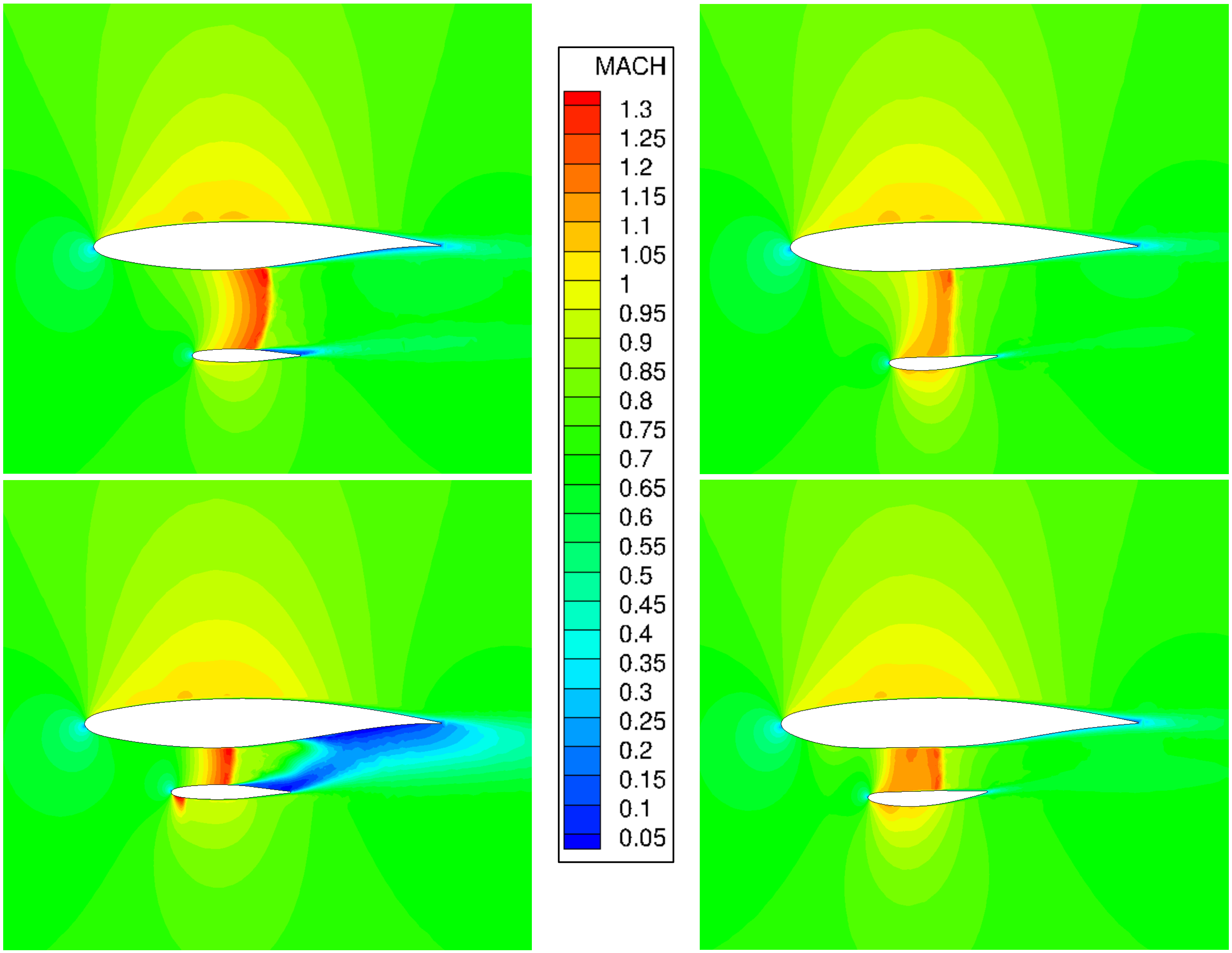


CDISC Results: Mach Contour

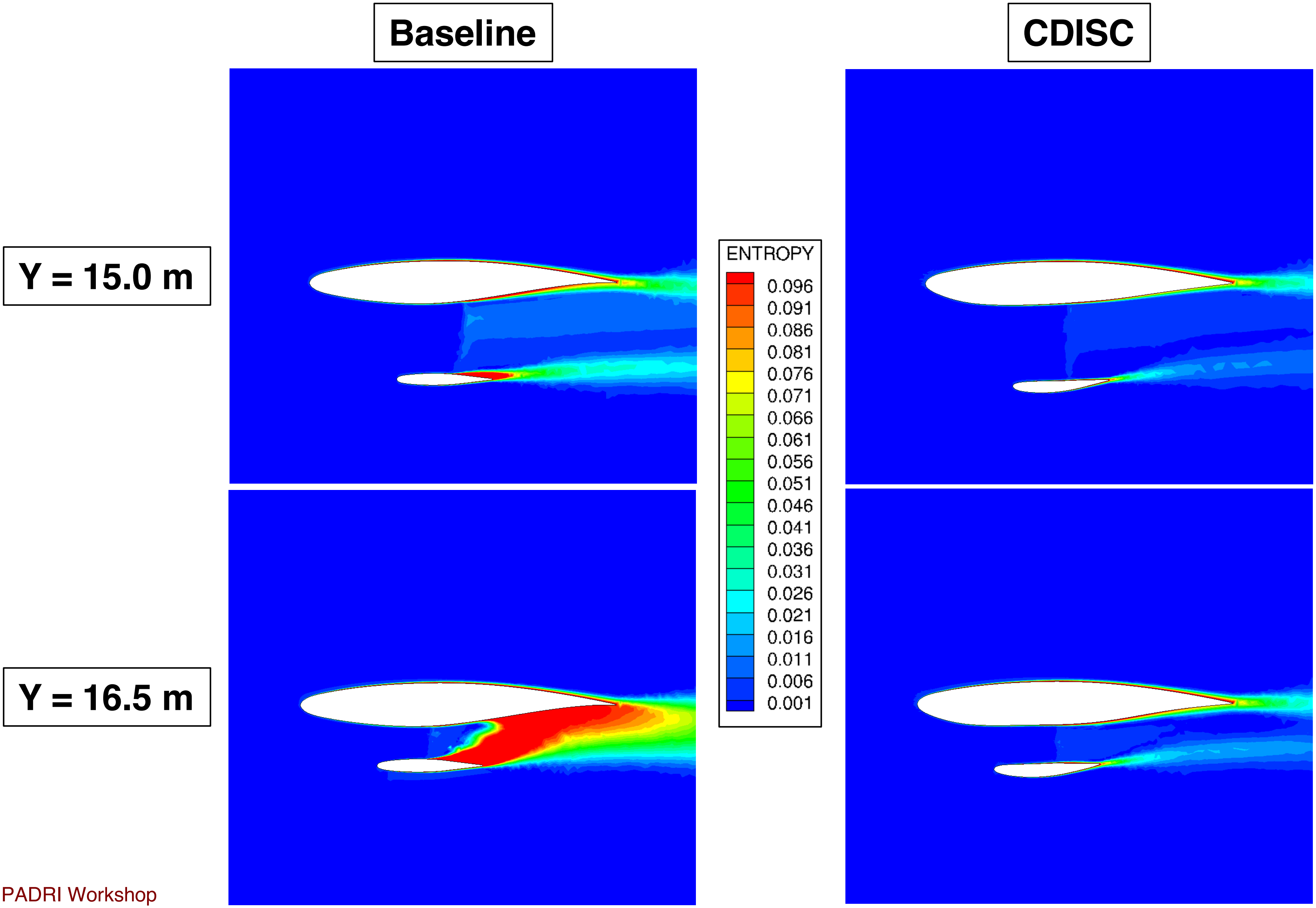
Baseline | **CDISC**

Y = 15.0 m

Y = 16.5 m

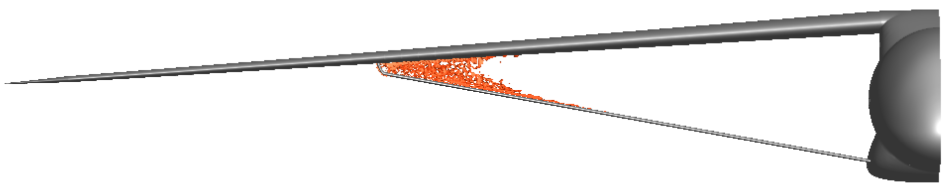


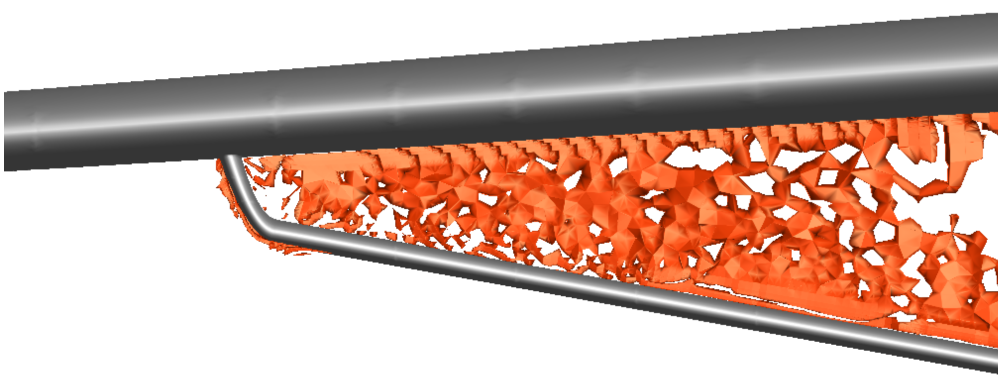
CDISC Results: Entropy Contour



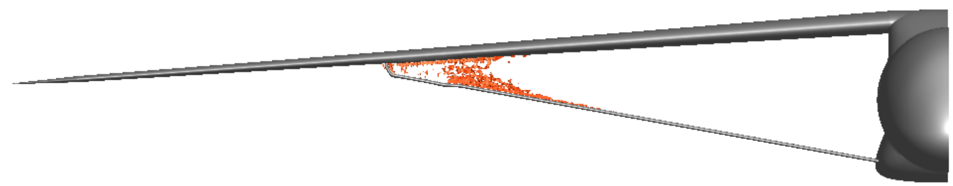
CDISC Results: M = 1.1 Shock Isosurface

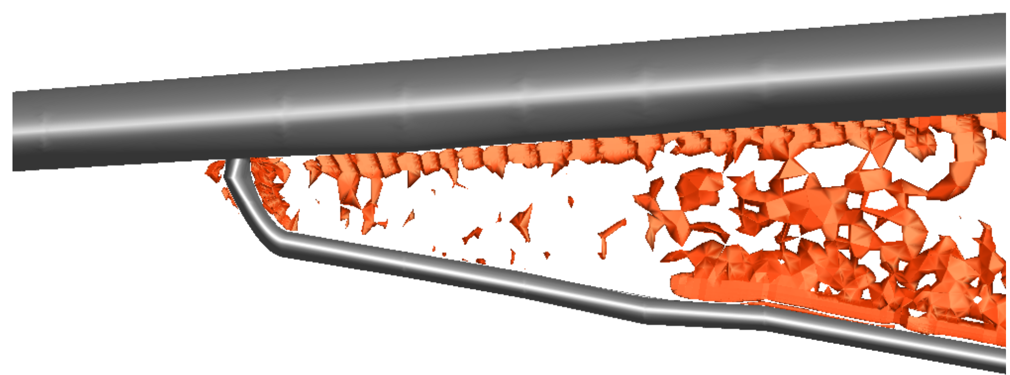
Baseline





CDISC





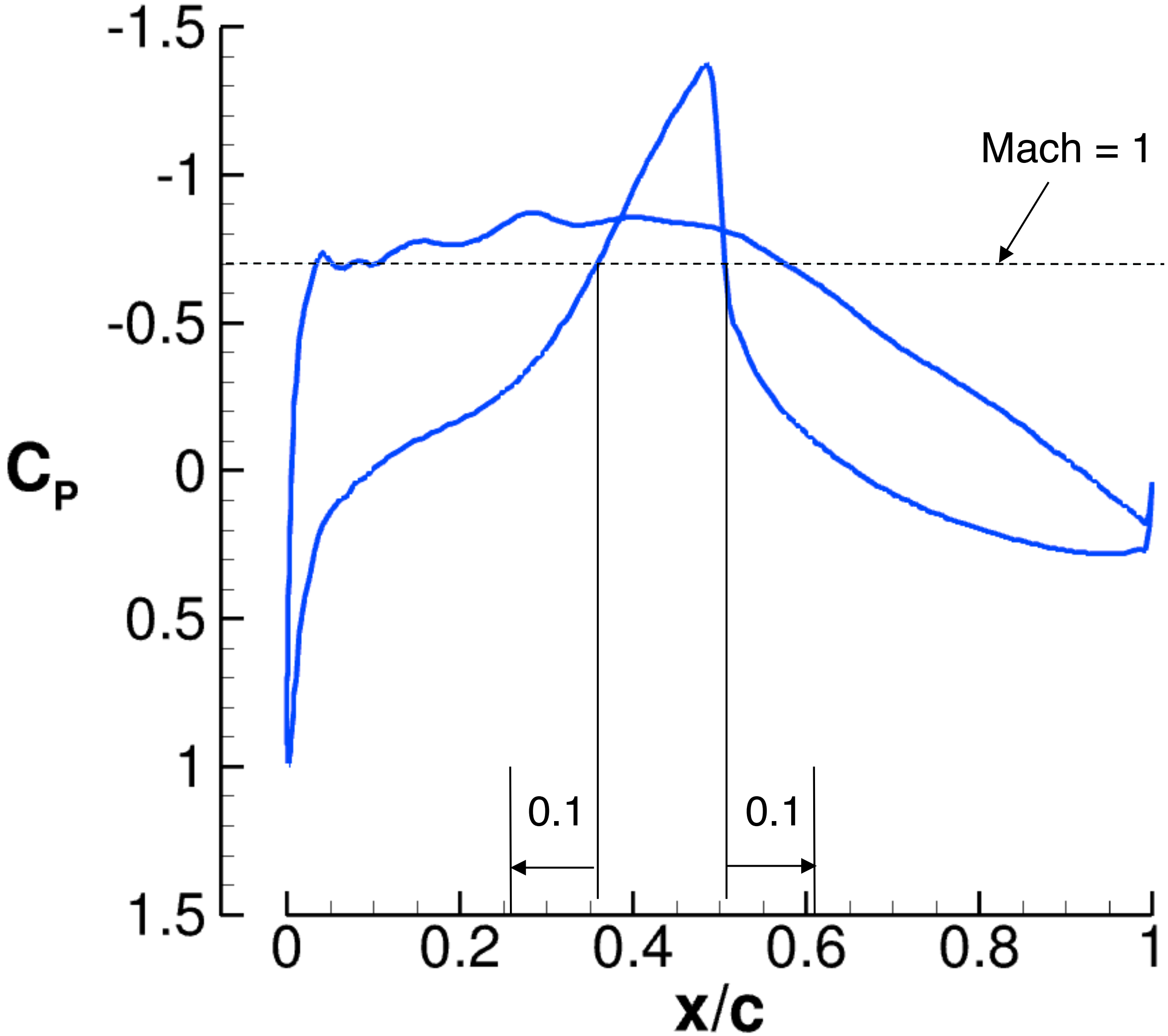
One-Shot Design Approach

- CDISC CHANL constraint creates a flat-sided channel between the wing lower surface and the strut upper surface
- Wing lower surface flattened while remaining outside of original airfoil, extent based on amount of supersonic flow
- Strut rotated down slightly, then cambered to make most of upper surface flat
- Lower surface curvature constrained while maintaining original maximum t/c
- No target pressures used, only 1 CDISC cycle required

➔ Wing-only, strut-only, and wing-strut cases run, wing-strut case had the most drag reduction

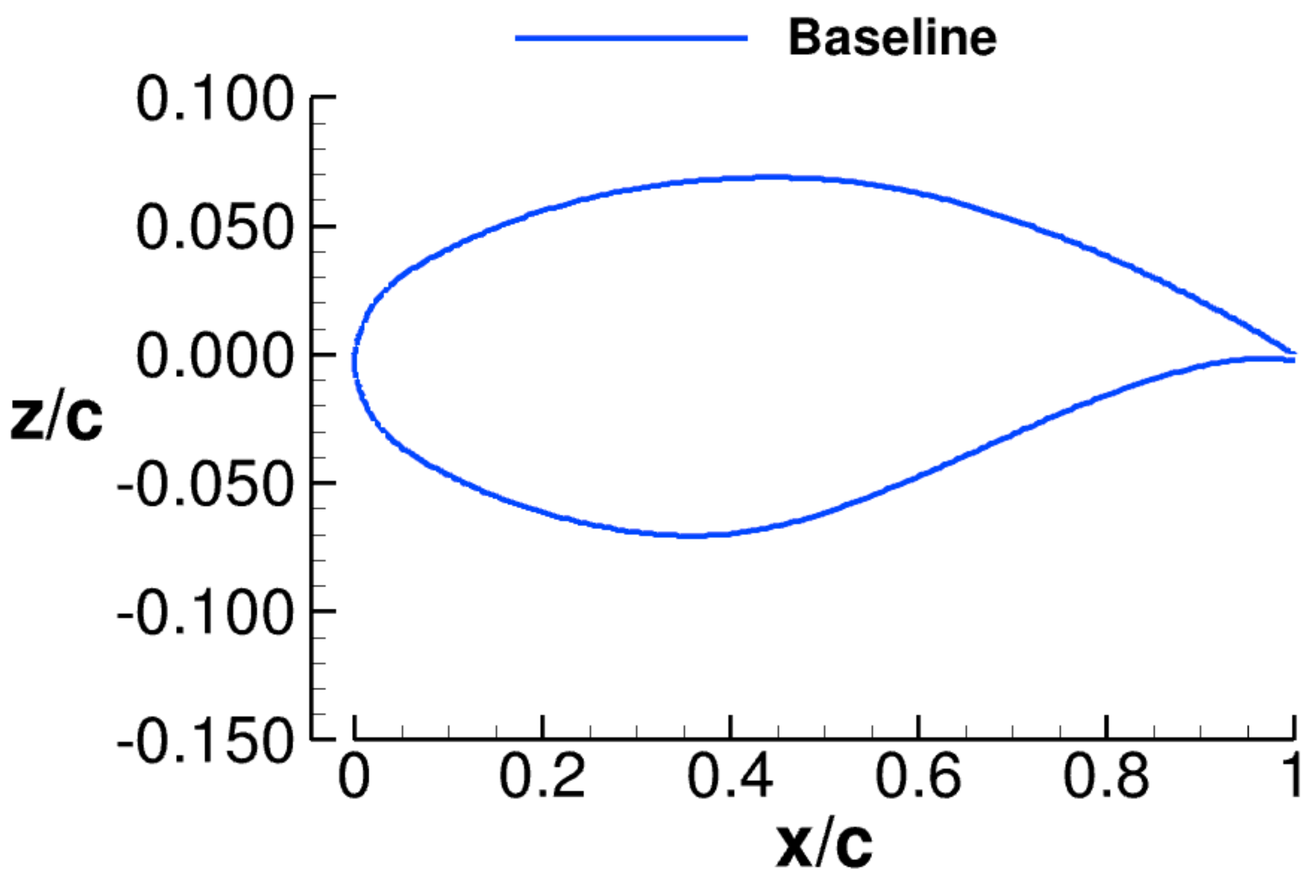
One-Shot Design Process for Wing

Define lower surface region to be flattened



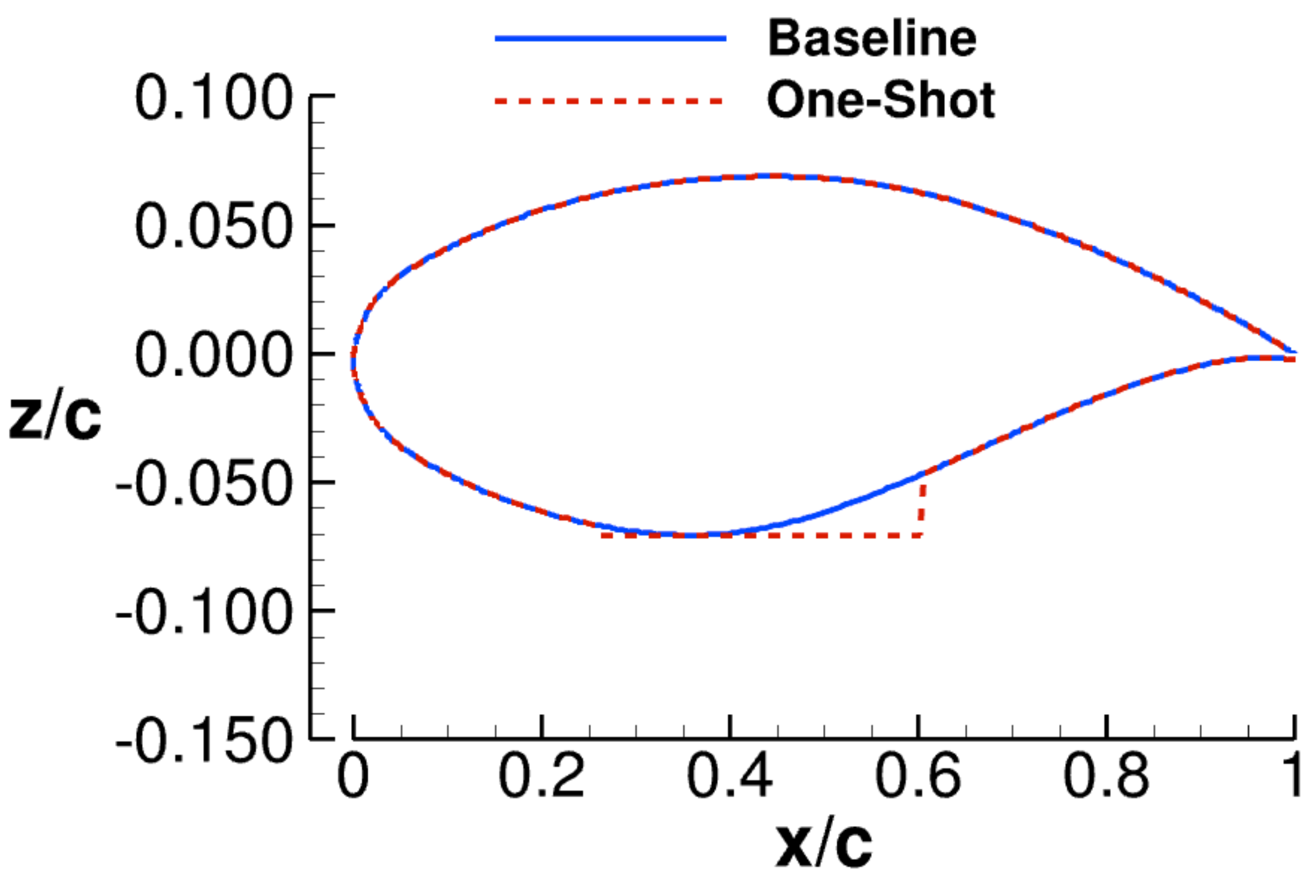
One-Shot Design Process for Wing

Baseline airfoil



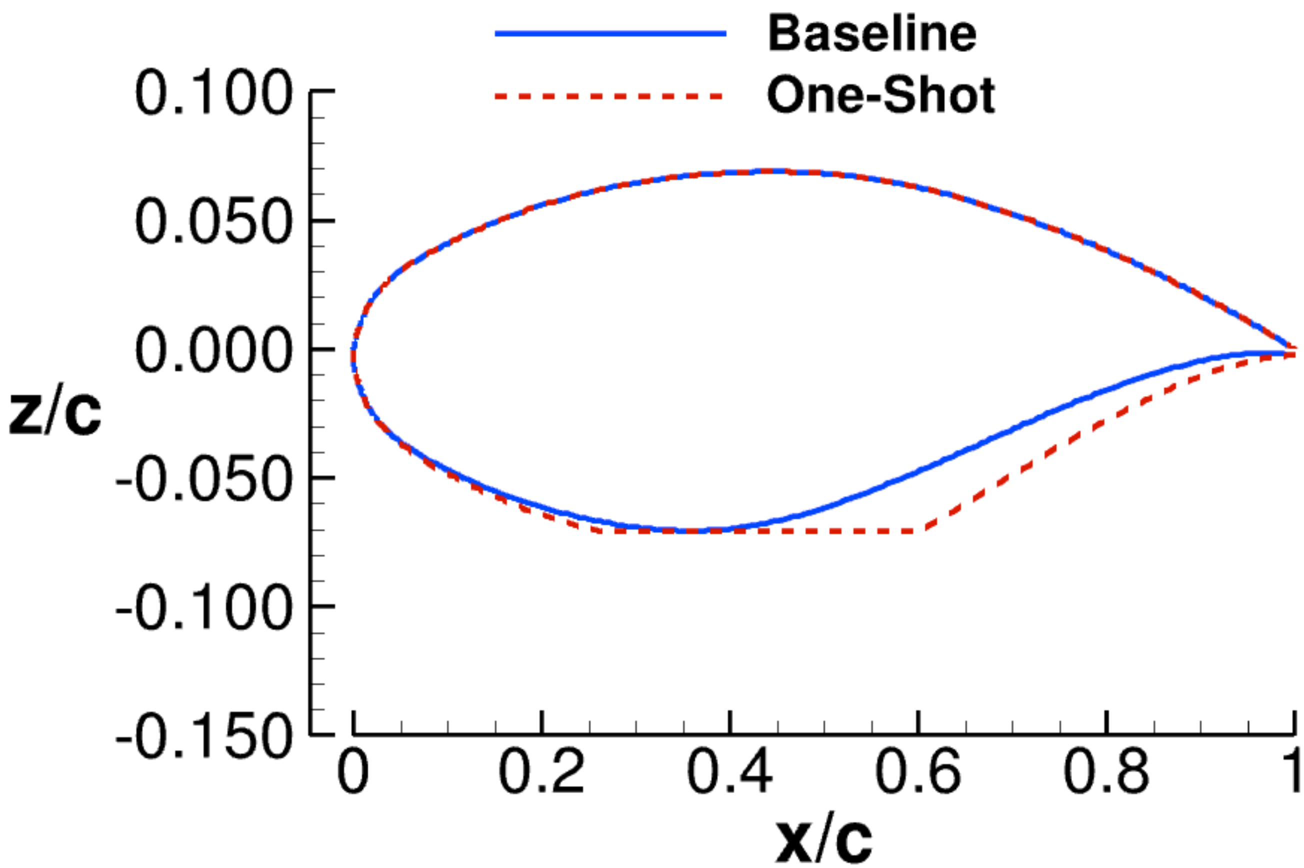
One-Shot Design Process for Wing

Add flattened region



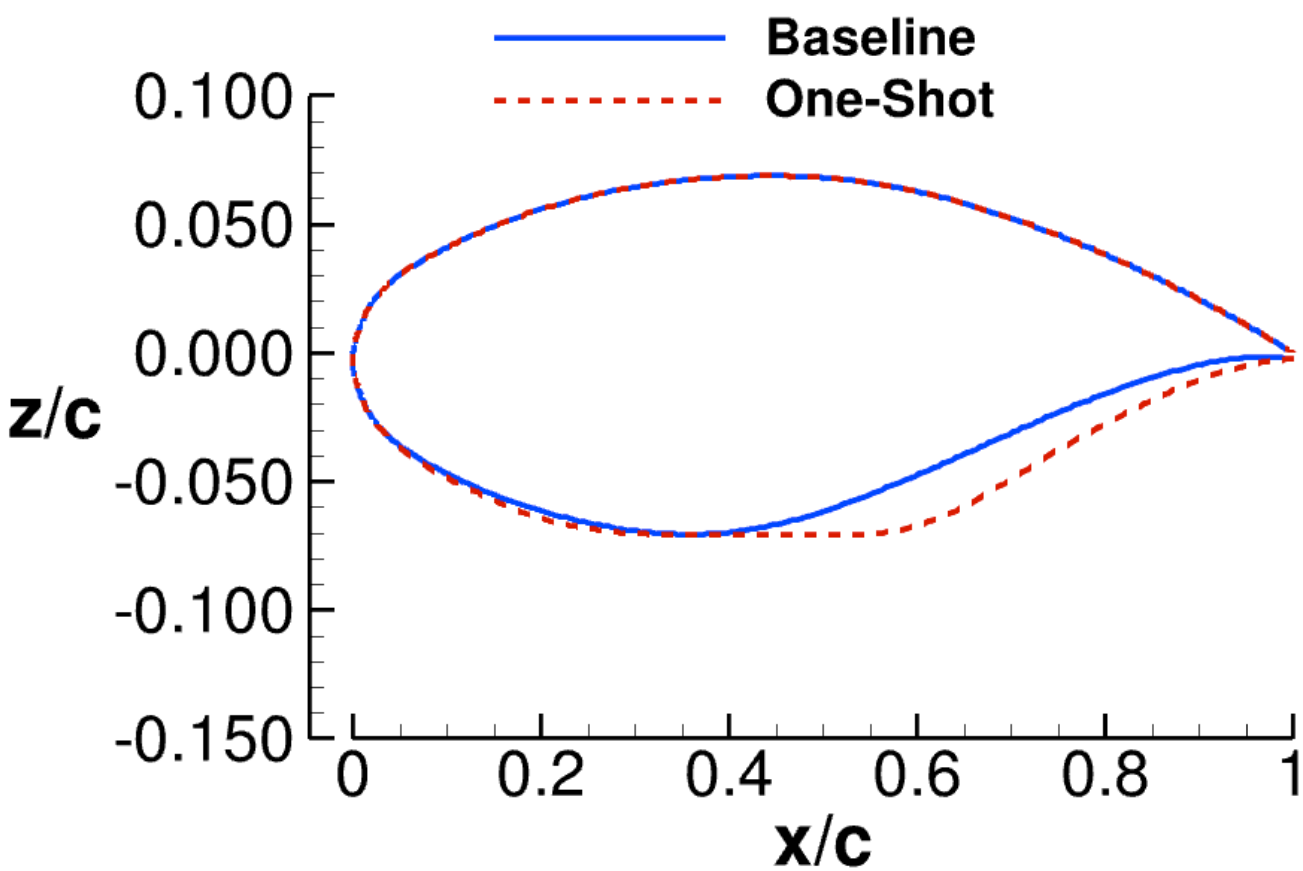
One-Shot Design Process for Wing

Blend flattened region into rest of lower surface



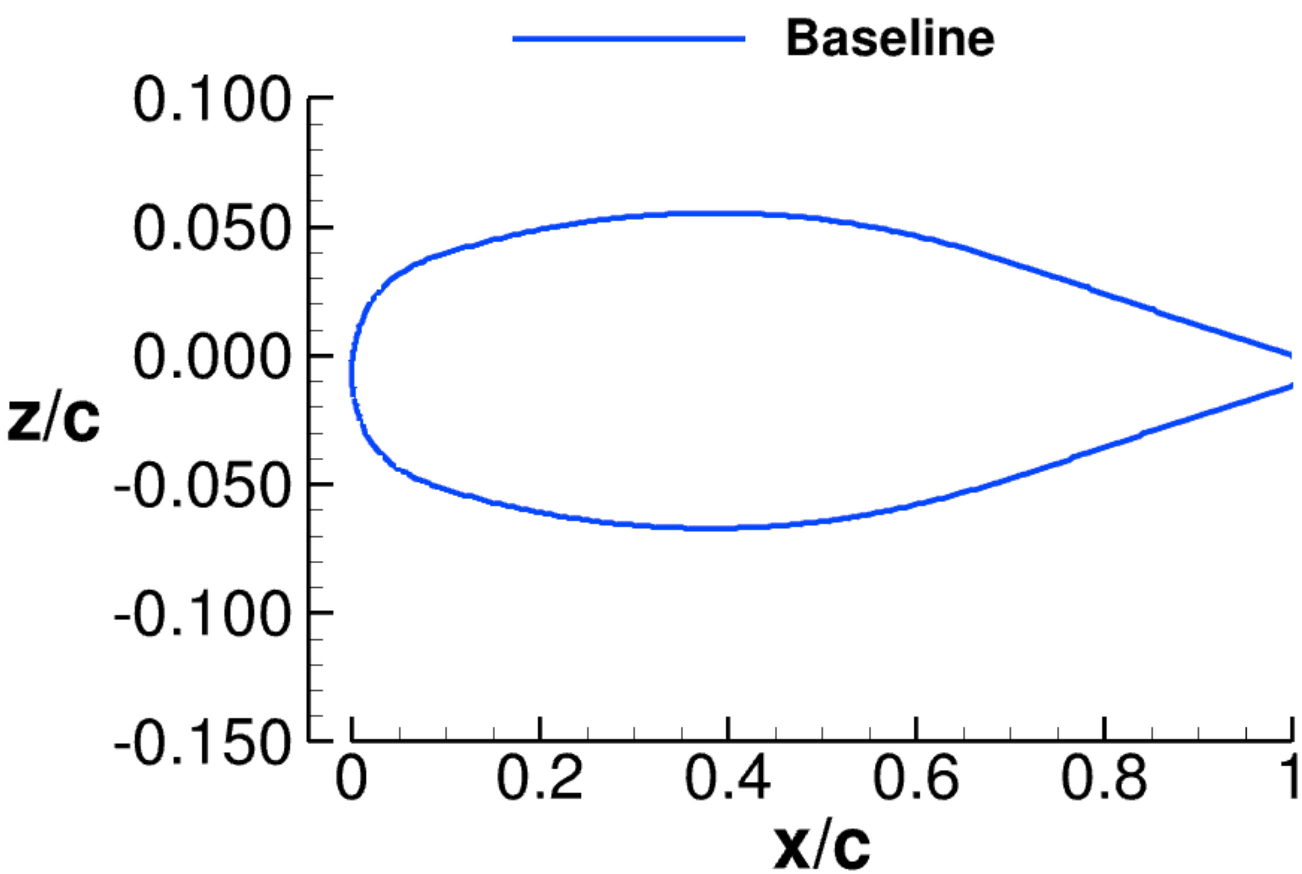
One-Shot Design Process for Wing

Smooth corners



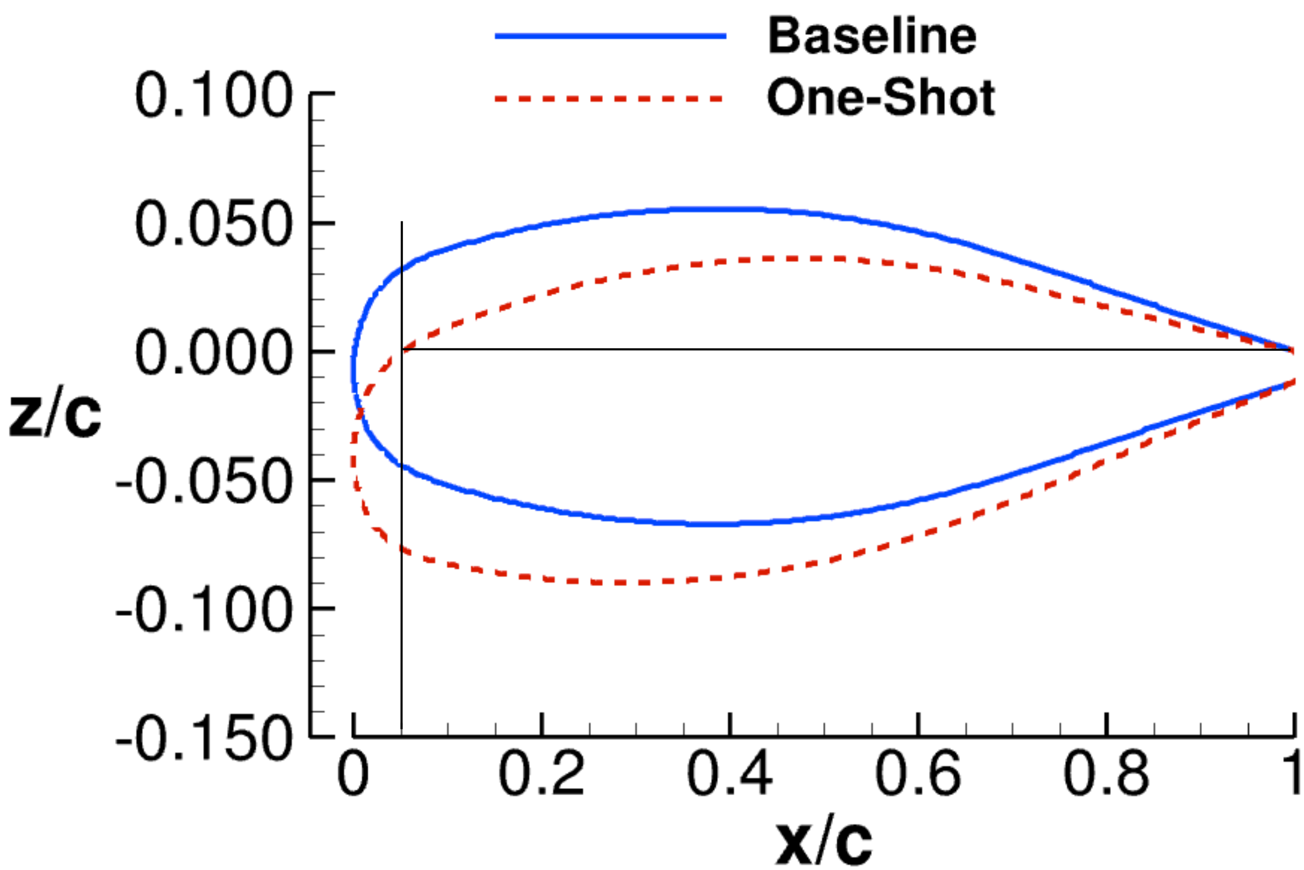
One-Shot Design Process for Strut

Baseline airfoil



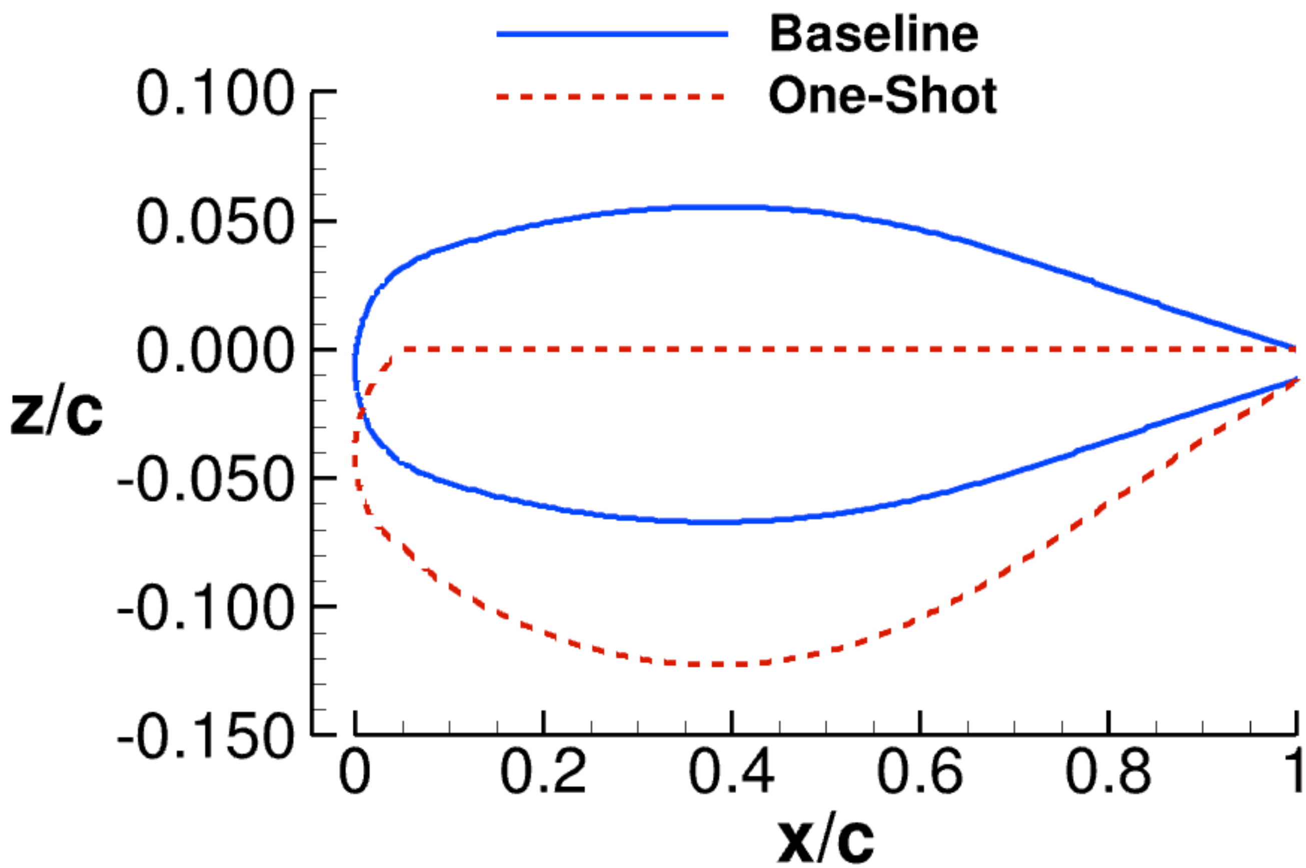
One-Shot Design Process for Strut

Rotate airfoil down to align upper surface ordinate at x/c = 0.05 with the ordinate at the upper surface trailing edge



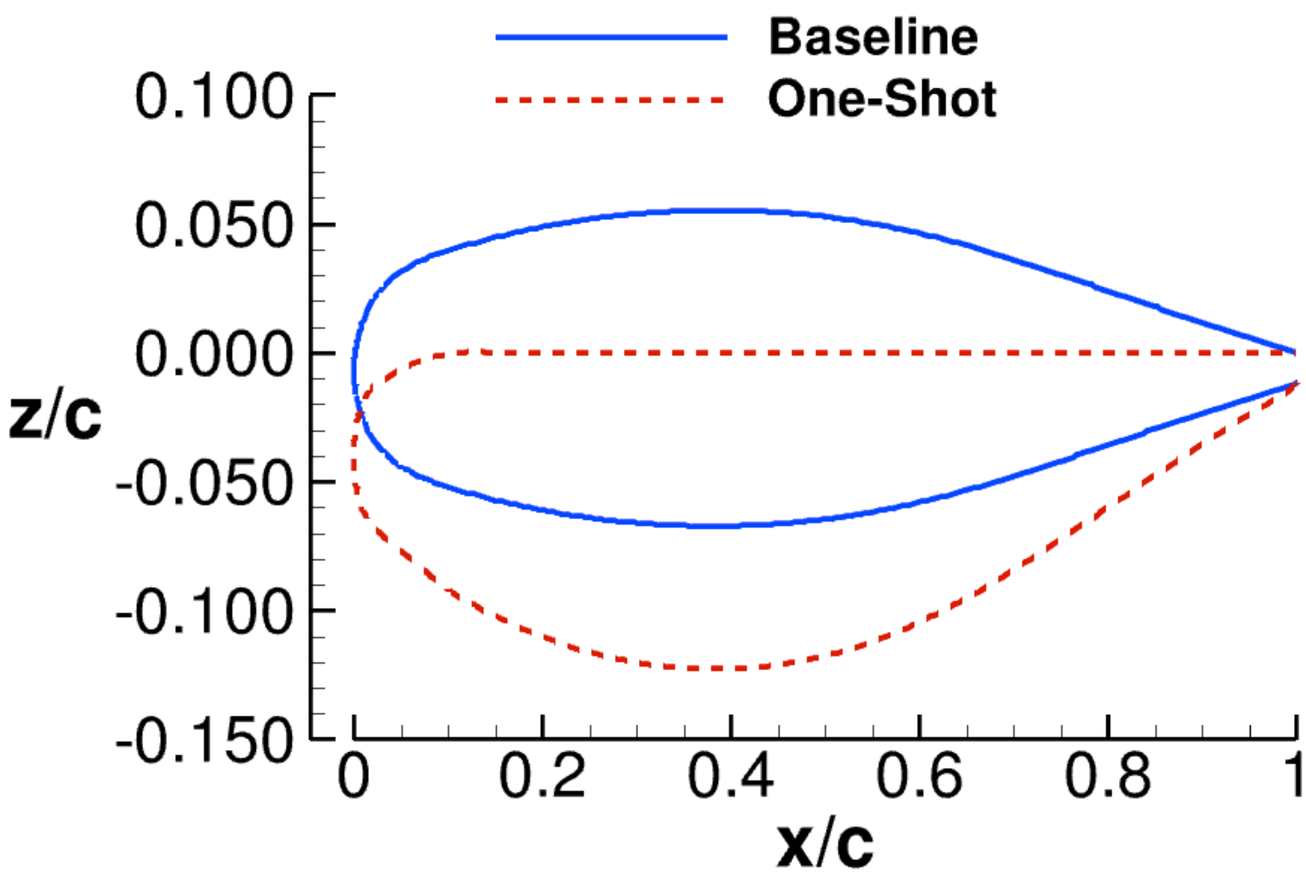
One-Shot Design Process for Strut

Flatten upper surface ordinates from x/c = 0.05 to the trailing edge while maintaining the baseline thickness distribution

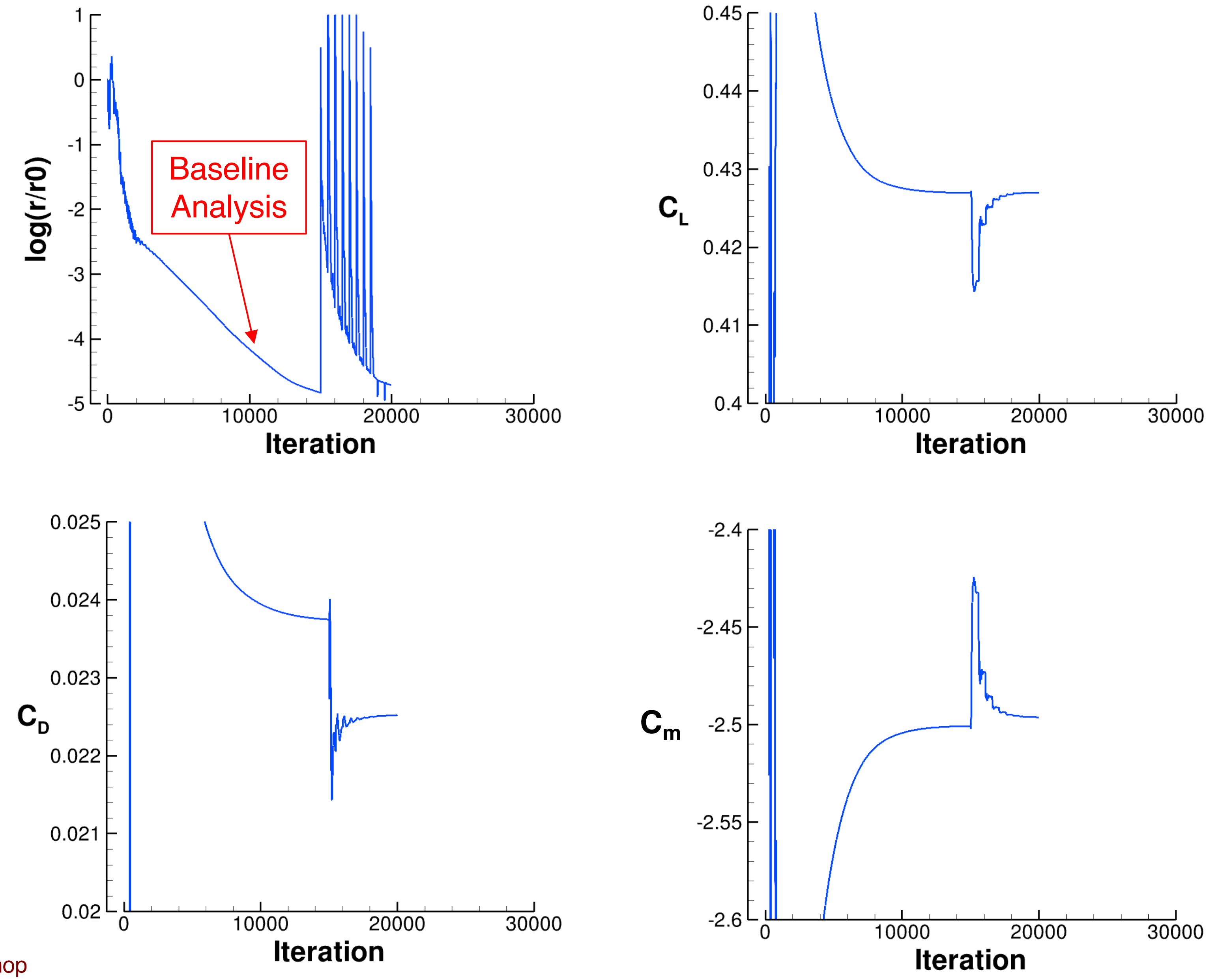


One-Shot Design Process for Strut

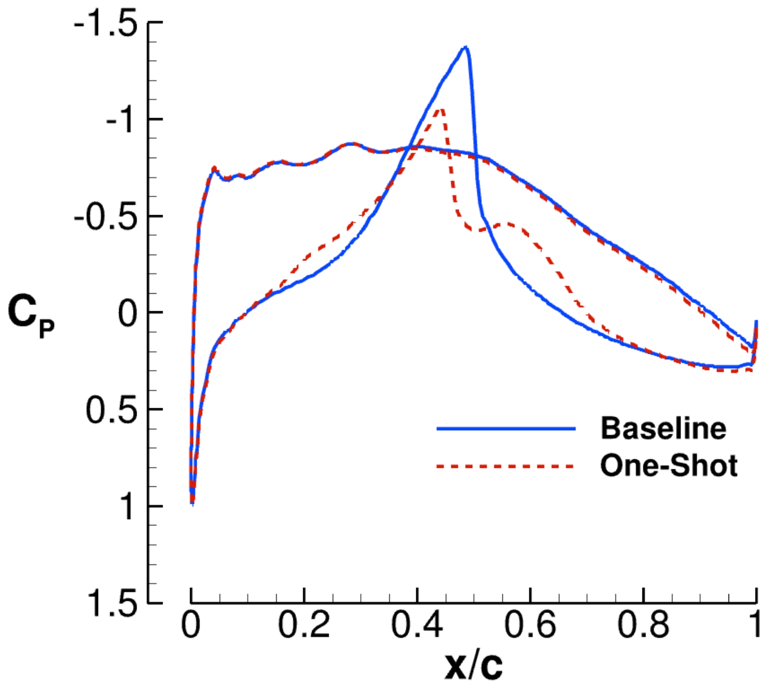
Smooth corners

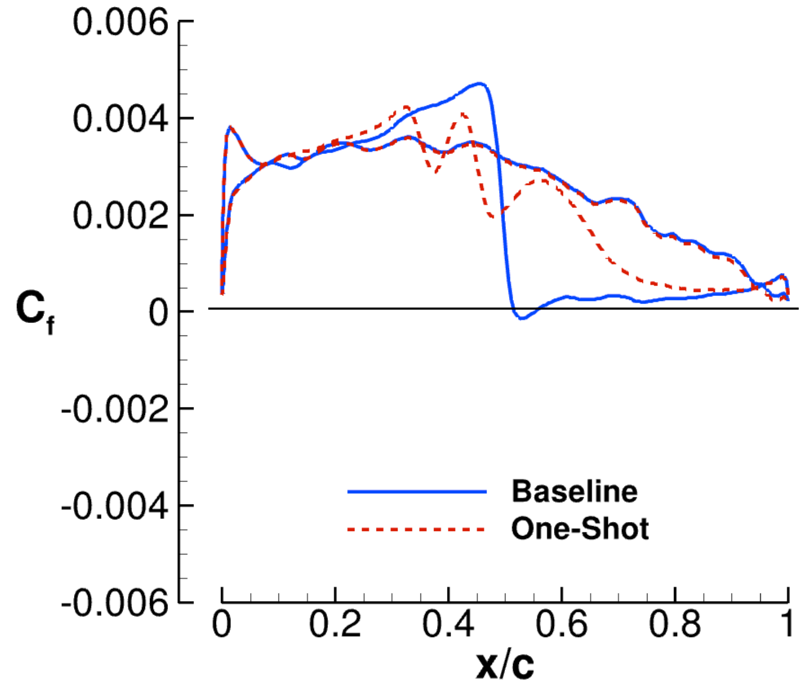


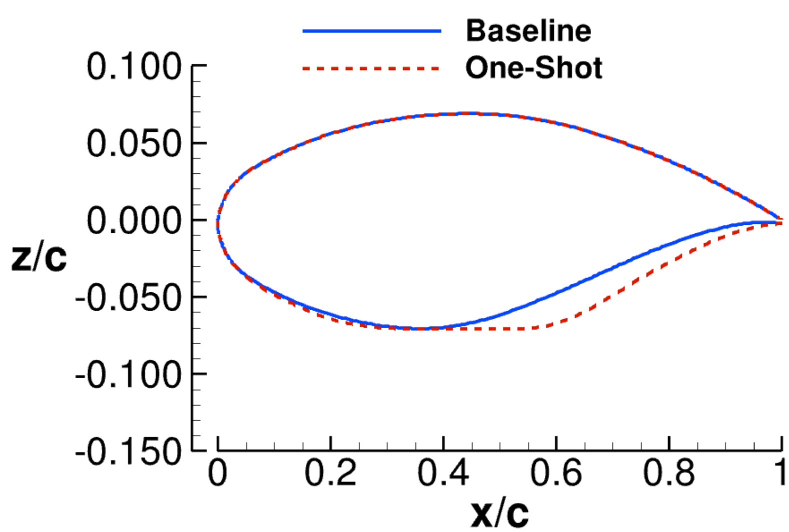
USM3D Convergence for CDISC Design



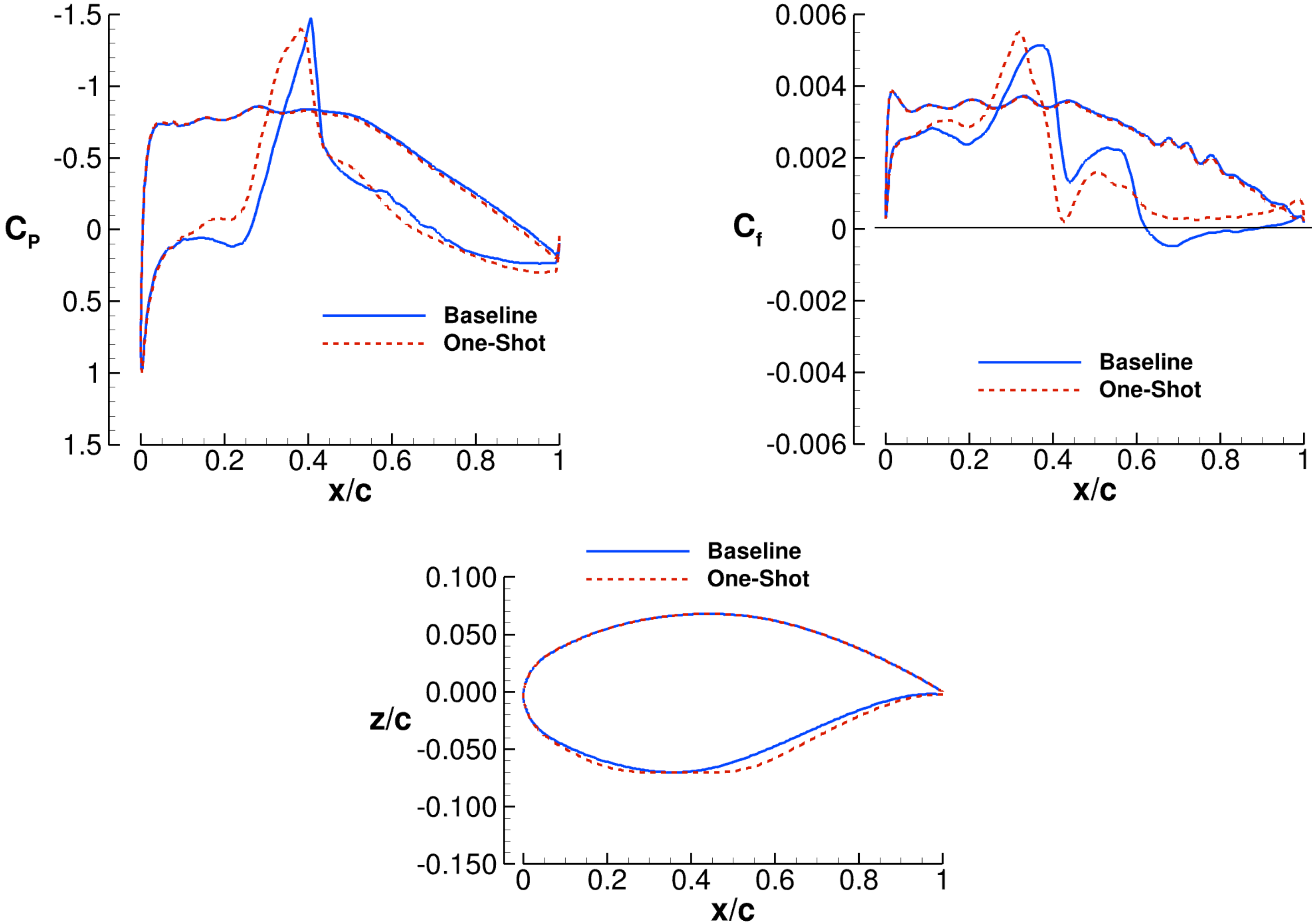
One-Shot Results: Wing at Y = 15.0 m



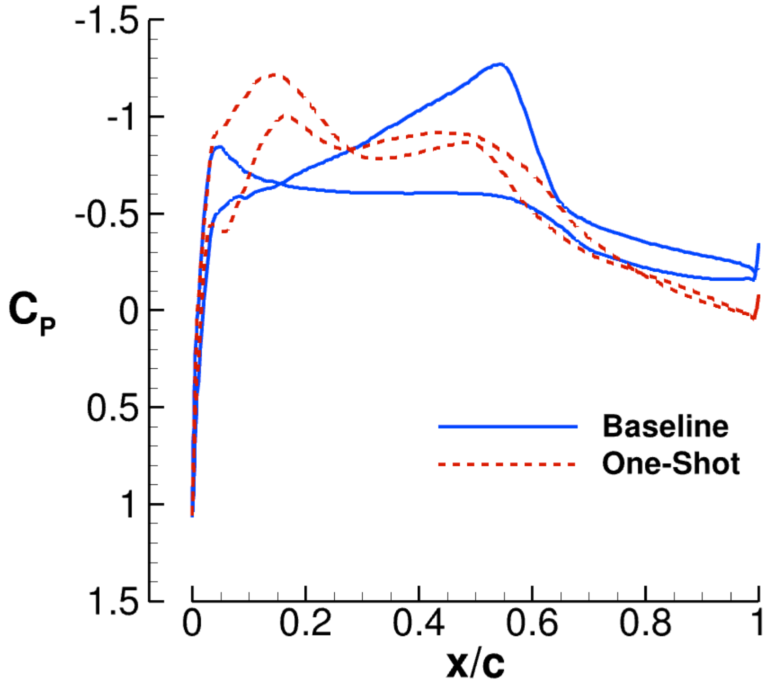


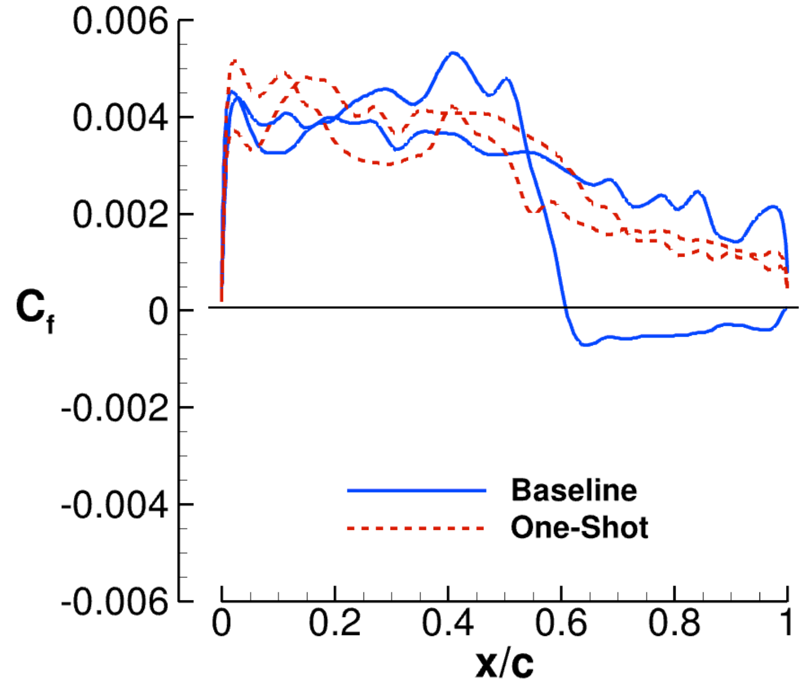


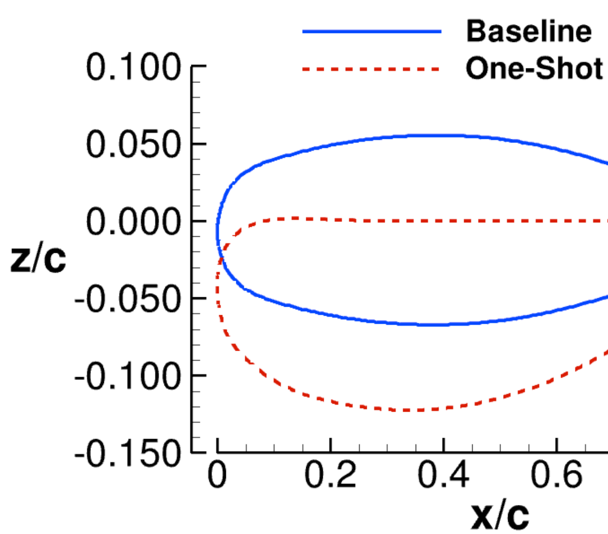
One-Shot Results: Wing at Y = 16.5 m



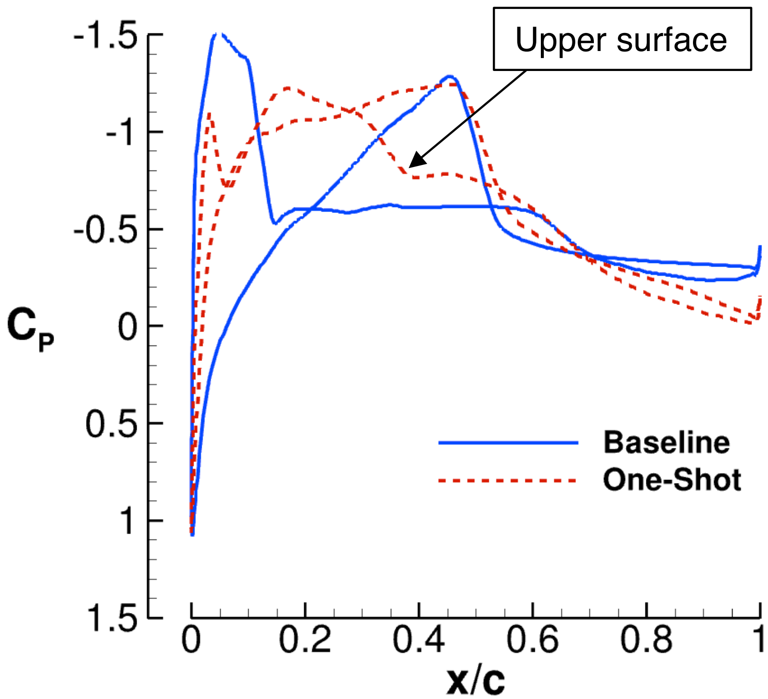
One-Shot Results: Strut at Y = 15.0 m

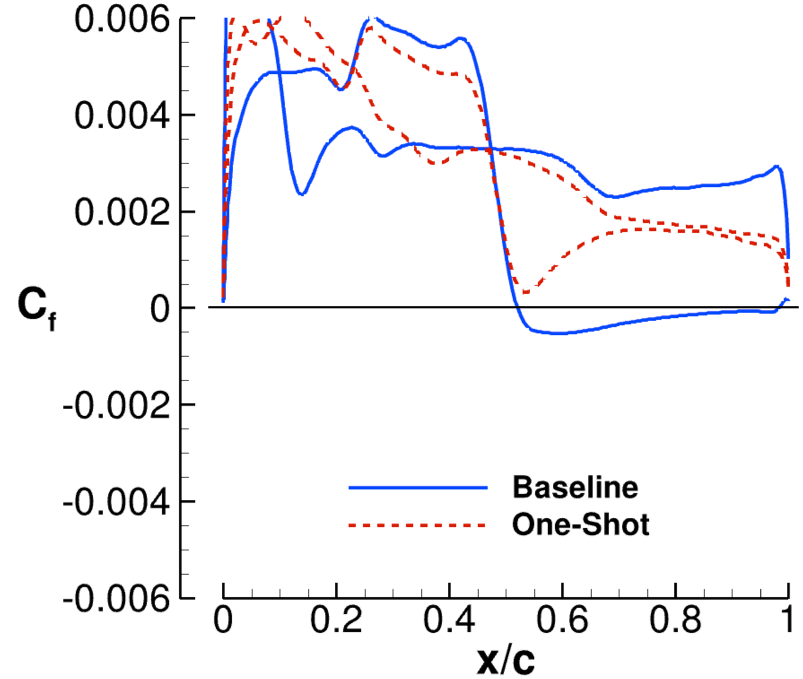


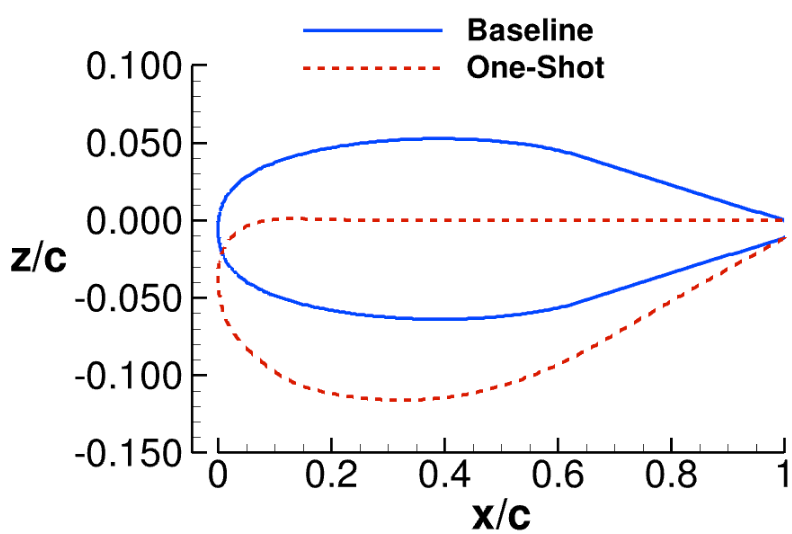




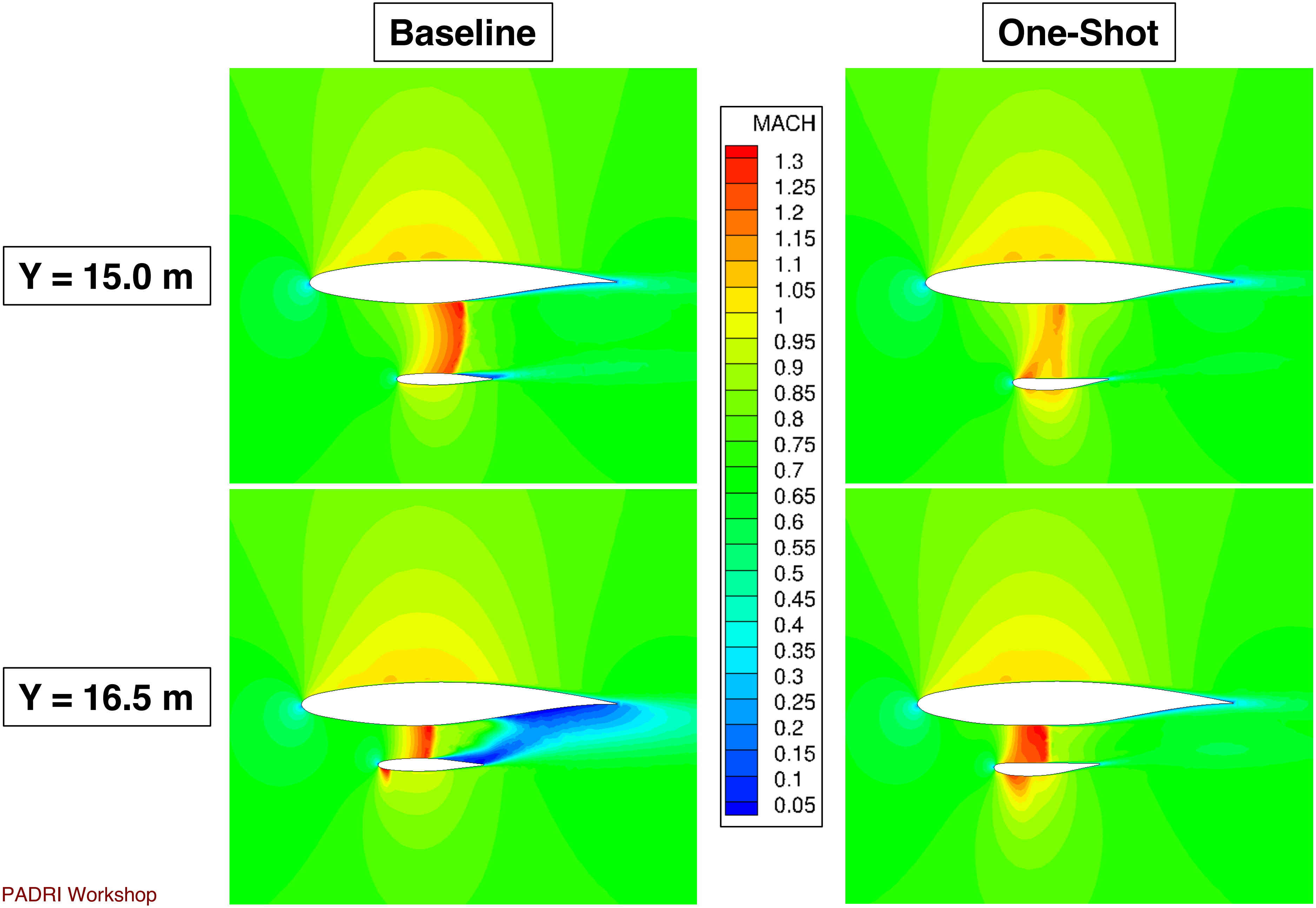
One-Shot Results: Strut at Y = 16.5 m







One-Shot Results: Mach Contour

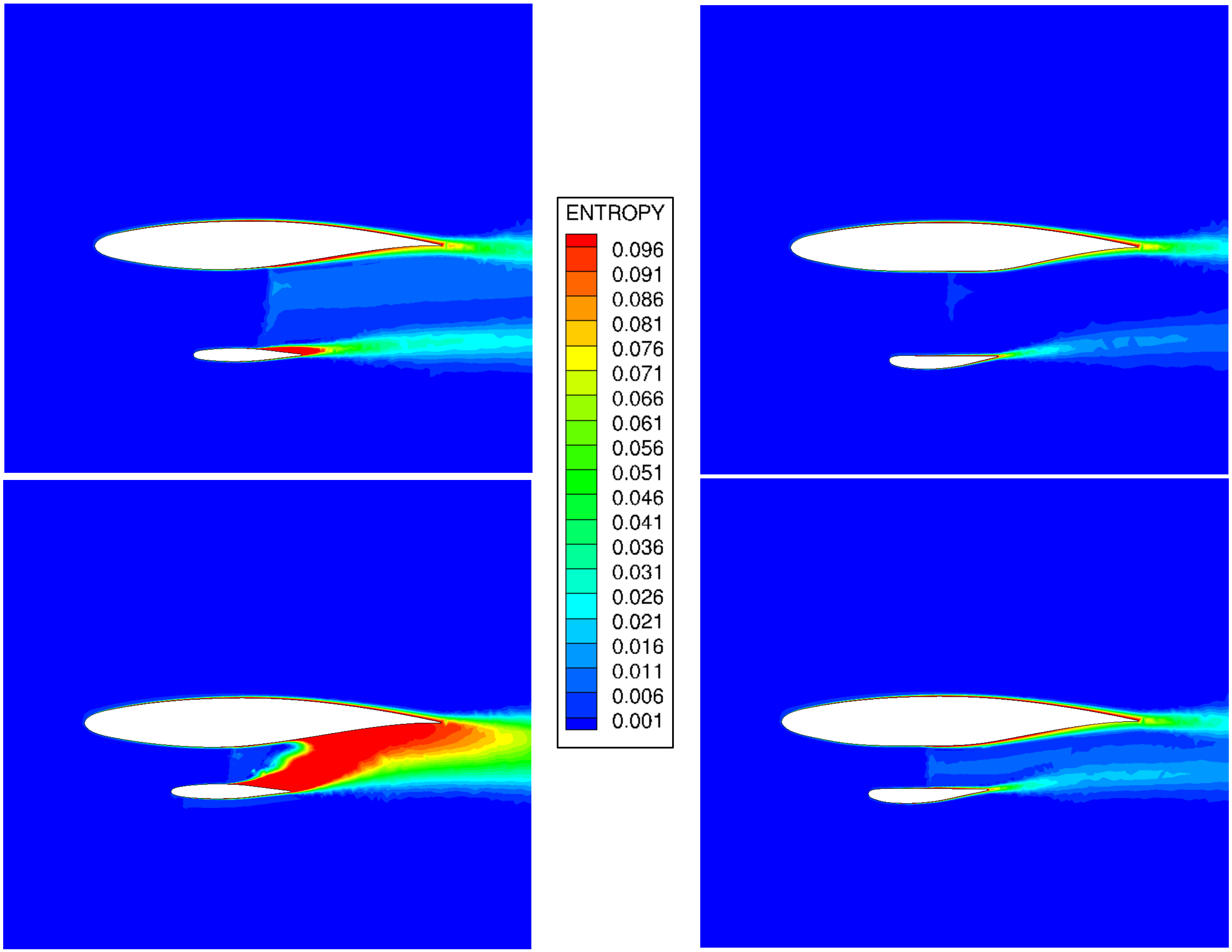


One-Shot Results: Entropy Contour

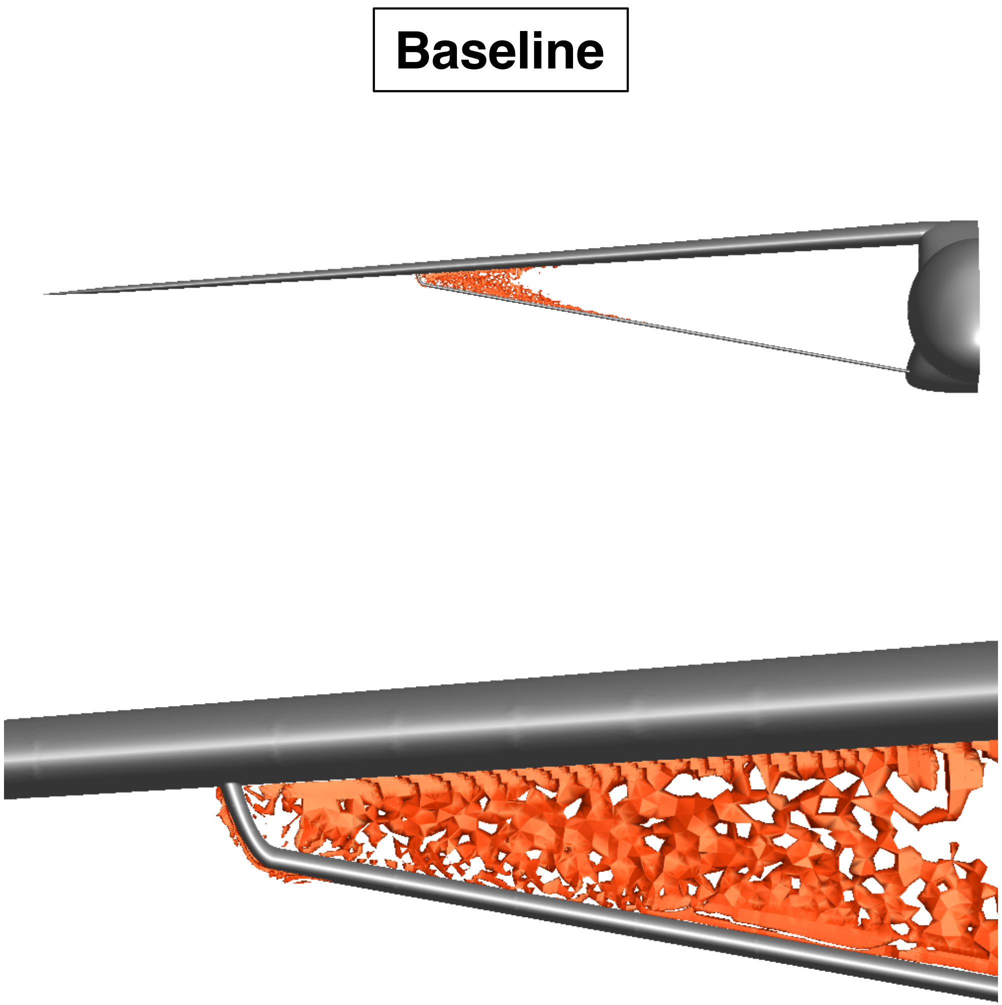
Baseline | **One-Shot**

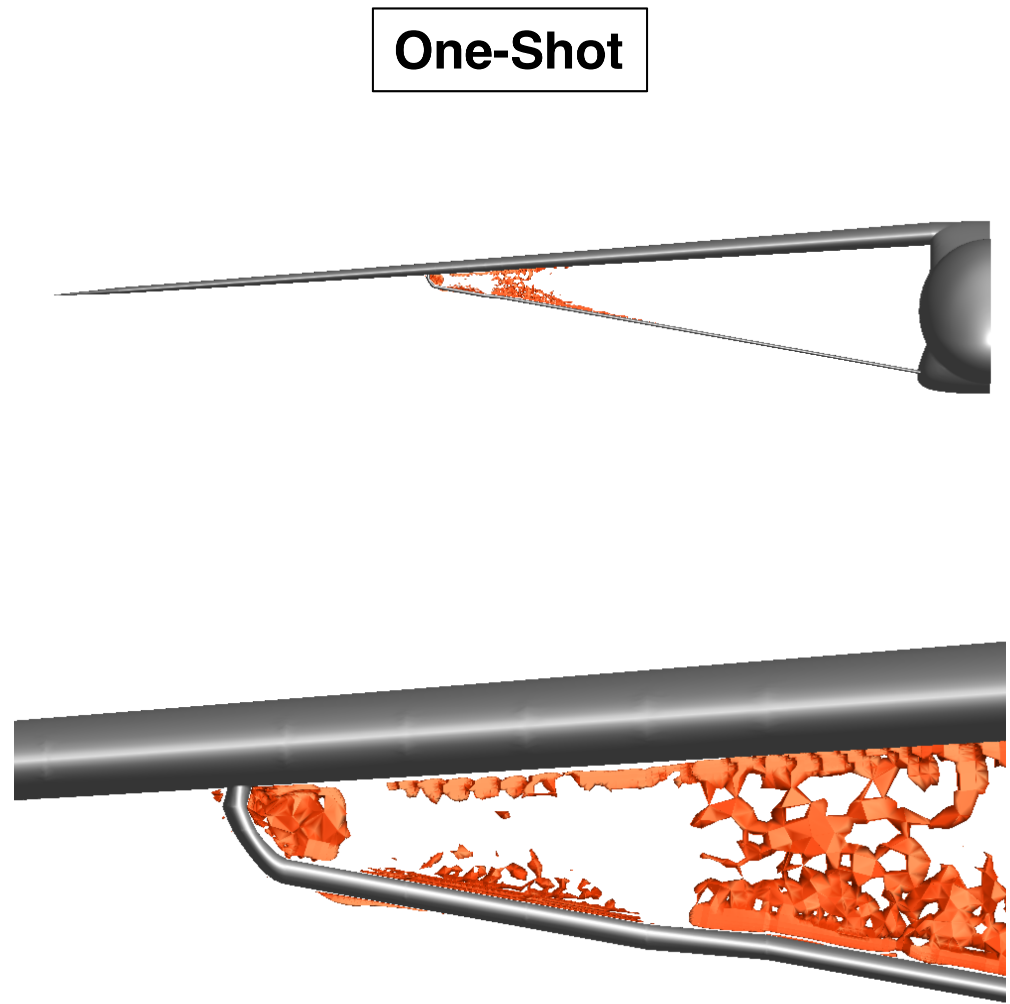
Y = 15.0 m

Y = 16.5 m



One-Shot Results: M = 1.1 Shock Isosurface





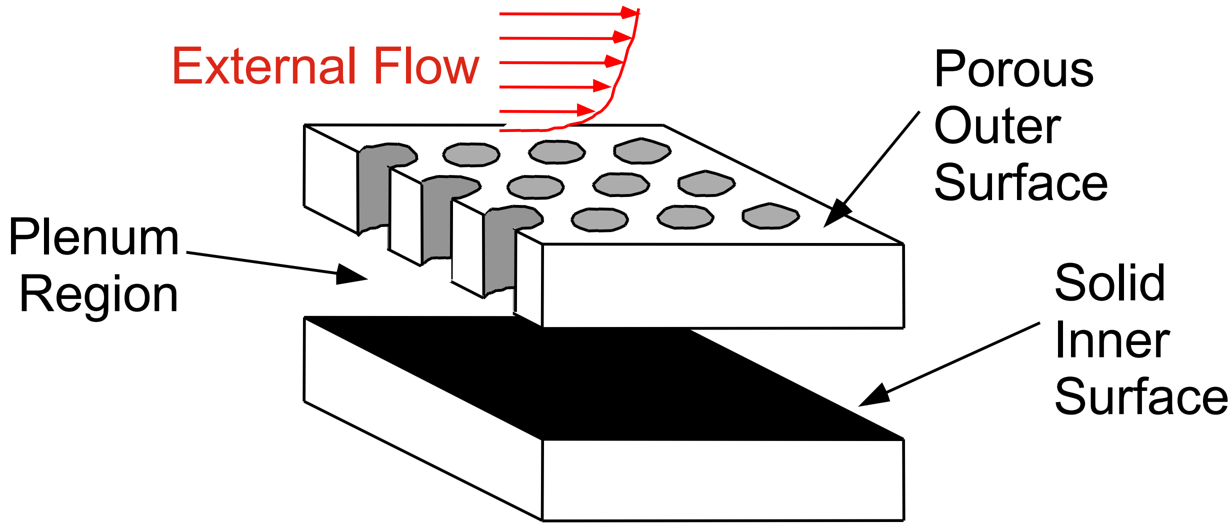
Force Results for Design Cases

Configuration	C_L	C_D	ΔC_D	$\Delta C_{D,wing}$	$\Delta C_{D,strut}$
Baseline	0.427	0.0238	-	-	-
CDISC (wing and strut)	0.426	0.0226	-0.0012	-0.0007	-0.0004
One-Shot (wing)	0.427	0.0234	-0.0004	-0.0006	0.0002
One-Shot (strut)	0.427	0.0228	-0.0010	-0.0006	-0.0003
One-Shot (wing and strut)	0.427	0.0225	-0.0013	-0.0010	-0.0002

Approaches to Drag Reduction

- Introduction
- Baseline Evaluation
- **Approaches to Drag Reduction**
  - Aerodynamic Design (CDISC)
  - **Passive Porosity (PASSPORT)**
  - Comparison of CDISC and PASSPORT Results
- Concluding Remarks

Passive Porosity (PASSPORT) Concept

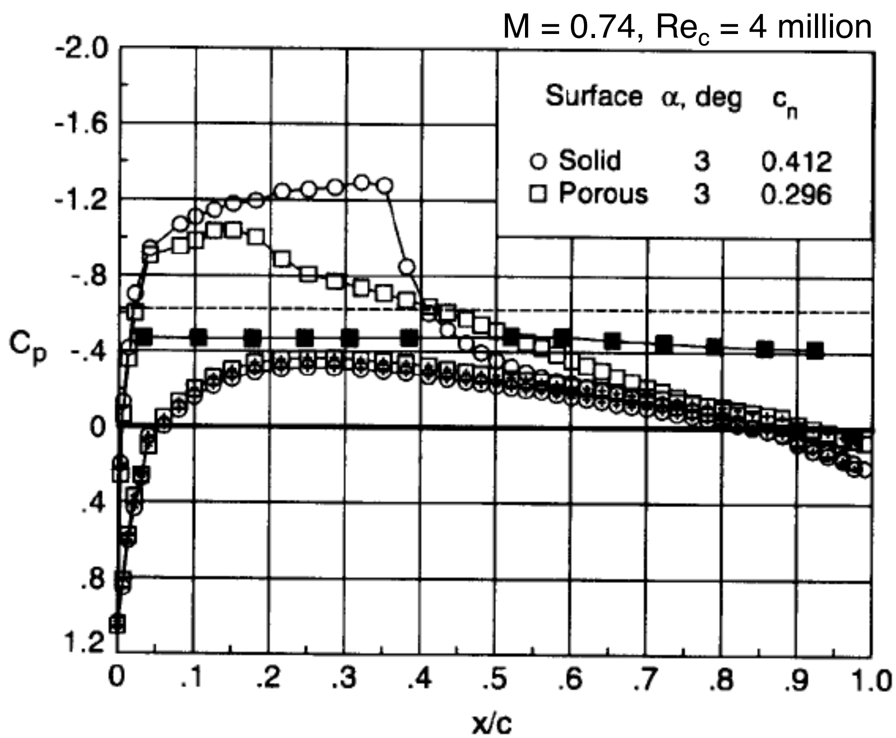


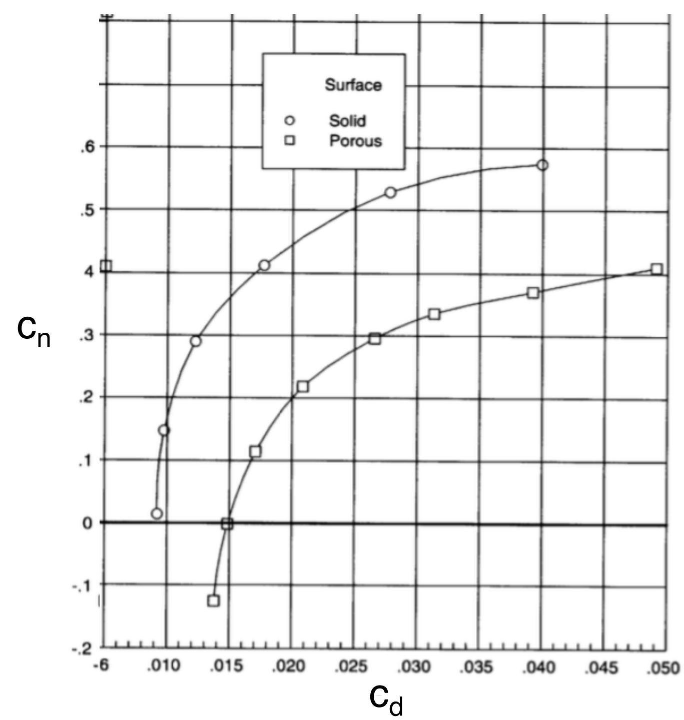
- Originally developed in the 1980s for shock-boundary layer interaction control
- Applications include shock strength reduction and aerodynamic flow control
- Pressure differences on the outer surface "communicate" through the plenum
- Small amounts of flux through the porous surface alters its effective aerodynamic shape

Application of Porous Boundary Condition

Porous control effector wind tunnel test

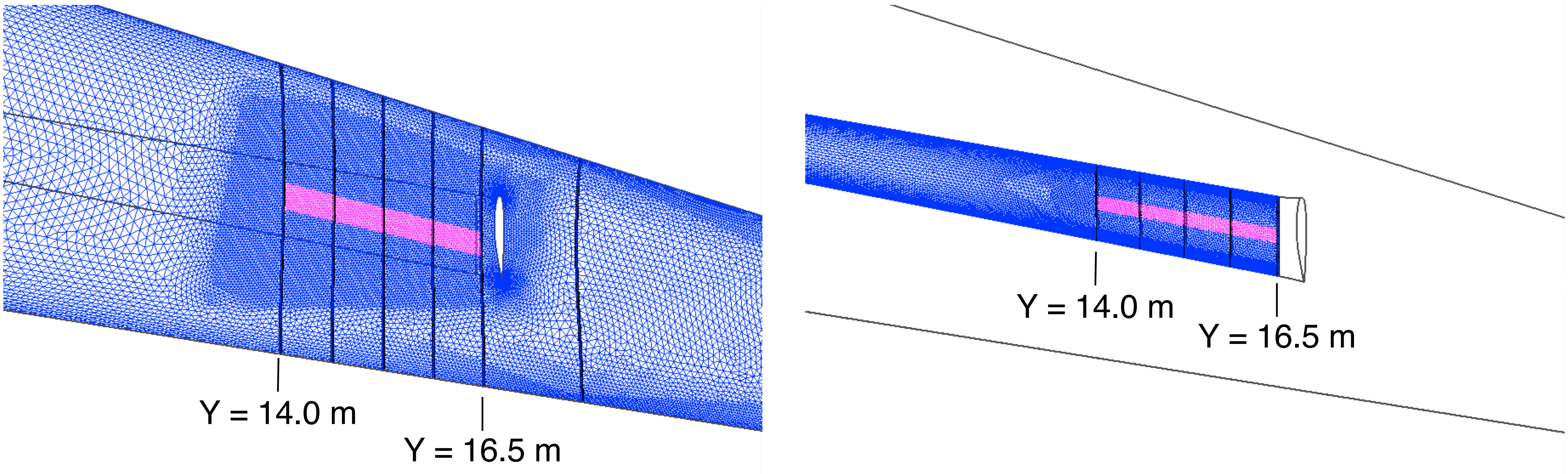
- NACA 0012 airfoil section
- NASA Langley 8-Foot Transonic Pressure Tunnel
- 1.08% average porosity on full-chord upper surface





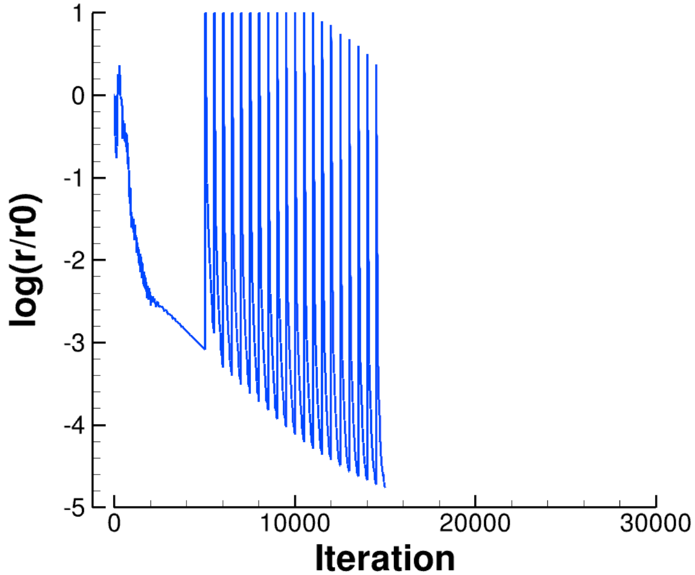
Reference: NASA TP 3591

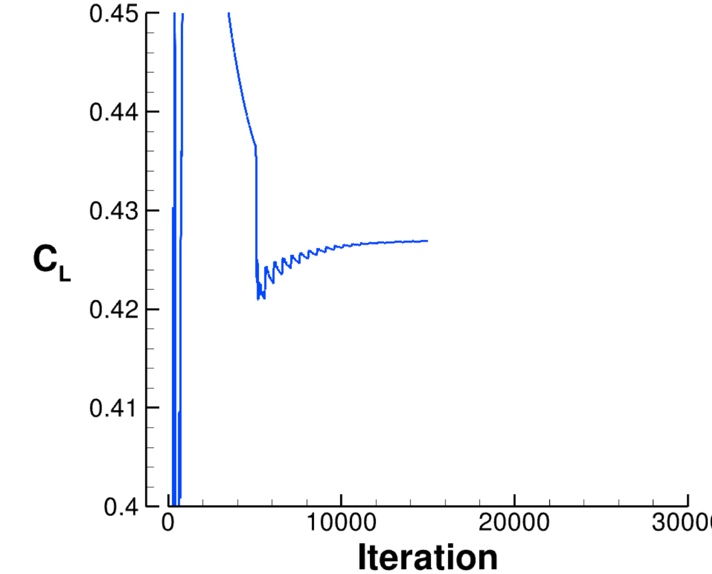
Porous Patch Locations

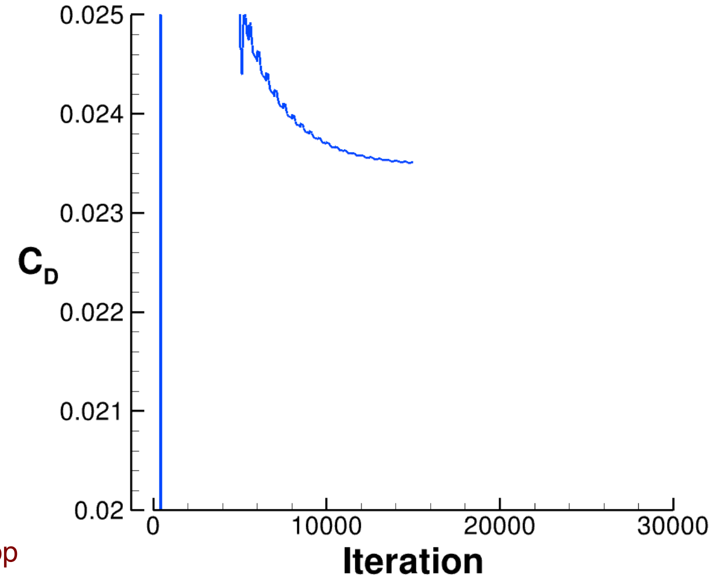


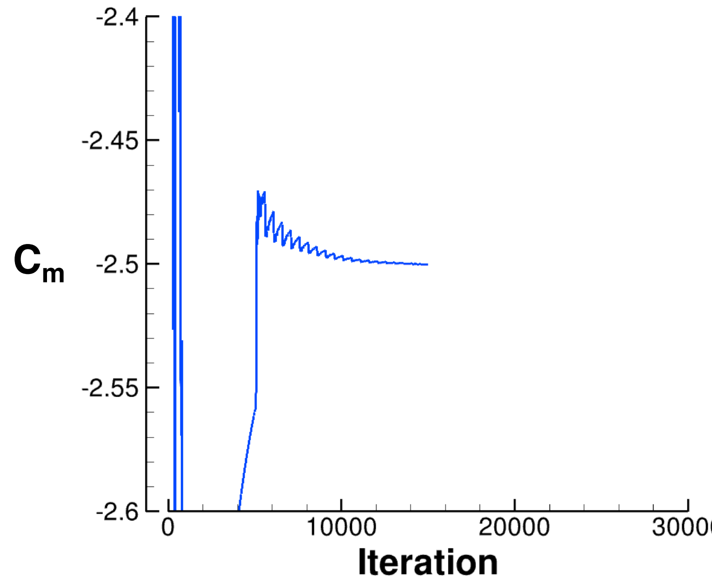
- 15% porosity on each patch
- Porous patches extending from Y = 14.5 m to 16.5 m
- Wing lower surface x/c = 0.4 – 0.5
- Strut upper surface x/c = 0.4 – 0.6
- Cases run with porous patch on wing-only, strut-only, and wing-strut
- Strut-only case had most drag reduction

USM3D Convergence for Porous Case

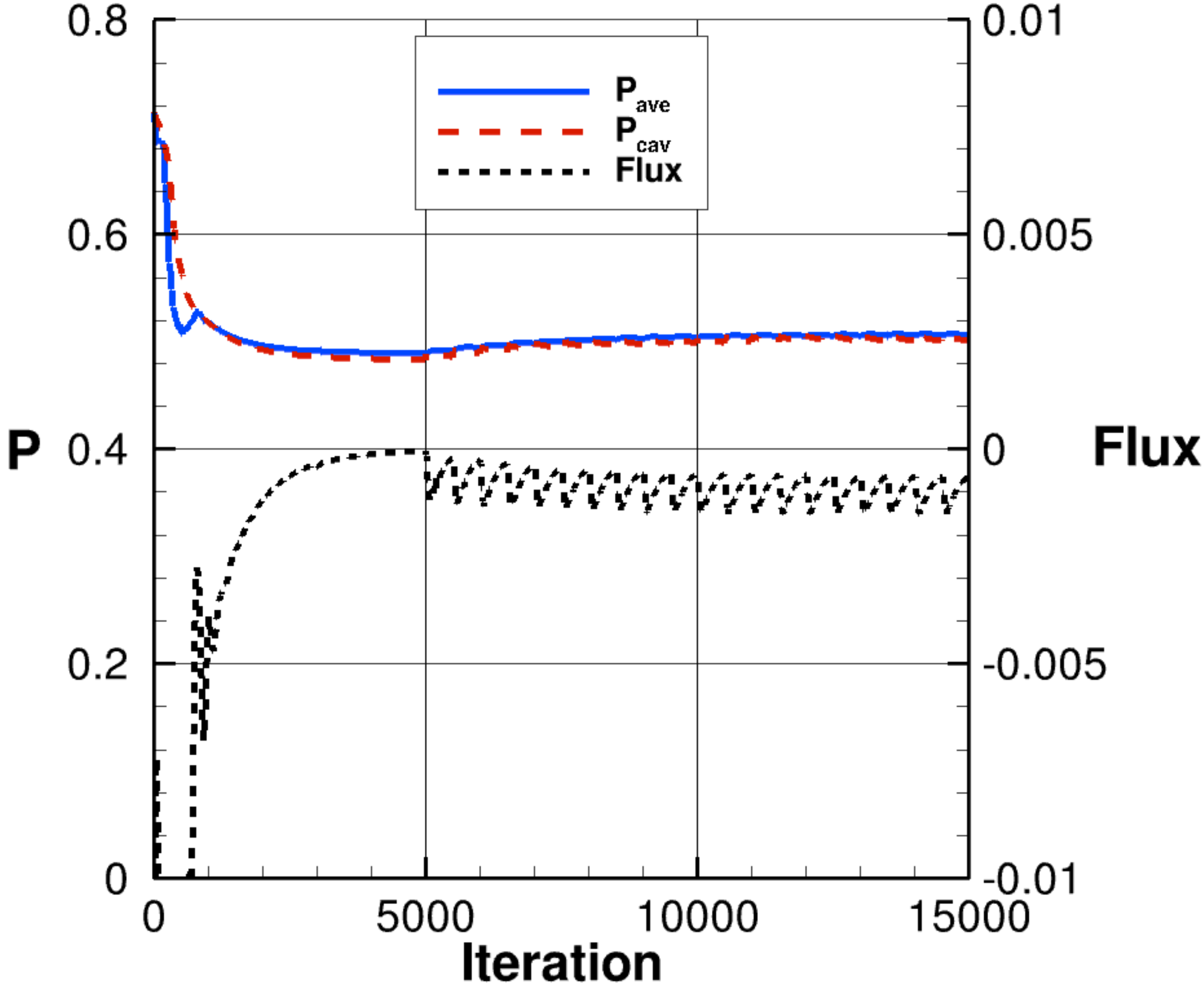




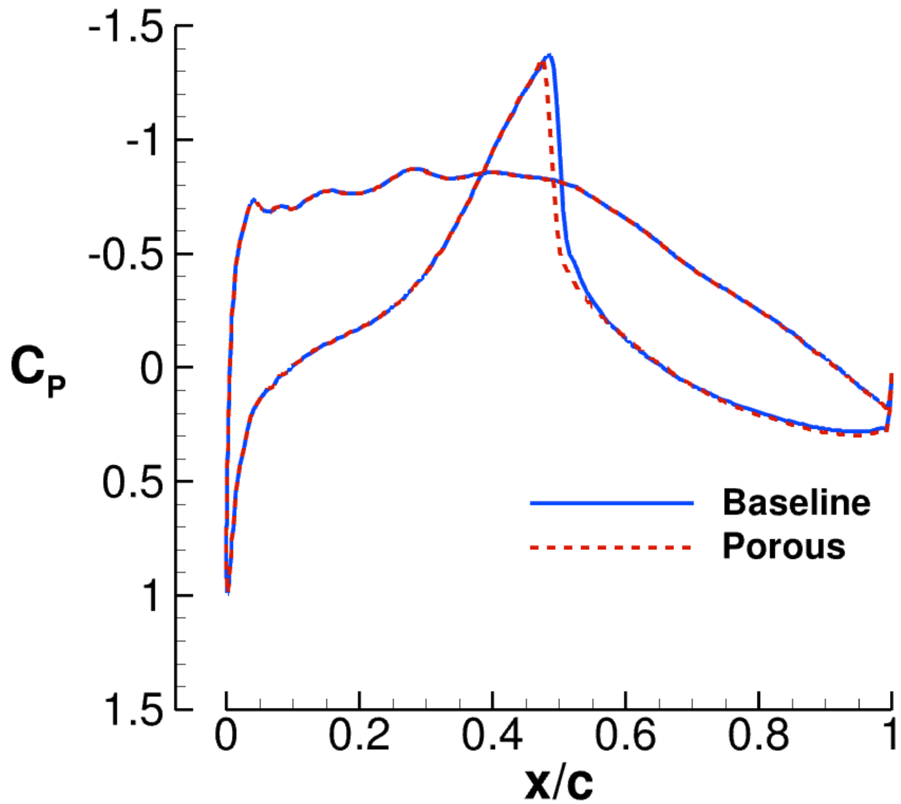


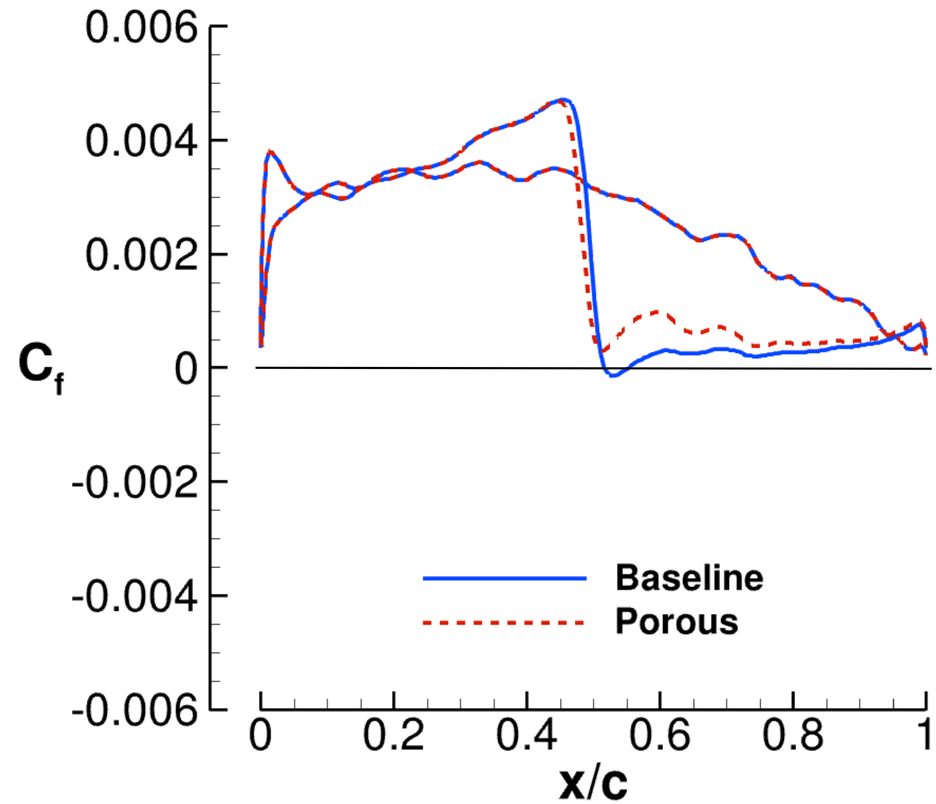


USM3D Convergence for Porous Case

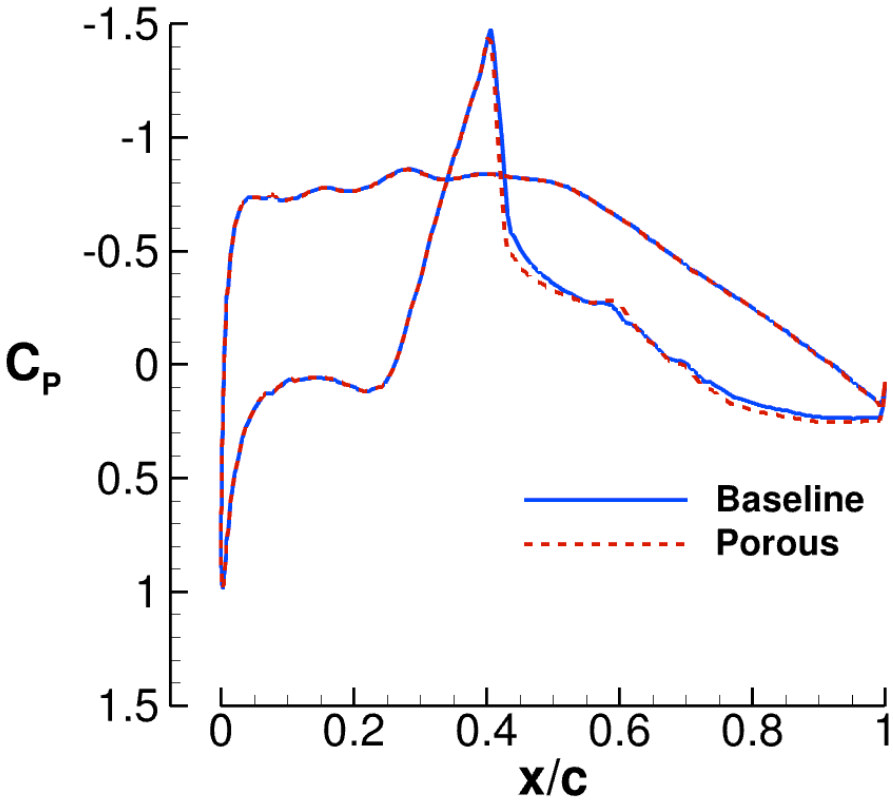


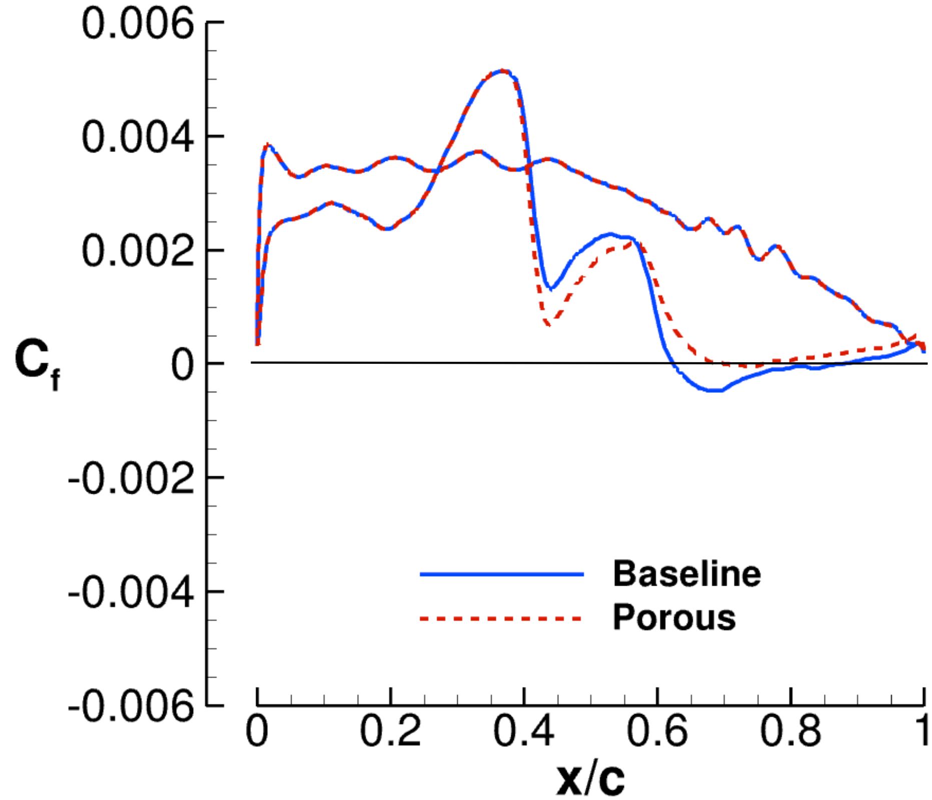
Porous Results: Wing at Y = 15.0 m



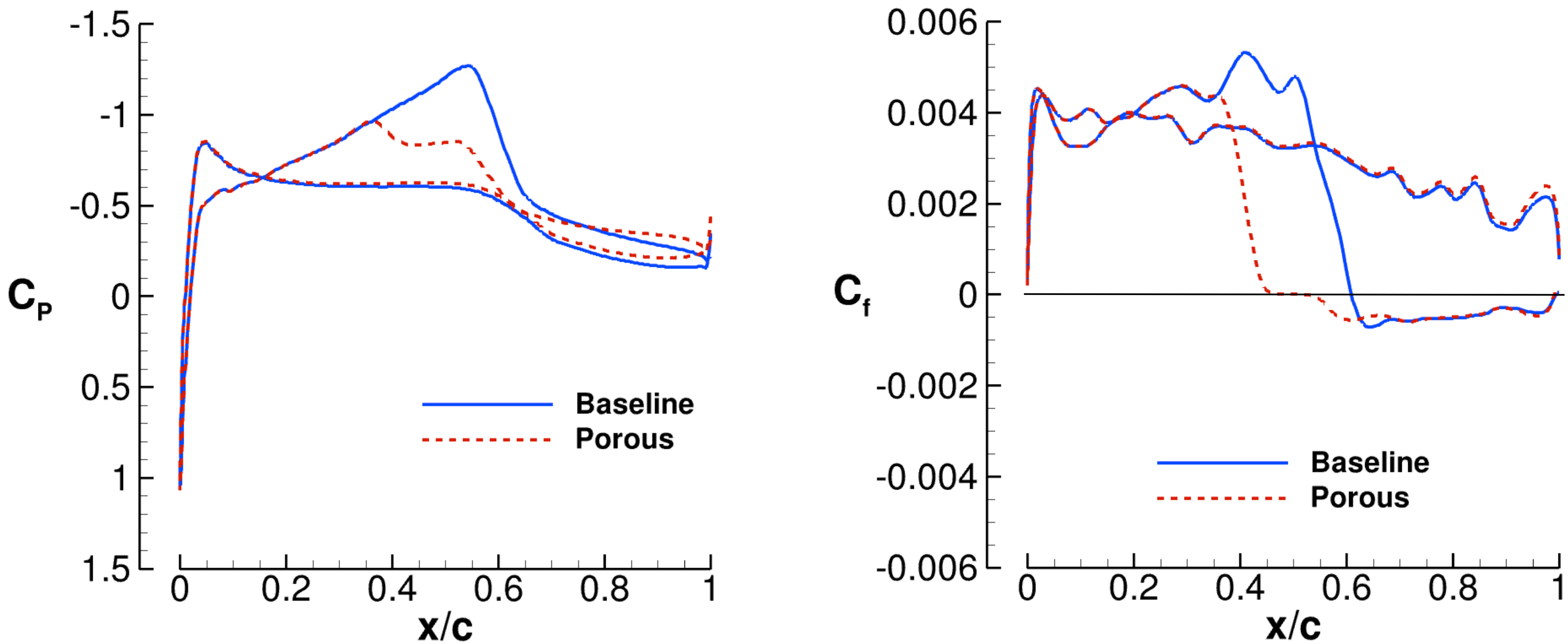


Porous Results: Wing at Y = 16.5 m

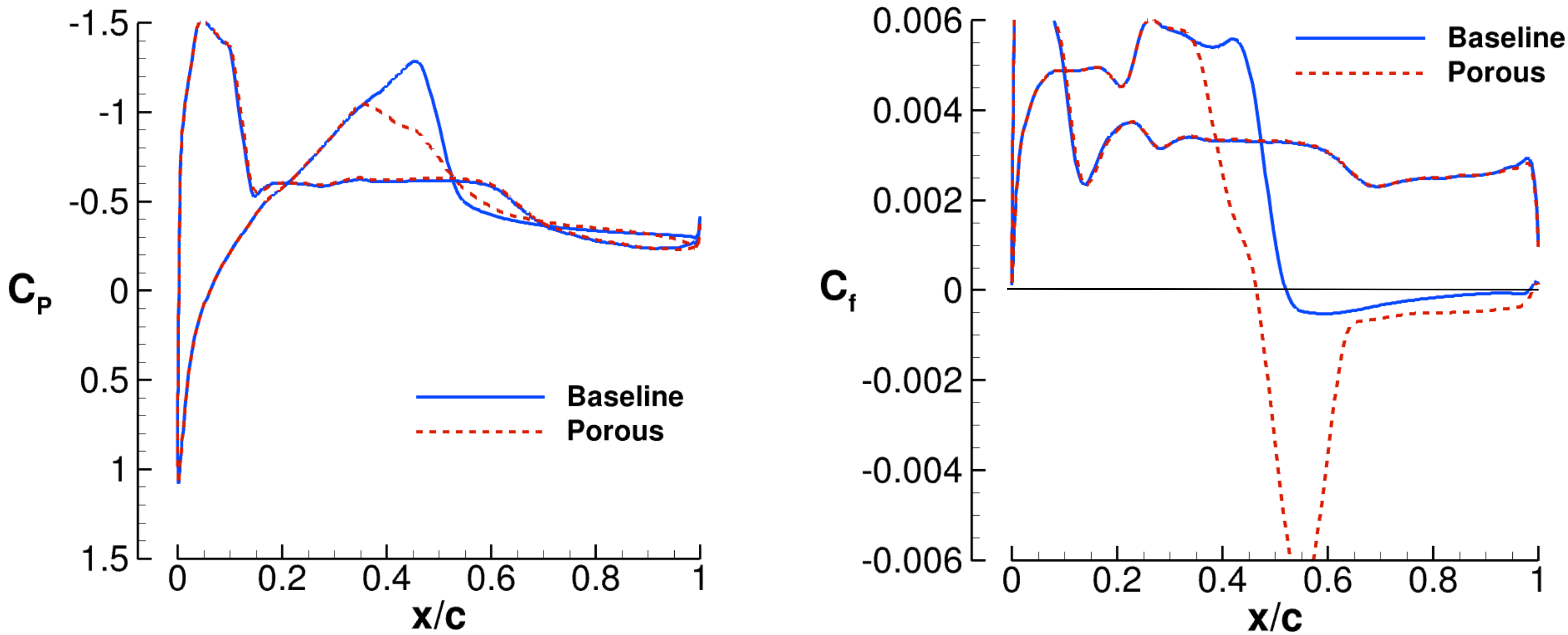




Porous Results: Strut at Y = 15.0 m



Porous Results: Strut at Y = 16.5 m

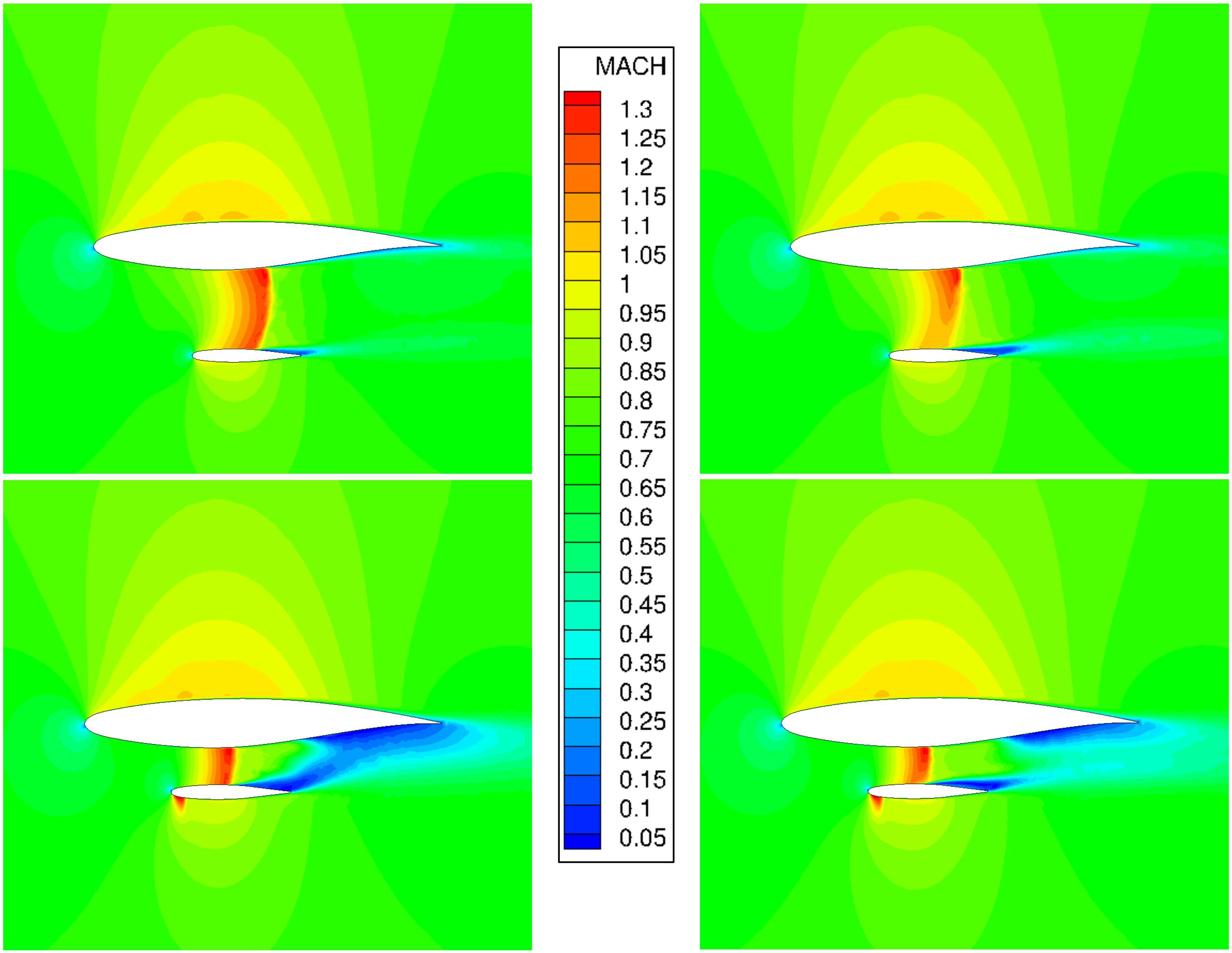


Porous Results: Mach Contour

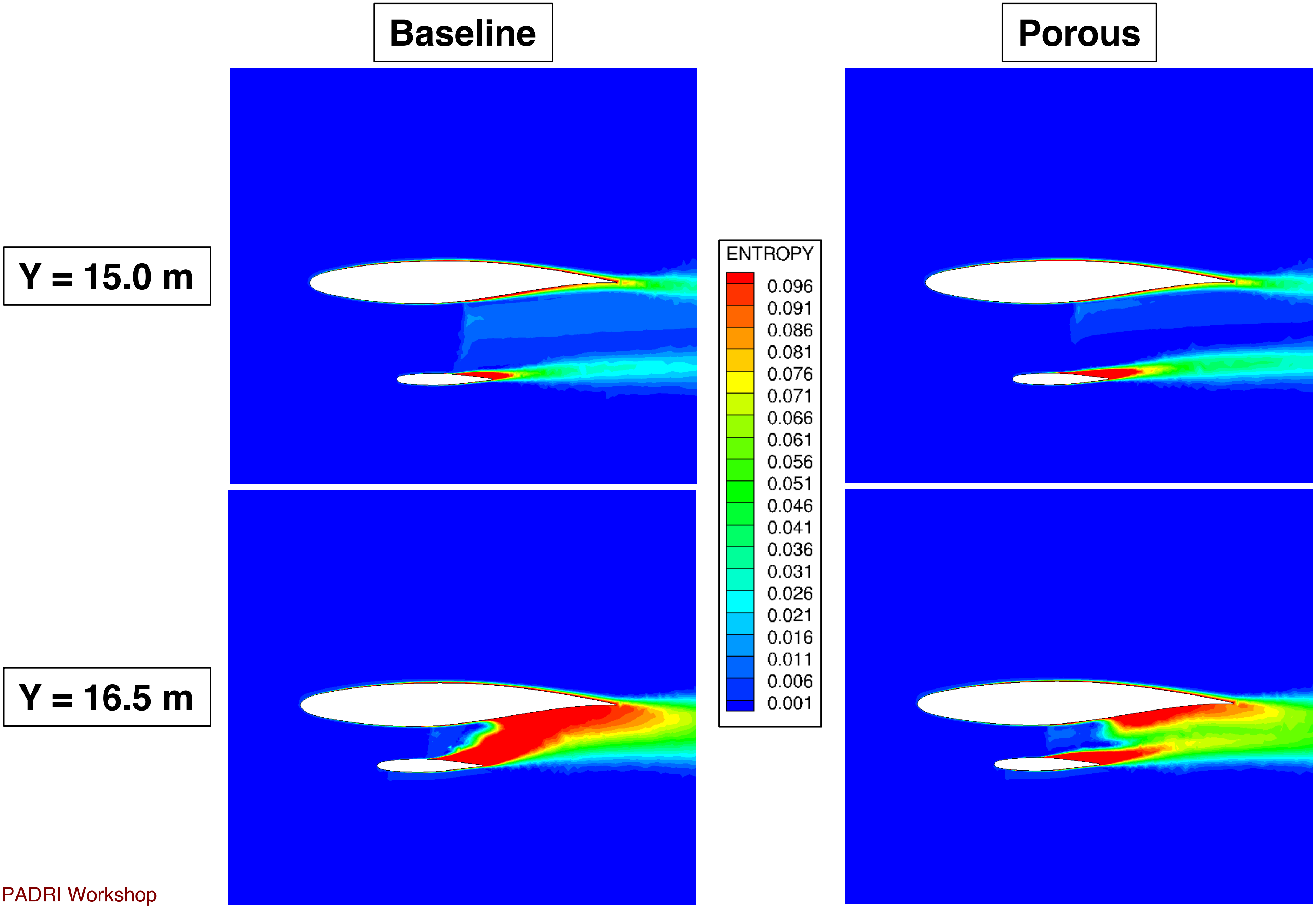
Baseline | **Porous**

Y = 15.0 m

Y = 16.5 m

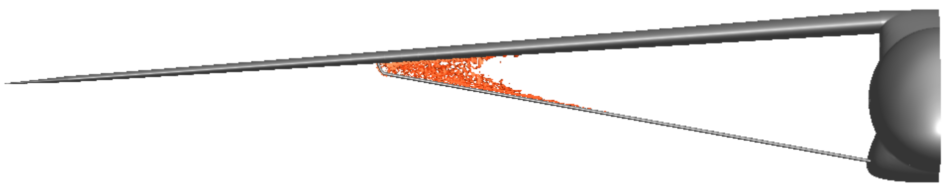


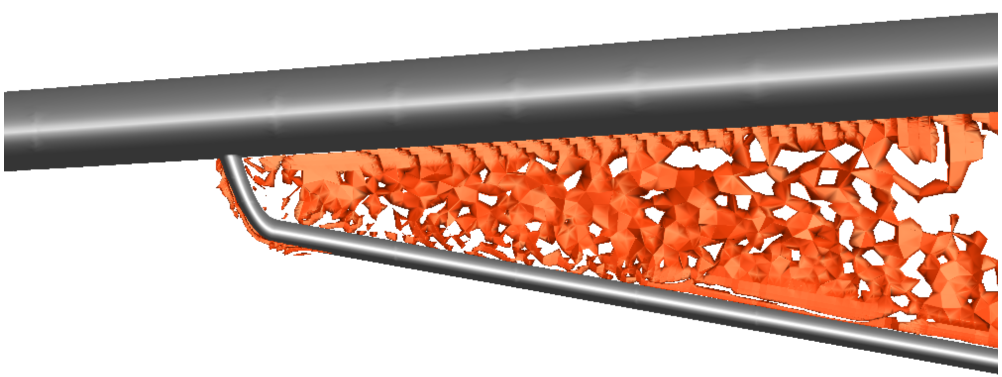
Porous Results: Entropy Contour



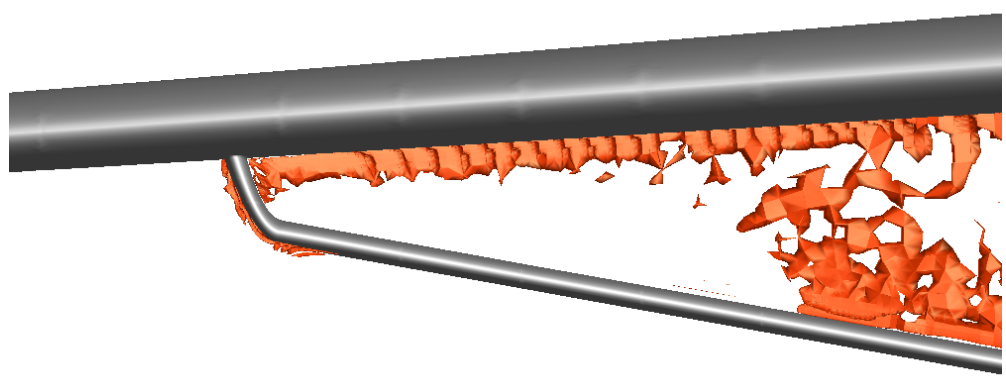
Porous Results: M = 1.1 Shock Isosurface

Baseline





Porous



Force Results for Porous Cases

Configuration	C_L	C_D	ΔC_D	$\Delta C_{D,wing}$	$\Delta C_{D,strut}$
Baseline	0.427	0.0238	-	-	-
Porous (wing)	0.427	0.0237	-0.0001	0.0006	-0.0006
Porous (strut)	0.427	0.0235	-0.0003	-0.0002	-0.0001
Porous (wing and strut)	0.427	0.0237	-0.0001	0.0005	-0.0006

Approaches to Drag Reduction

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- Baseline Evaluation
- **Approaches to Drag Reduction**
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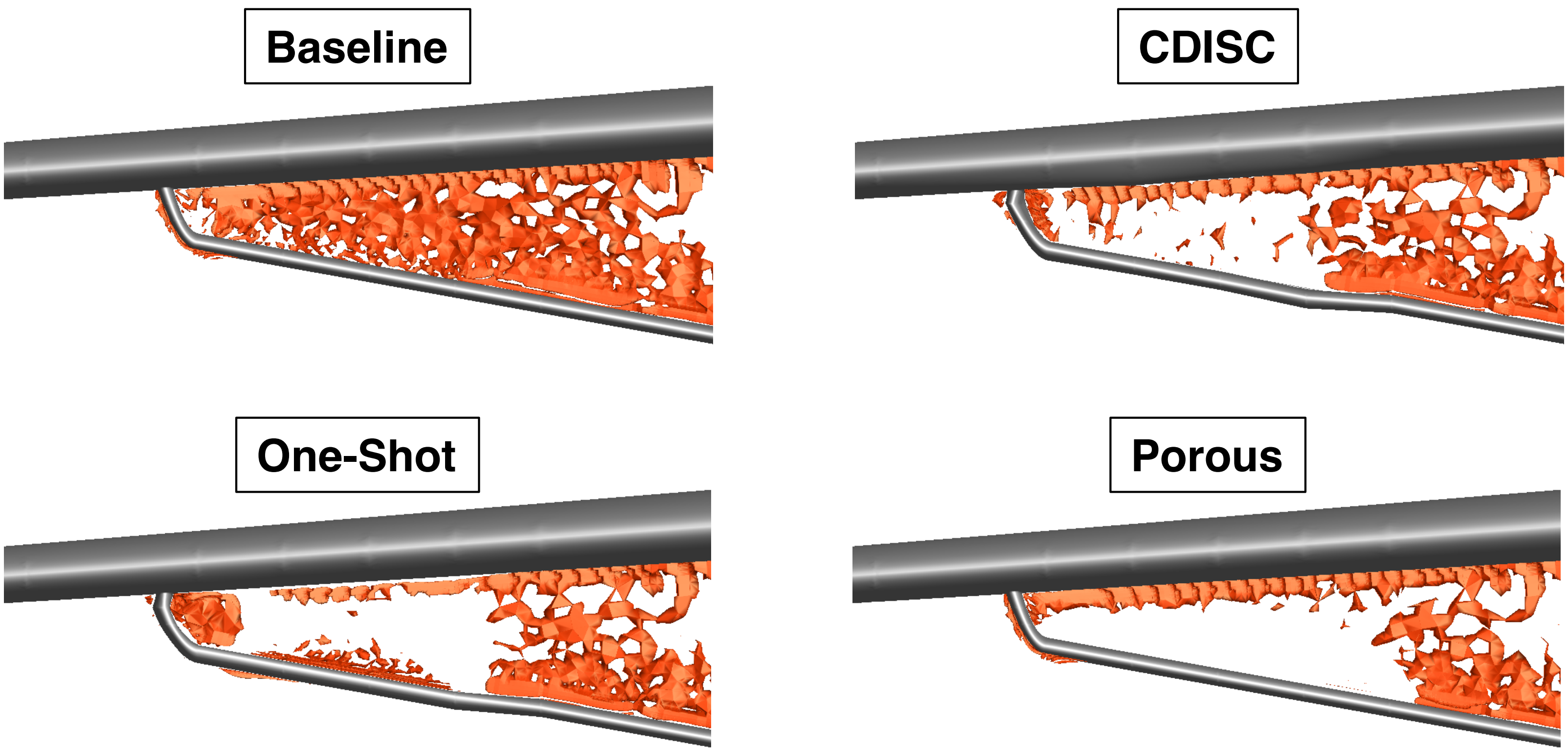
Summary of Drag Reduction Approaches

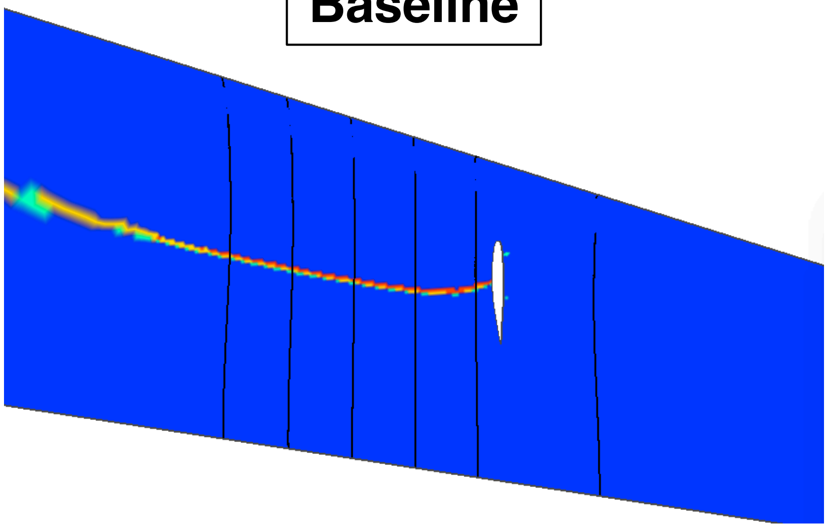
Configuration	CL	CD	ΔCD
Baseline	0.427	0.0238	-
CDISC (wing and strut)	0.426	0.0226	-0.0012
One-Shot (wing and strut)	0.427	0.0225	-0.0013
Porous (strut)	0.427	0.0235	-0.0003



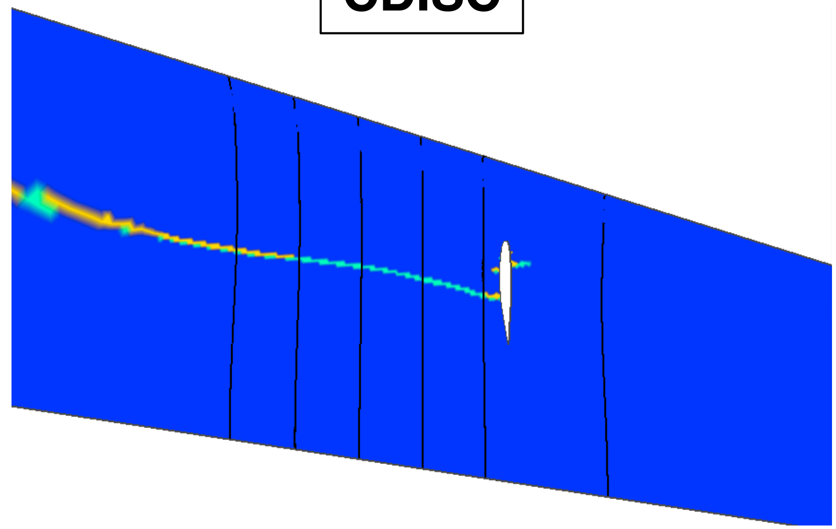
M = 1.1 Shock Isosurface

Wave Drag Function on Wing Lower Surface

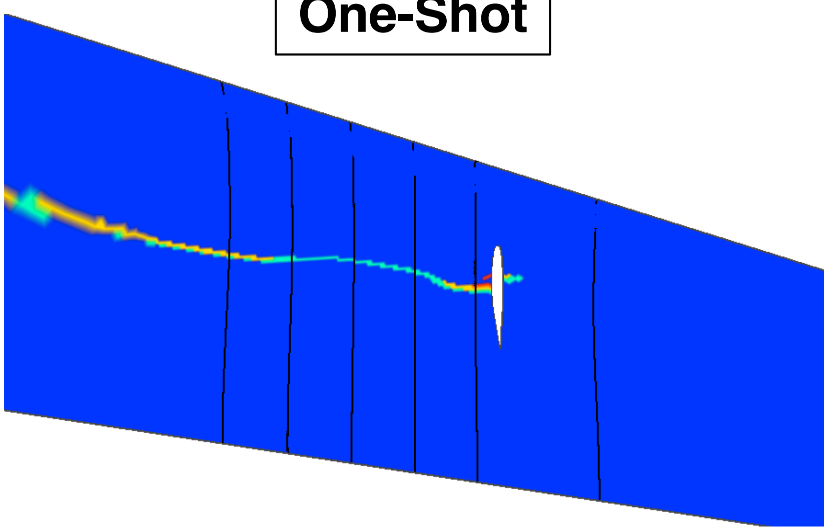
Baseline



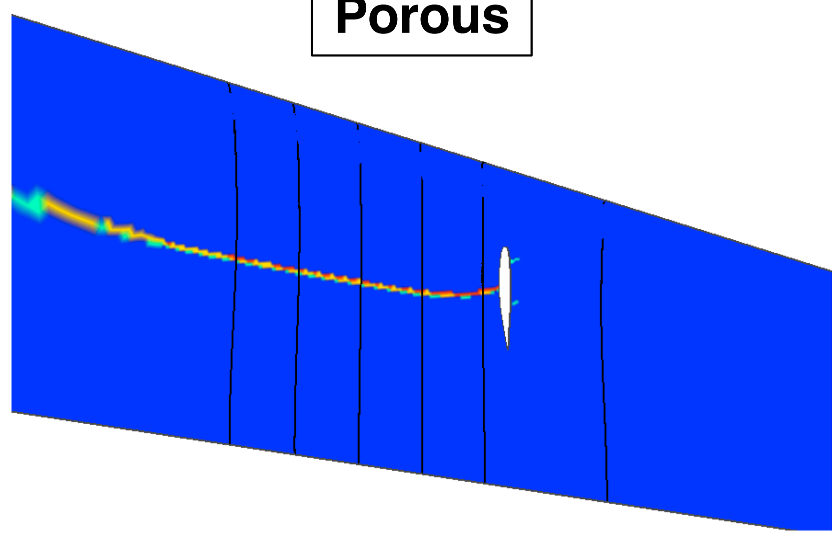
CDISC



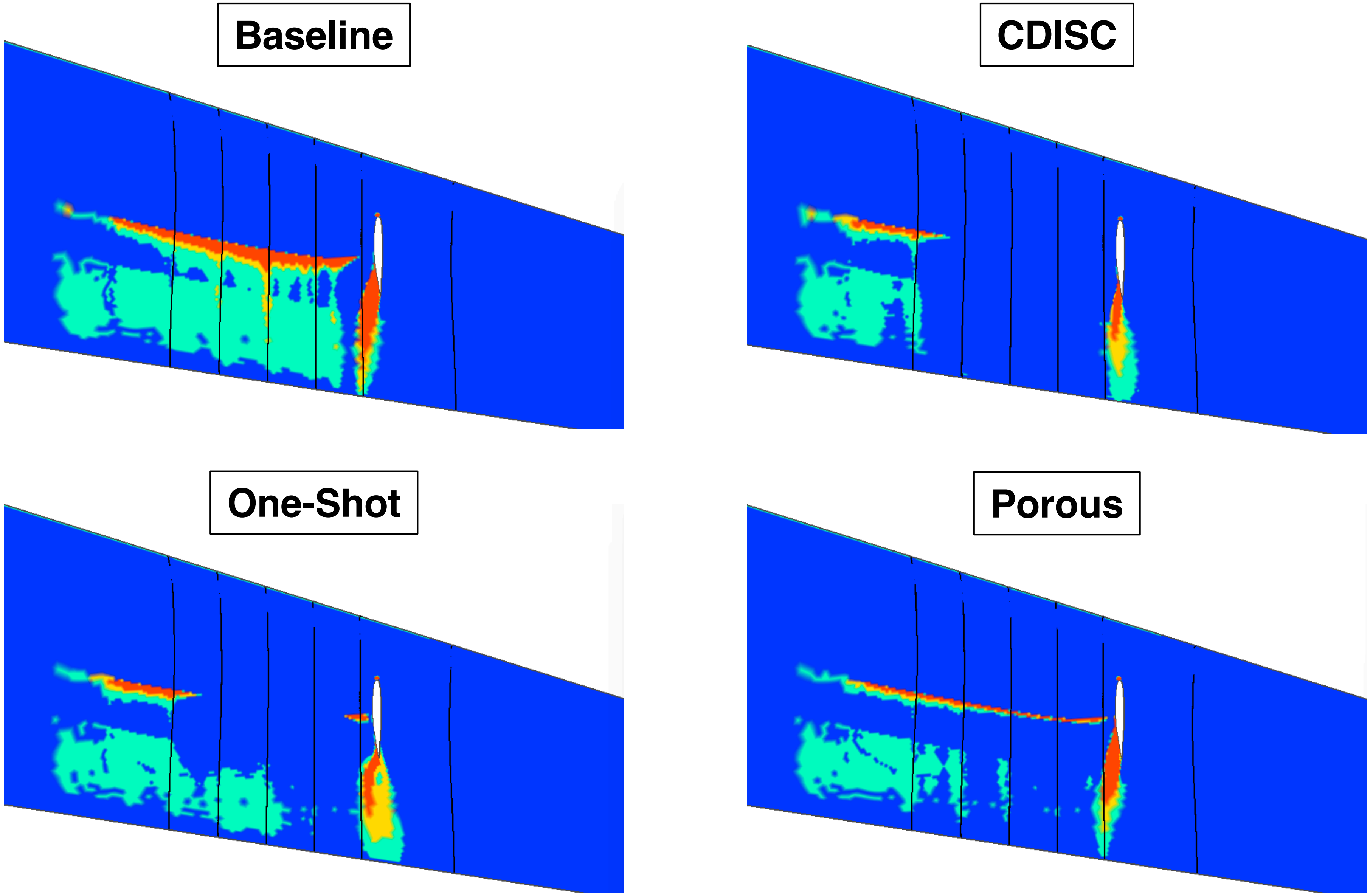
One-Shot



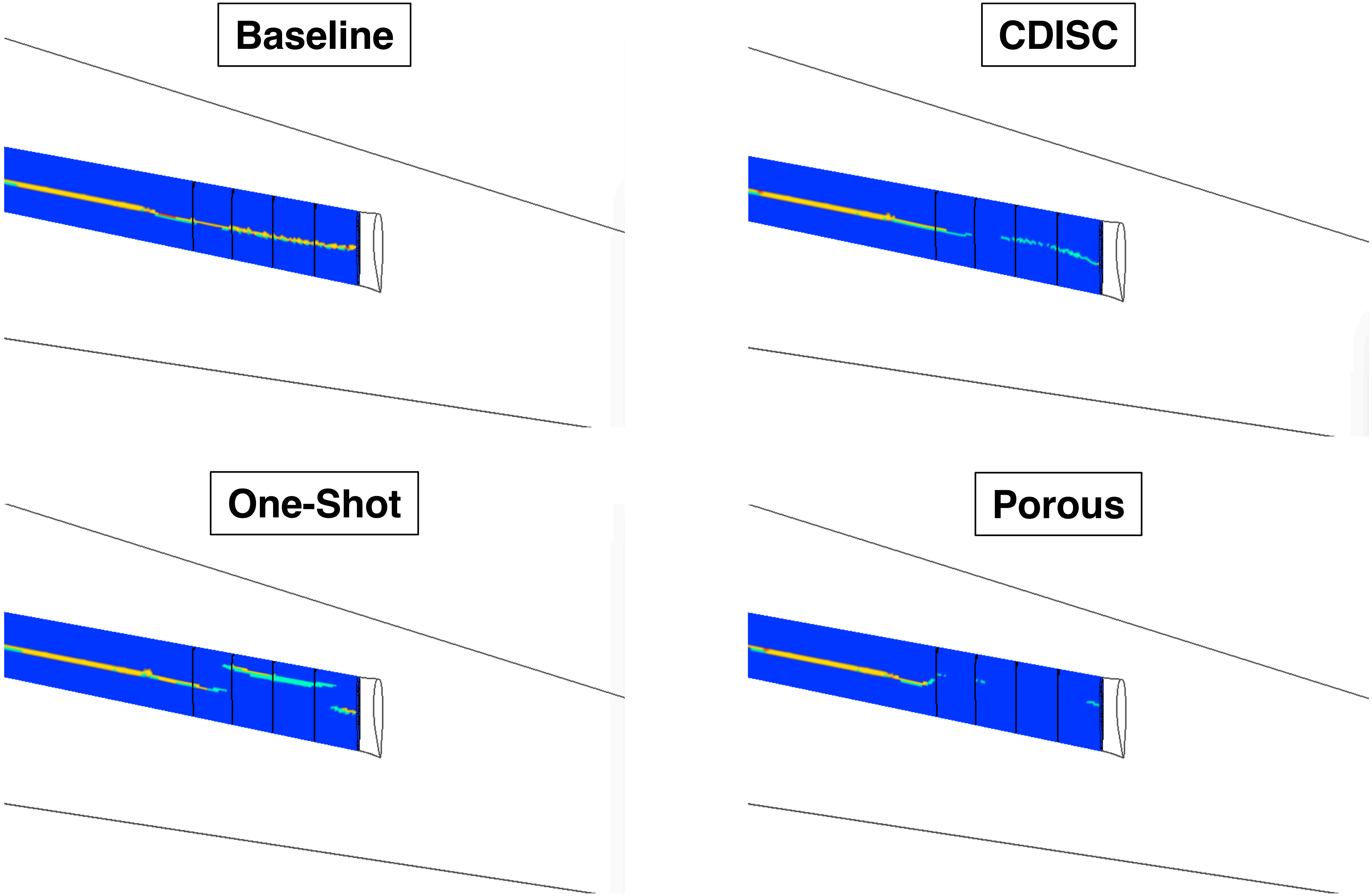
Porous



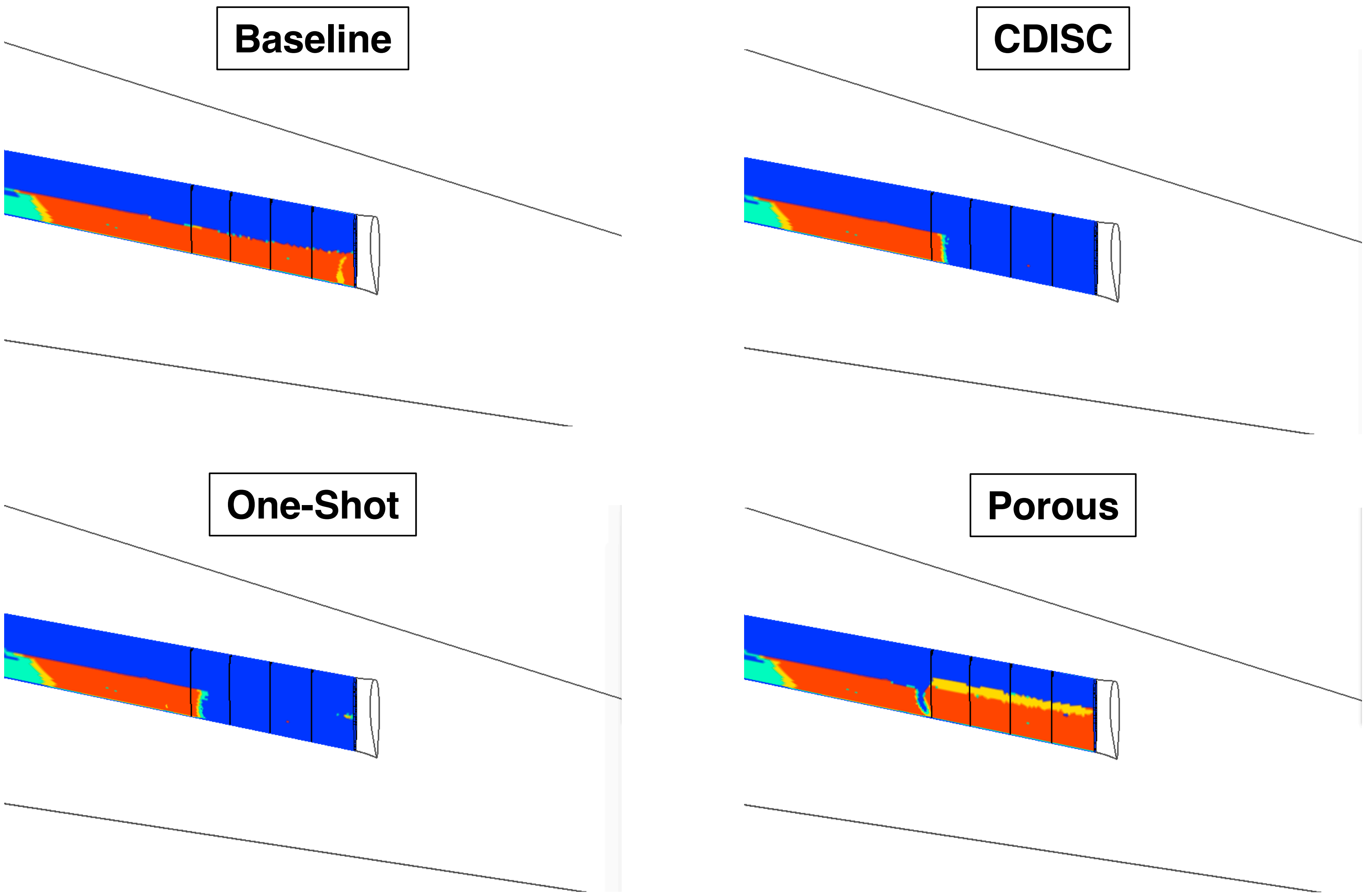
Separation Function on Wing Lower Surface



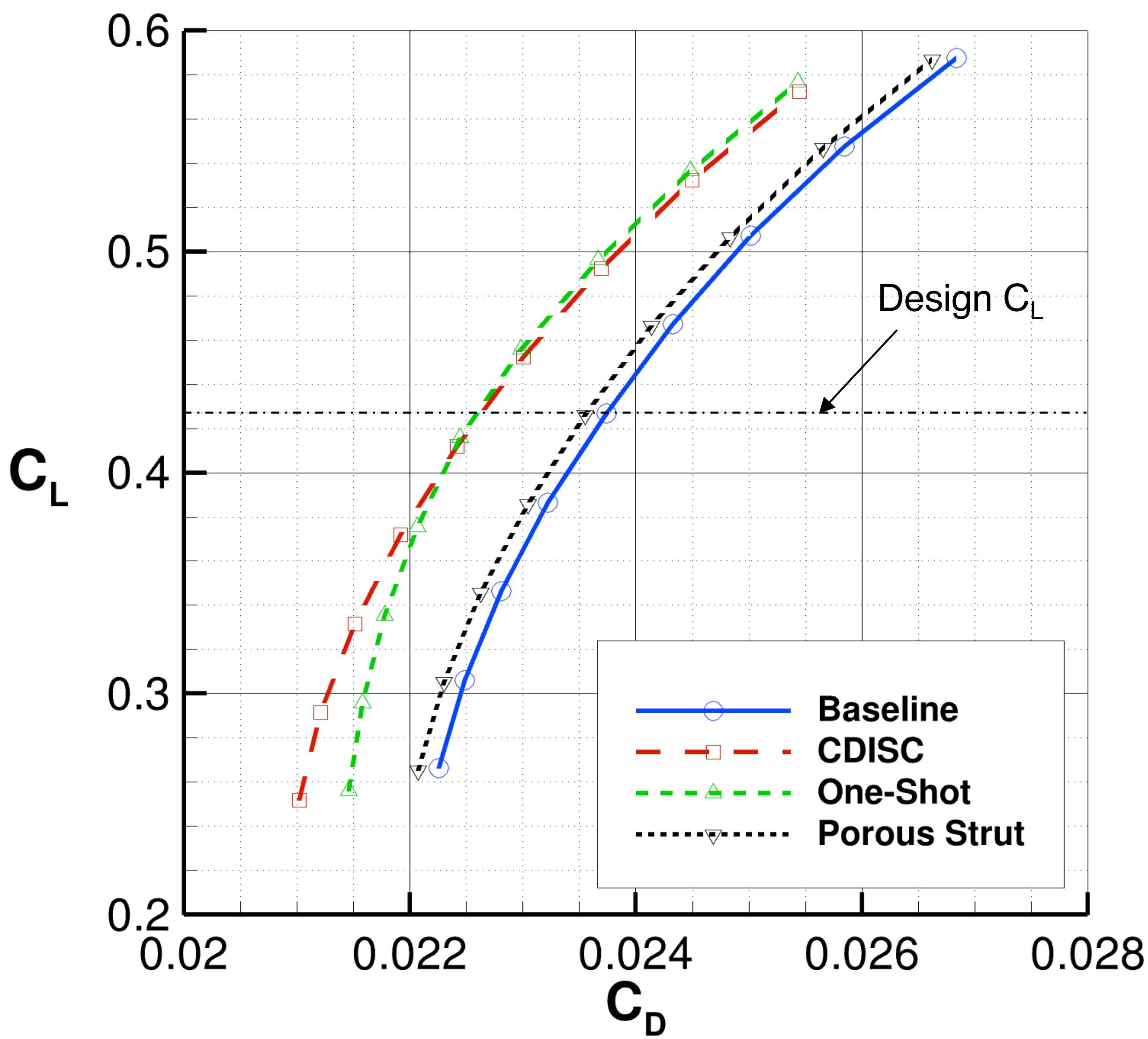
Wave Drag Function on Strut Upper Surface



Separation Function on Strut Upper Surface



Off-Design Performance



Concluding Remarks

- Introduction
- Baseline Evaluation
- Approaches to Drag Reduction
  - Aerodynamic Design (CDISC)
  - Passive Porosity (PASSPORT)
  - Comparison of CDISC and PASSPORT Results
- **Concluding Remarks**

Concluding Remarks

- USM3D and Workshop baseline solutions appeared to be similar, more information needed to assess minor differences
- Both CDISC and One-Shot design approaches were effective at reducing shock strength and flow separation in the design region
- CDISC required about the same time as the baseline analysis, One-Shot required less than a third of that
- The porous cases all had weakened shocks on the component(s) to which porosity was applied, but flow separation occurred from the porous region to the trailing edge, negating the wave drag benefits
- As the above methods are passive, no operational penalty is expected, though manufacturing costs could be increased

Contact: **richard.l.campbell@nasa.gov**

Potential Follow-On Work

- Use the One-Shot case as a starting point for optimization or further refinement with CDISC
- Design entire strut, perhaps including a spanwise loading constraint
- Investigate both passive and active approaches to eliminating the flow separation associated with porosity
- Look at off-design performance, perhaps a multipoint design

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