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Mesh Effects on Flow Solutions for a 2-D Multi-Element Airfoil Using Structured Overset Methods

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AMS Seminar

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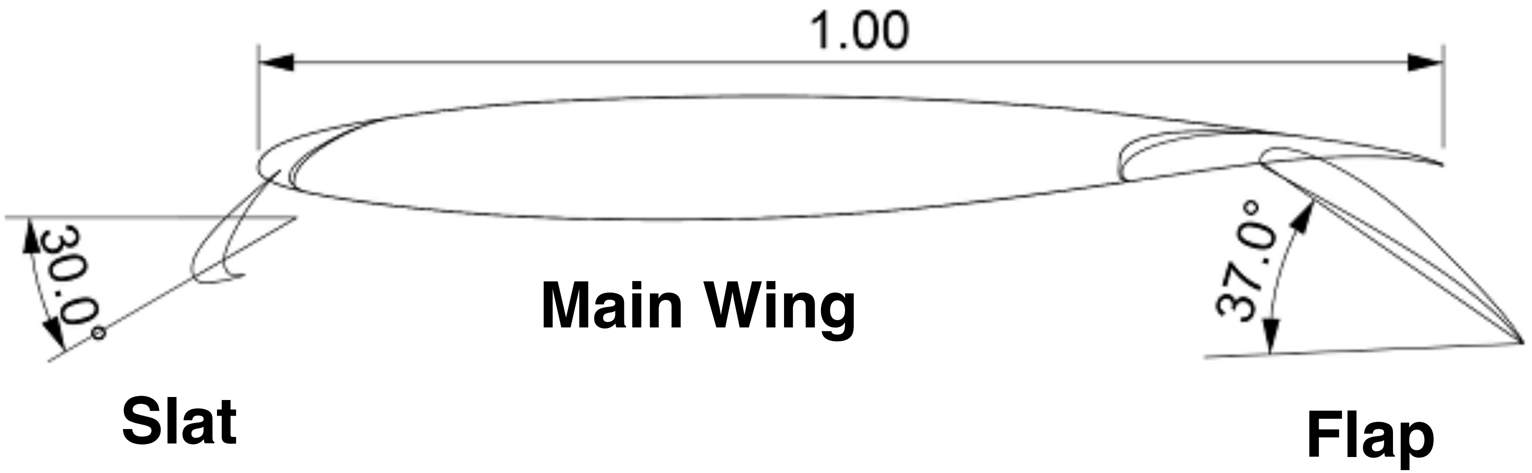
Overview

- Problem Summary
- Flow Solver and Mesh Generator Tools
- Mesh Generation Procedure
- Results
  - Mesh Parameter Study
  - Grid Convergence Study
  - Adaption Study
- Recent Results

Problem Summary

- Develop best-practice mesh from mesh-parameter study ($\alpha = 8°$) on 2D HLCRM cut to determine effect of mesh on solution.
- Perform grid-convergence study ($\alpha = 8°, 16°$)
- Perform adaptive mesh study ($\alpha = 8°, 16°$)
- Flow Parameters:

  M_∞: 0.2
  Re: 5.0×10^6
  c_{ref}: 1.0



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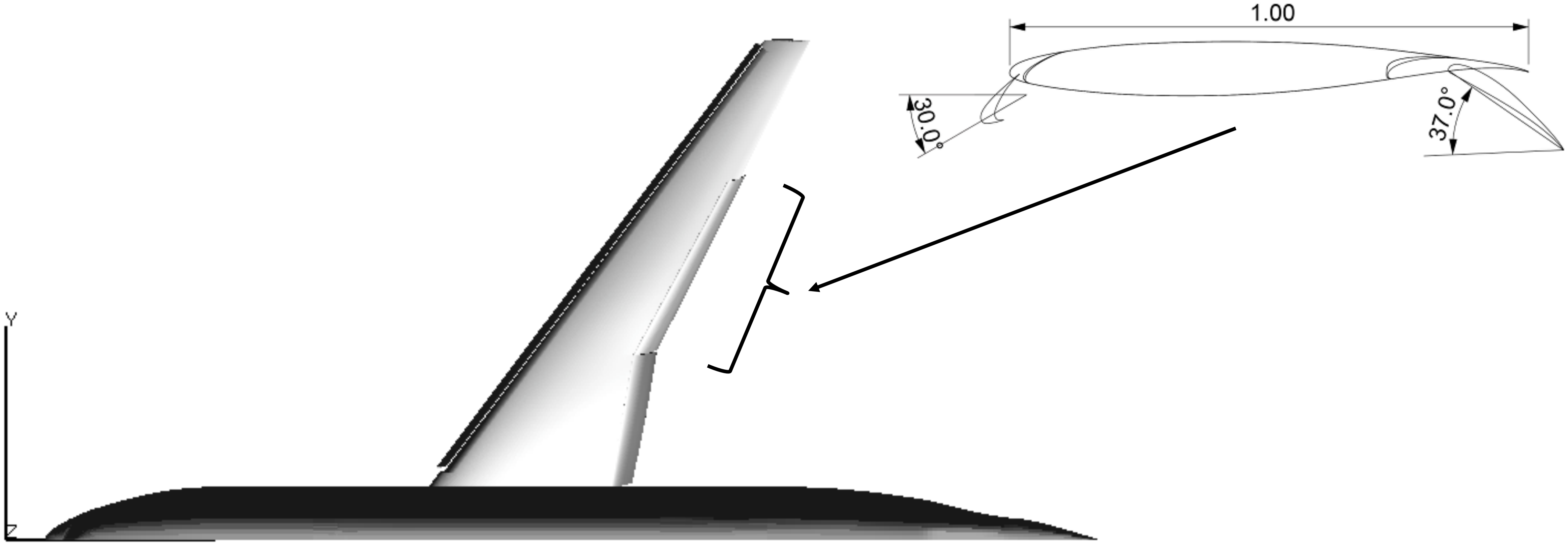
Span-Wise Location of Cut



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Chimera Grid Tools (CGT)

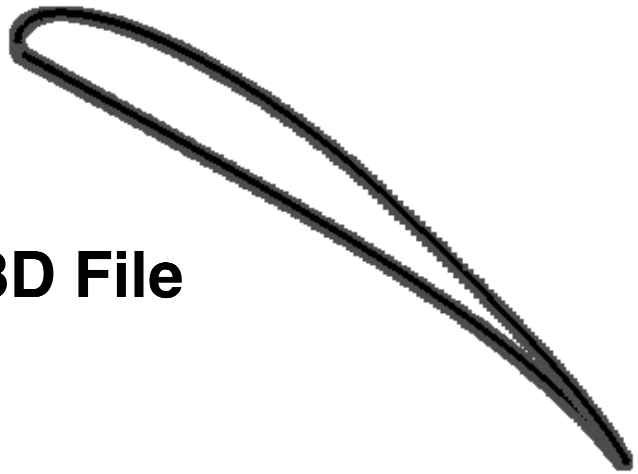
- Collection of software tools for pre- and post-processing of CFD simulations using structured overset grids
- Geometry/Grid Tools: geometry/grid processing, algebraic and hyperbolic surface and volume grid generation
- Analysis Tools: grid quality, aerodynamic loads, flow solution
- High Level Tools: OVERGRID graphical interface, Script Library (200+ macros)

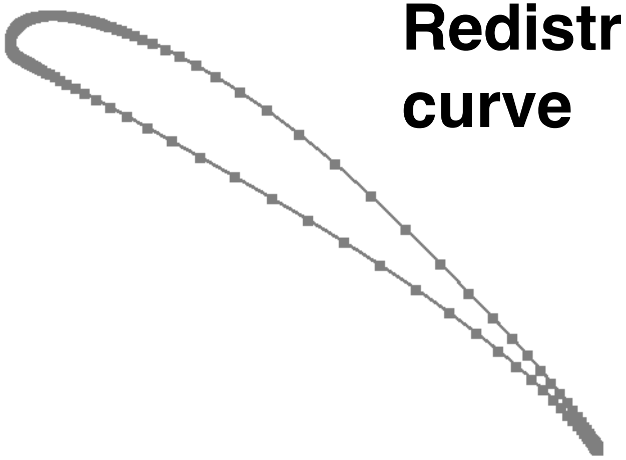
Chan, W., “Advances in software tools for pre-processing and post-processing of overset grid computations,” 2004. URL https://ntrs.nasa.gov/search.jsp?R=20050186738.
Chan, W. M., “Developments in strategies and software tools for overset structured grid generation and connectivity,” 20th AIAA Computational Fluid Dynamics Conference 2011, American Institute of Aeronautics and Astronautics, Reston, Virigina, 2011. https://doi.org/10.2514/6.2011-3051, URL http://arc.aiaa.org/doi/10.2514/6.2011-3051.

Mesh Generation Procedure

- Surface Processing
  - Convert IGES/STEP file to Plot3D format with fine resolution using Pointwise™
  - Redistribute points for initial curves in CGT
    - Cluster points at regions of high curvature, trailing edges

Fine Plot 3D File

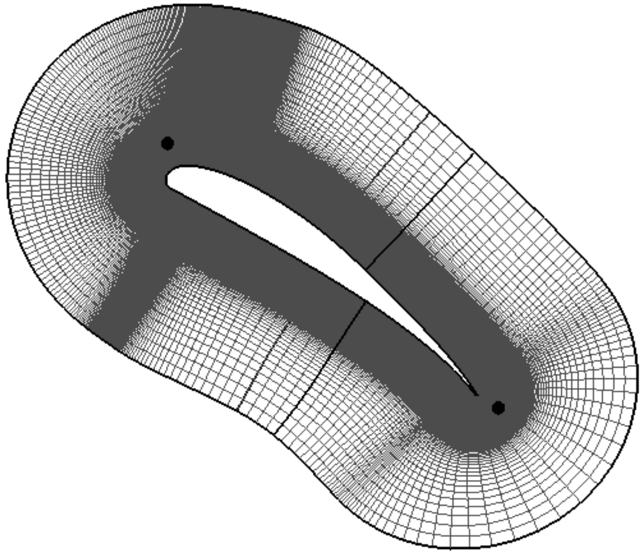


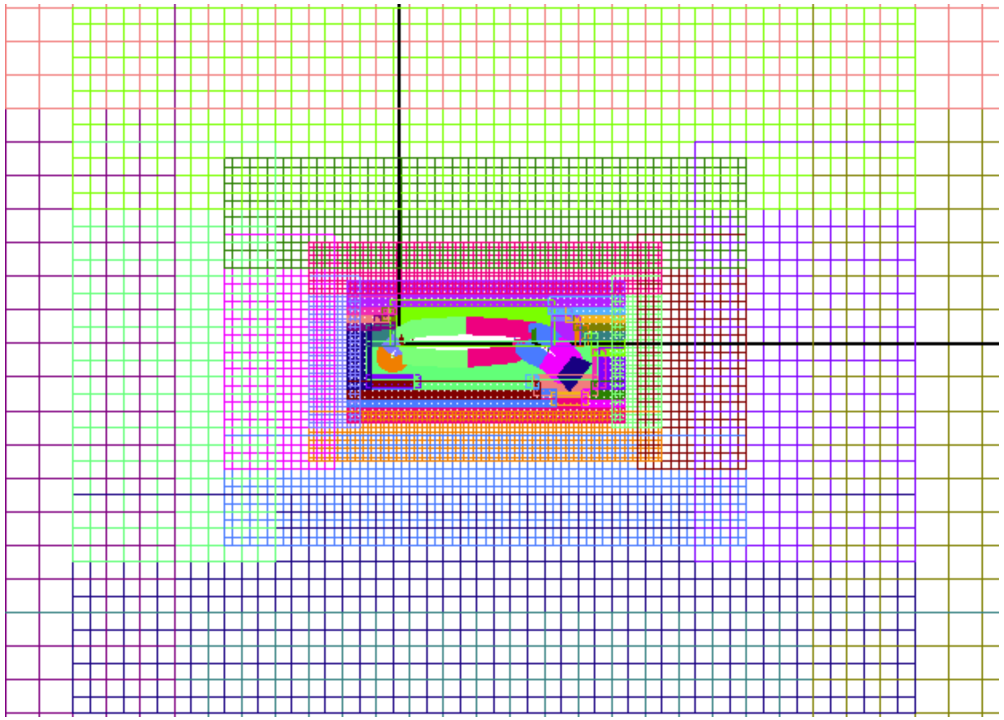


Redistributed curve

Mesh Generation Procedure

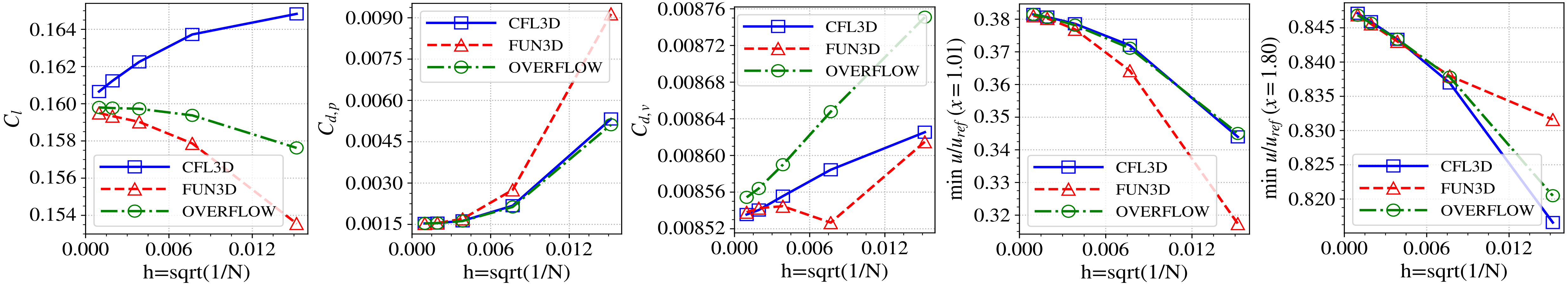
- Volume Mesh Generation
  - Near-body hyperbolic grids generated in CGT
  - Off-body Cartesian grids generated in OVERFLOW
- Domain Connectivity
  - X-ray hole-cutting using OVERFLOW





OVERFLOW

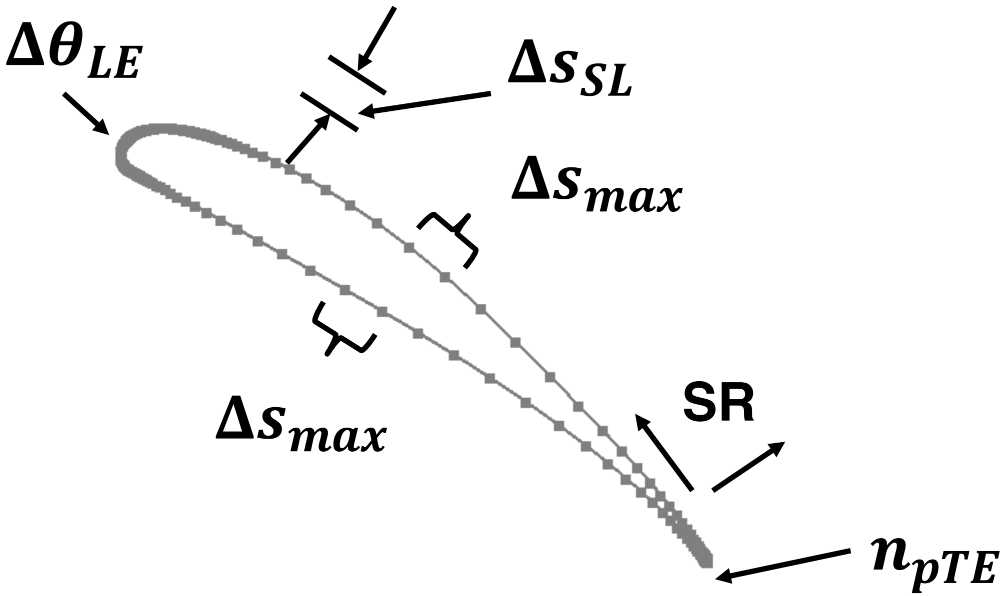
- Implicit Finite-Difference on Structured Overset Grids
  - 3rd Order HLLC scheme with Koren Limiter
  - SSOR solver, non-time accurate time-stepping
  - Multi-level off-body box mesh generation, X-ray based domain connectivity
- Spalart-Allmaras Turbulence Model Verification
  - 2D Airfoil Near Wake – 500c Far-Field Extent



Nichols, R. H., Tramel, R. W., and Buning, P. G., "Solver and turbulence model upgrades to OVERFLOW 2 for unsteady and high-speed applications," Collection of Technical Papers - AIAA Applied Aerodynamics Conference, Vol. 1, American Institute of Aeronautics and Astronautics, Reston, Virigina, 2006, pp. 91–124. https://doi.org/10.2514/6.2006-2824, URL http://arc.aiaa.org/doi/10.2514/6.2006-2824.

Mesh Parameters

- Best practice mesh based on:
  - A priori knowledge of physics (shear layers, wakes, etc.)
  - O vs C mesh topology
  - Mesh parameter study



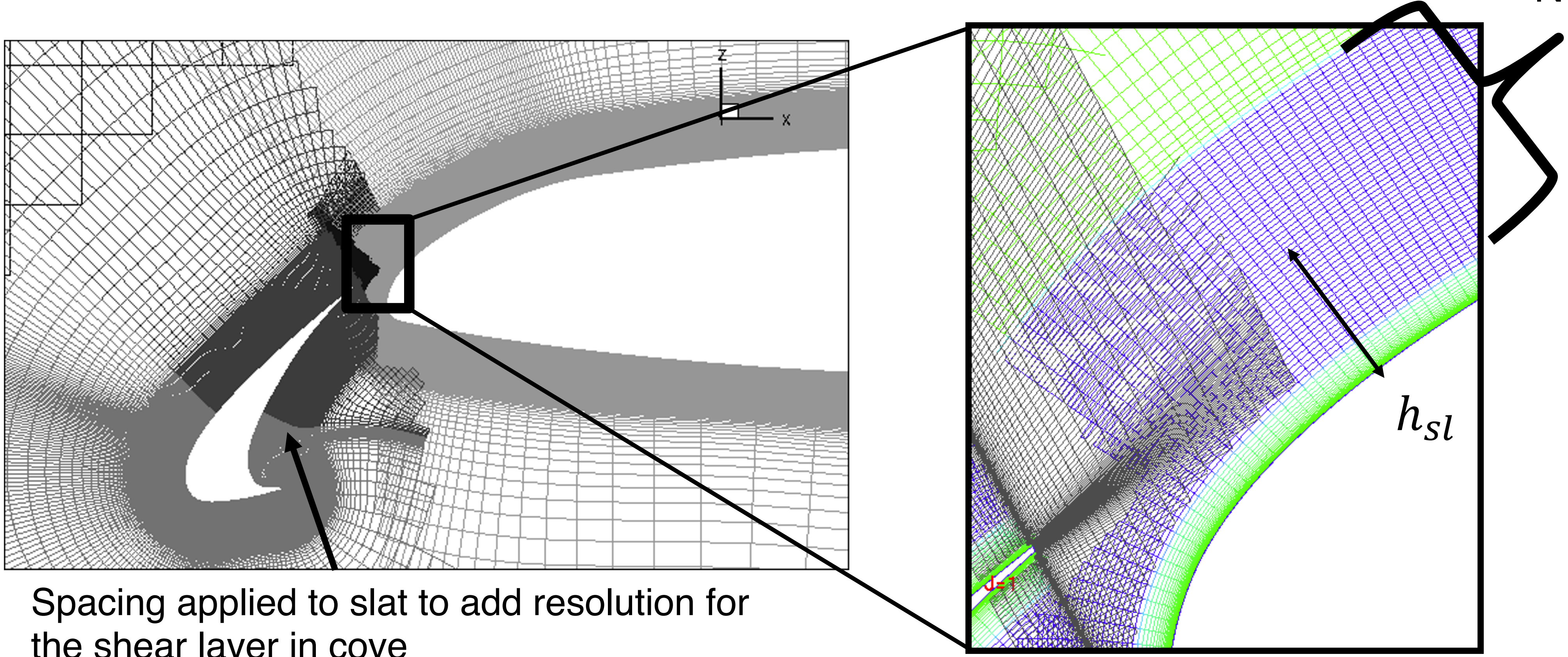
Mesh Parameter	Values
$\Delta\theta_{LE}$ (Leading Edge Max Turning Angle)	0.125°, 0.25°, 0.5°, **1**°, 2°
n_{pTE} (# of pts. on trailing edge)	3, 5, **9**, 11, 17, 21
Stretching Ratio	1.05, 1.1, **1.15**, 1.2, 1.3, 1.4
Δs_{max} (% of c_{ref}, Max tangential wall spacing)	1.0, 1.33, 2.0, **3.0**, 4.5
Δs_w (Wall spacing)	4.323×10^{-6}
Δs_{wgTE} (Wake-grid spacing at trailing edge)	$5\Delta s_w$
Δs_{SL} ($\times\Delta s_w$, Shear-layer spacing)	25, 50, **100**, 200, 400
h_{SL} (Shear-layer center offset)	0.028
Near-Body Mesh Topology	O mesh
Far-Field Distance	$1000c_{ref}$

Shear-Layer Spacing

- Resolve wake of forward elements

Band of Uniform Normal Spacing

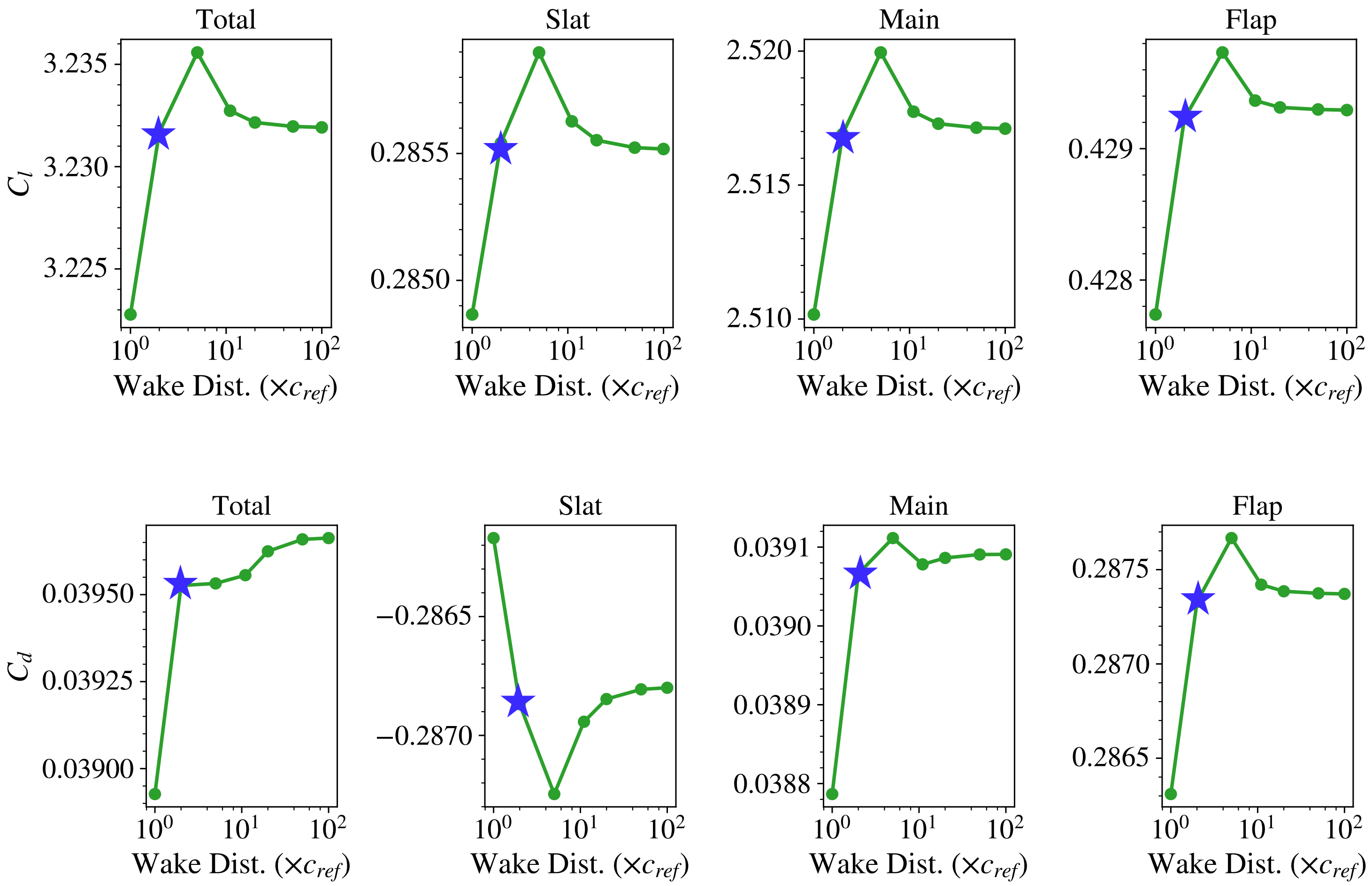
$\Delta s_{sl} = 100 \Delta s_w$

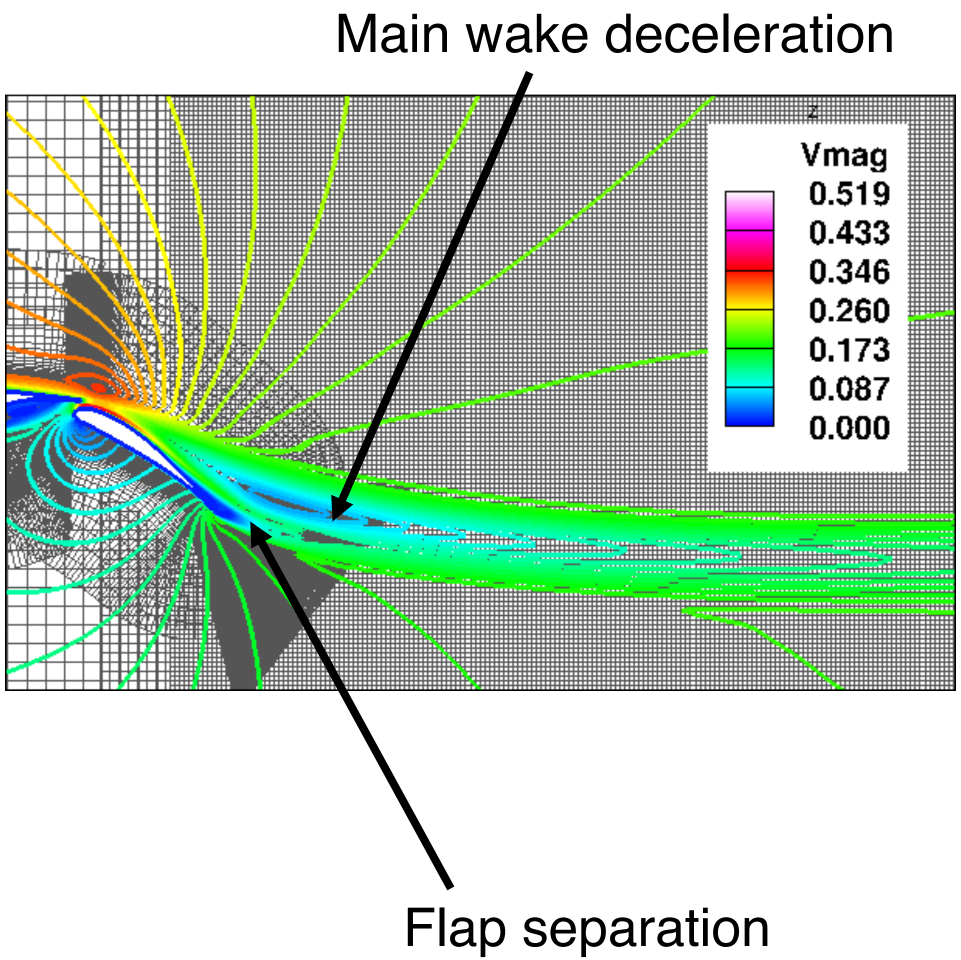


Spacing applied to slat to add resolution for the shear layer in cove

Rogers, S. E., “Progress in high-lift aerodynamic calculations,” Journal of Aircraft, Vol. 31, No. 6, 1994, pp. 1244–1251. https://doi.org/10.2514/3.46642, URL http://arc.aiaa.org/doi/10.2514/3.46642.

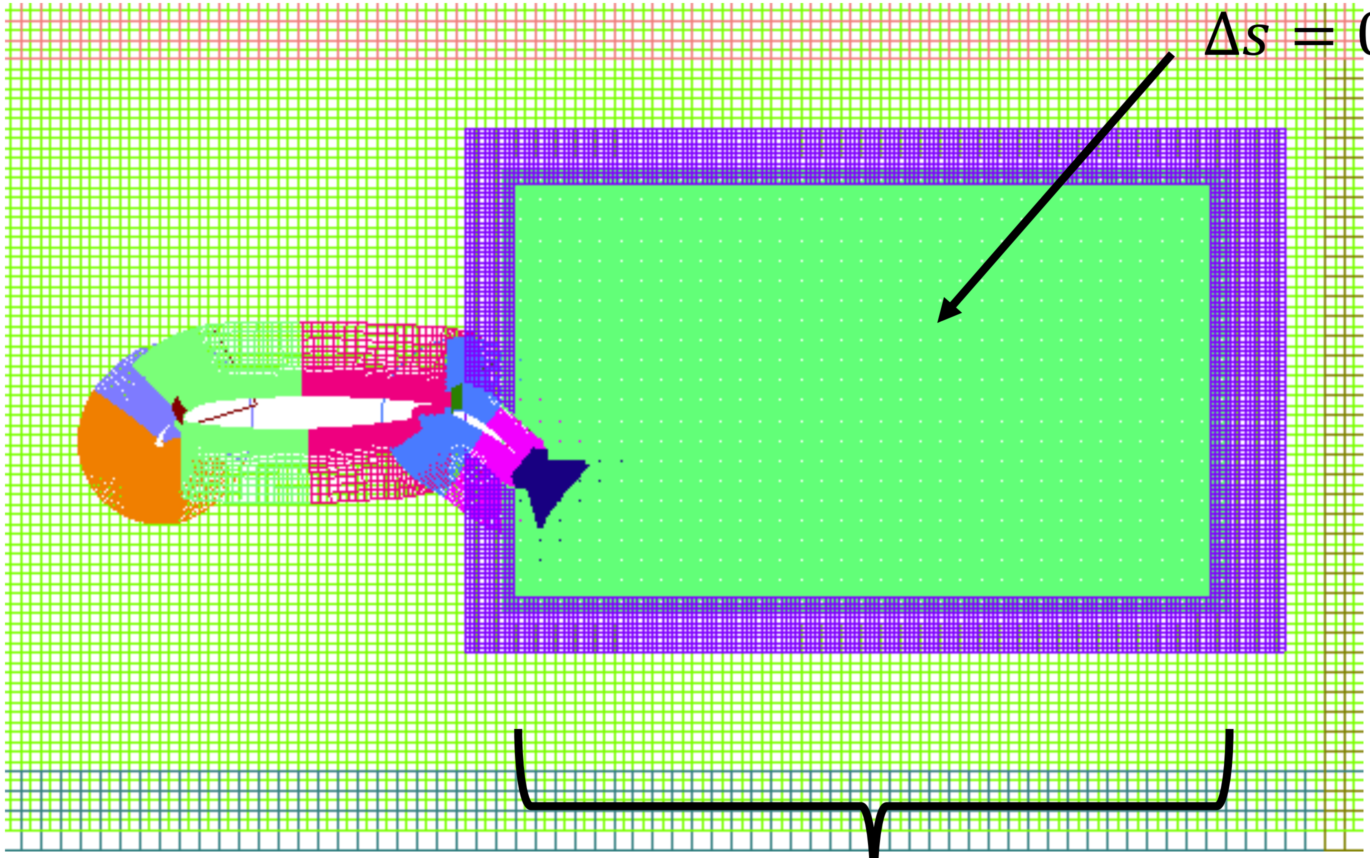
Wake Refinement Block





★ **Wake Distance = $2c_{ref}$**

Wake Refinement Block



$\Delta s = 0.25 \Delta s_{max}$

$h = 1.4 \times c_{ref}$

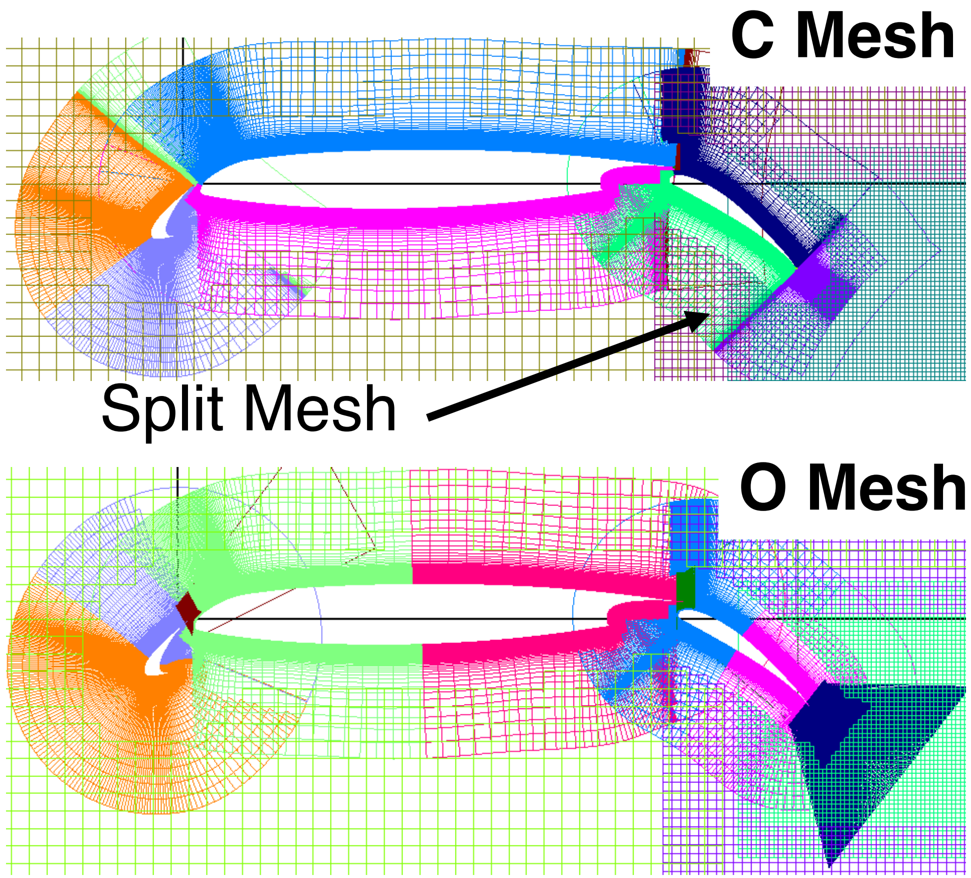
Height expanded for alpha-sweeps required for mesh-parameter study

$l = 2 \times c_{ref}$

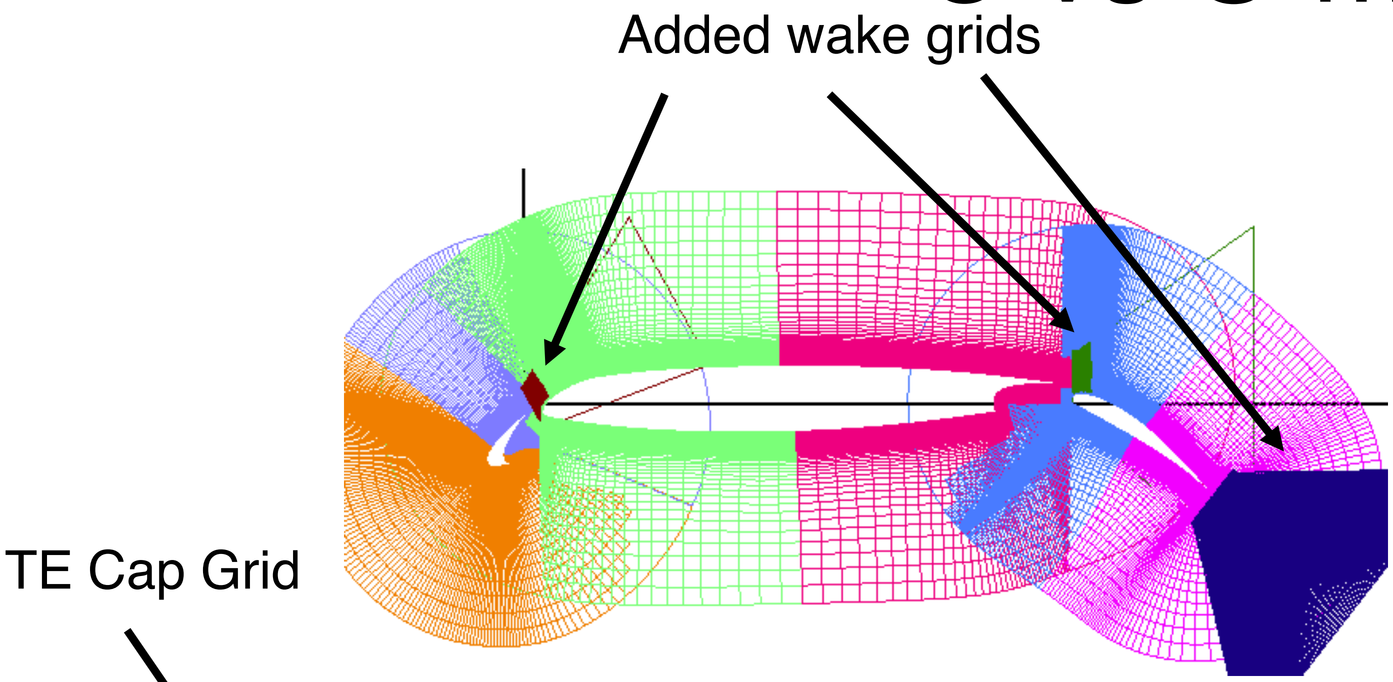
C vs O mesh

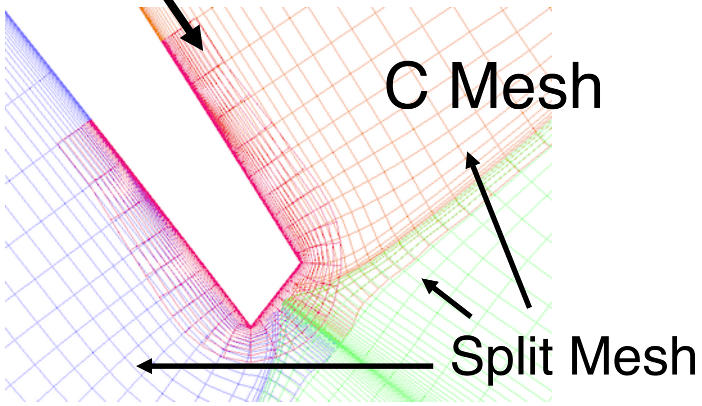
- Can potentially avoid cons of O mesh through overset-framework and wake-grid

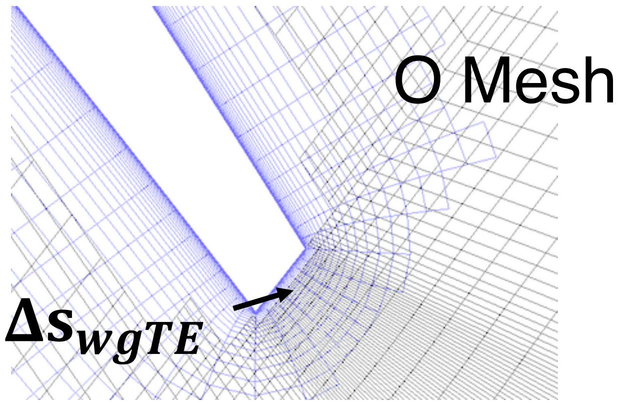
	Pros	Cons
O Mesh	• No explicit wake boundary • Good BL clustering for finite-thickness TE	• Poor downstream wake resolution
C Mesh	• Natural clustering at TE • Fine wake resolution	• Explicit boundary in wake • Only good for single AoA/excessive tight spacing far downstream • Poor aspect ratio for finite-thickness TE



C vs O mesh



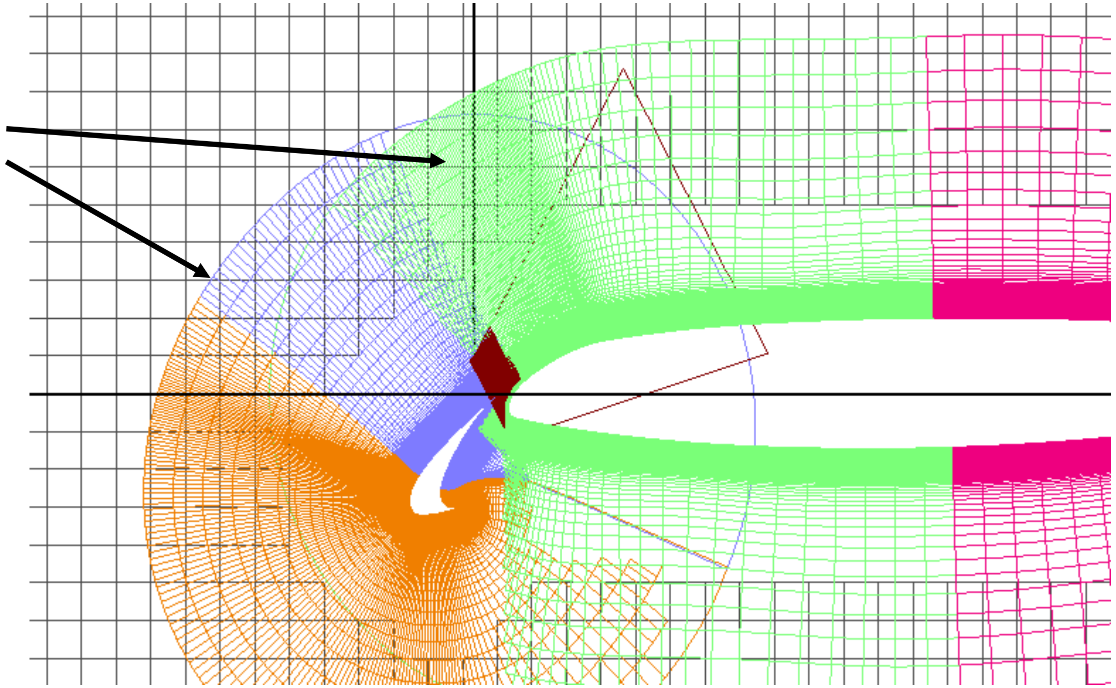




	O Mesh	C Mesh	Diff ($\times 10^4$)
Total C_l	3.22486	3.22499	1.23
Total C_d	0.04002	0.03960	-4.22
Total C_m	-0.52188	-0.52175	1.27
Slat C_l	0.28456	0.28486	2.96
Slat C_d	-0.28522	-0.28567	-4.53
Slat C_m	0.08262	0.08271	0.90
Main C_l	2.51266	2.51238	-2.77
Main C_d	0.03906	0.03915	0.95
Main C_m	-0.28350	-0.28339	1.09
Flap C_l	0.42765	0.42775	1.03
Flap C_d	0.28617	0.28611	-0.64
Flap C_m	-0.32100	-0.32107	-0.72

Hole-Cutting

- DCF-XRAYS used to set overlap between meshes
- Hole-Cutting Goals:
  - Minimize overlap, restrict overlap to cells of similar size & orientation
- Hole-cutting approach slightly deviates from typical best-practice
  - Off-Body (OB) & Near-Body (NB)
    - Use 8th outer-most shell from NB grids
  - Near-body & Near-Body
  - Wake Grid & Near-Body



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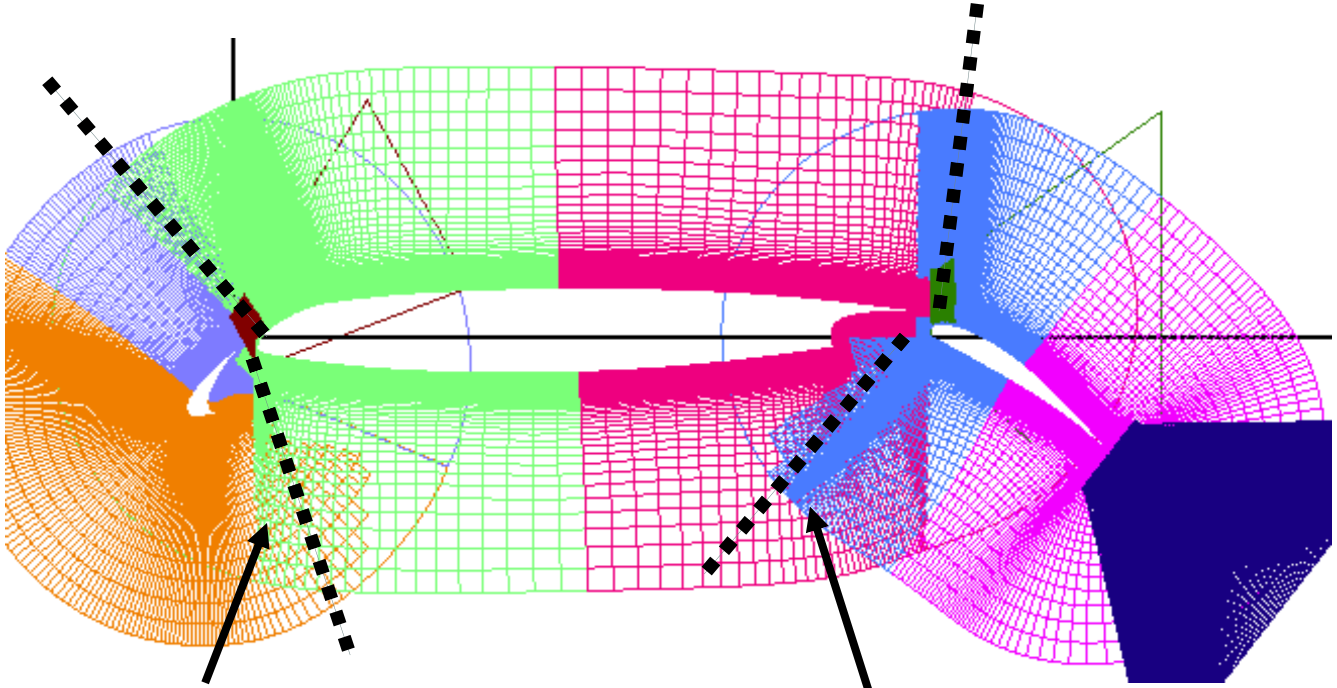
Hole-Cutting (cont'd.)

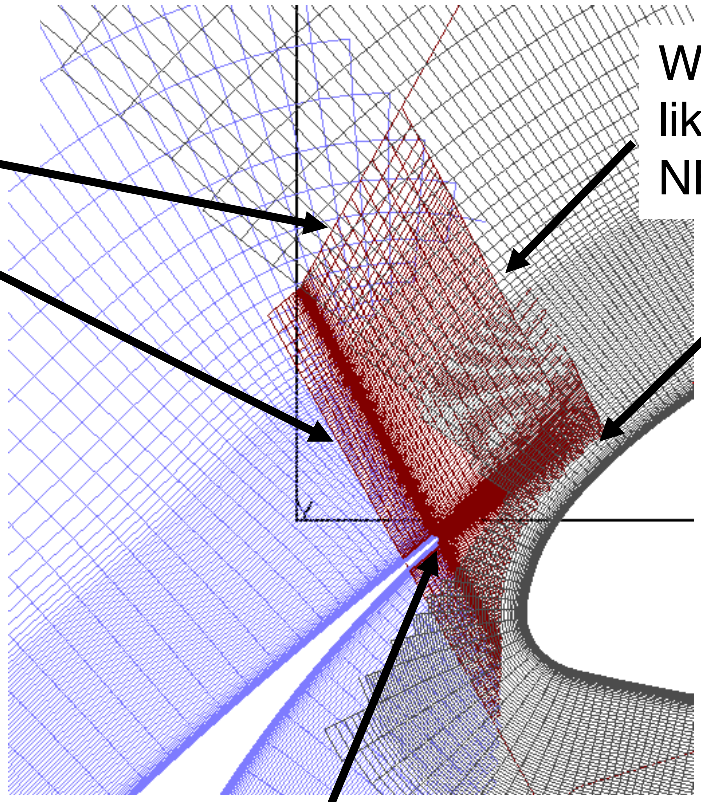
Near-body & Near-Body



Overlap occurs generally along dotted lines

Overlap between wake and respective NB-grid occurs at outer edges of wake grid

Wake grid cut like respective NB-mesh

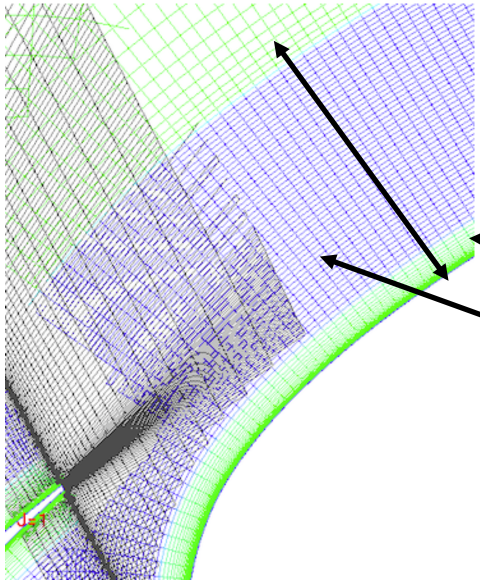


Wake grid wraps tightly around finite-thickness trailing edge

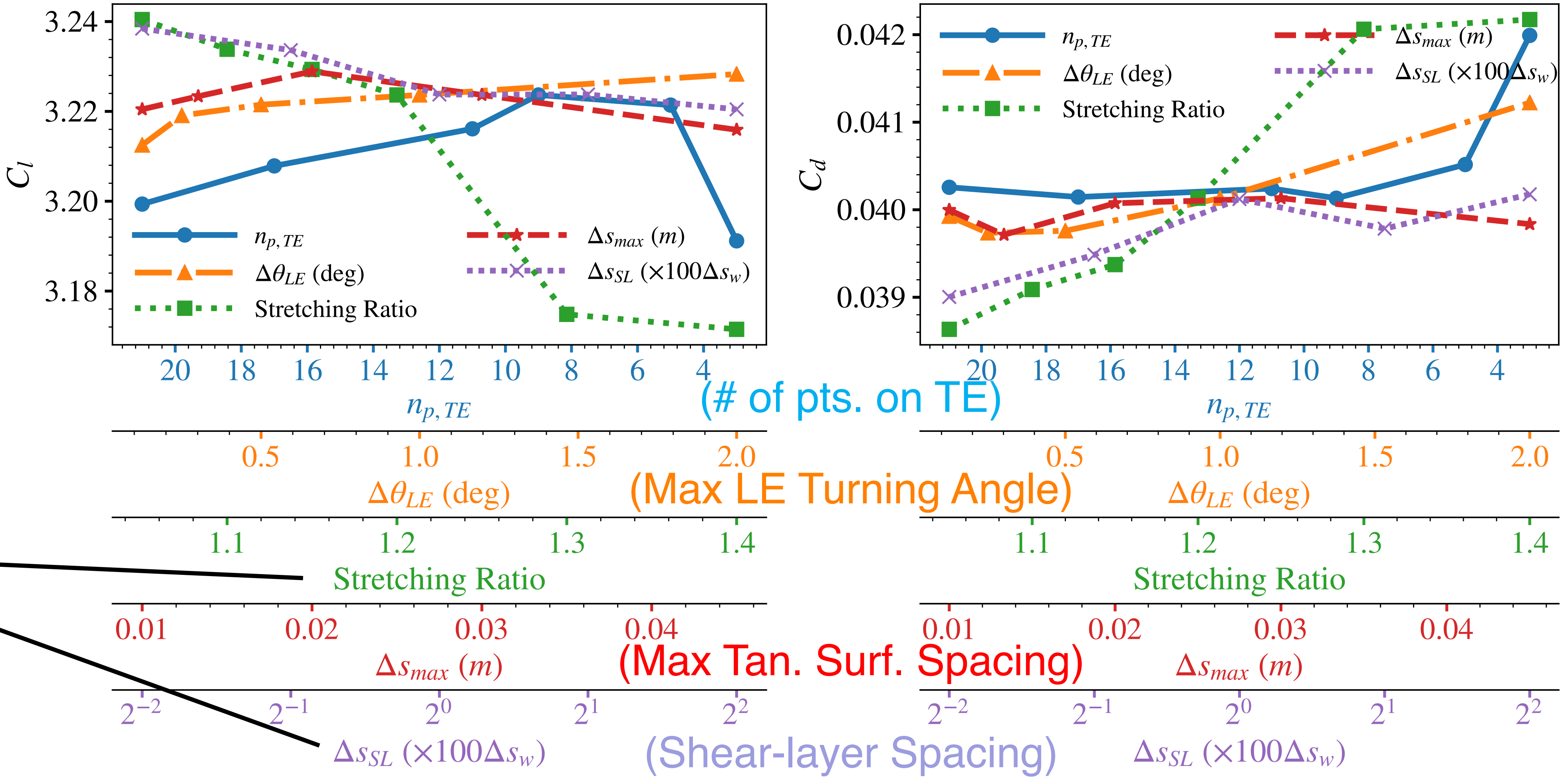
Wake Grid & Near-Body

Mesh Parameter Study

Params.	Baseline Values
n_{pTE}	9
$\Delta\theta_{LE}$	1.0
SR	1.2
Δs_{max}	$0.03c_{ref}$
Δs_{SL}	$100\Delta s_w$

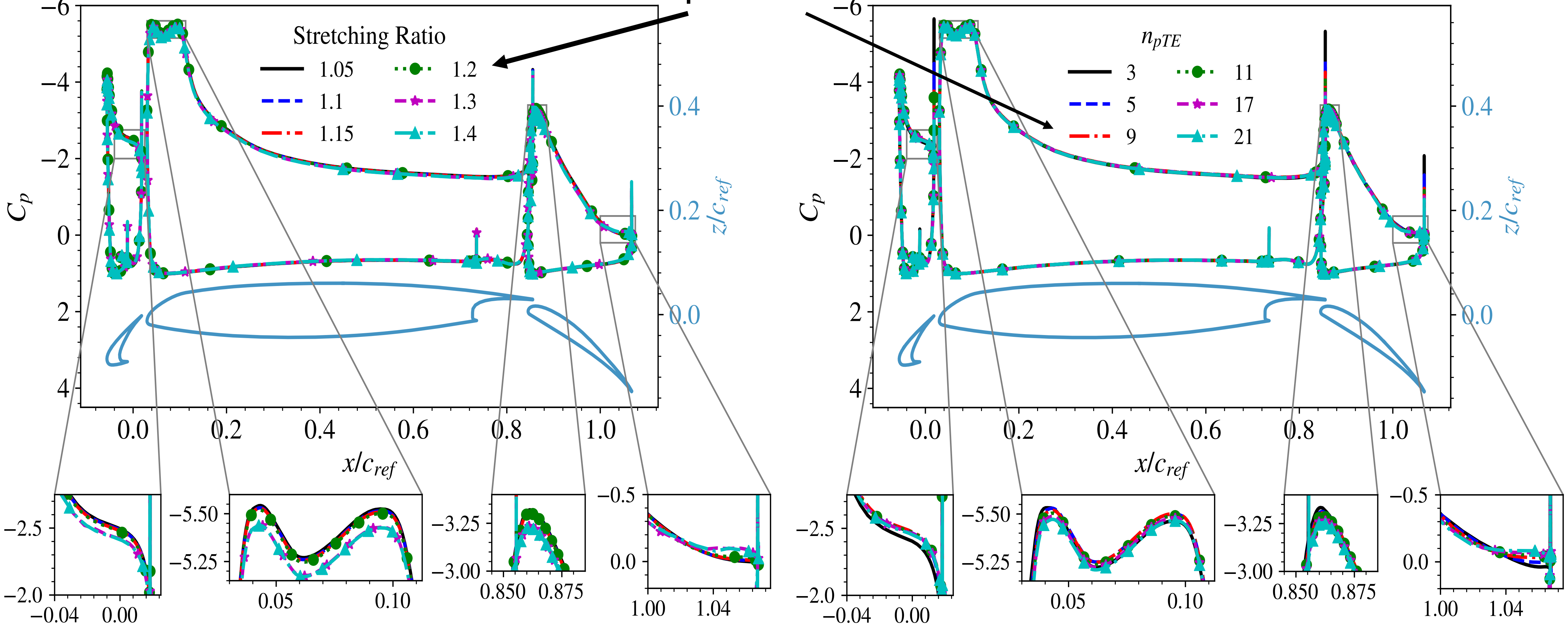


Fine ⟵ Coarse Fine ⟵ Coarse



Mesh Parameter Study

Baseline parameter values



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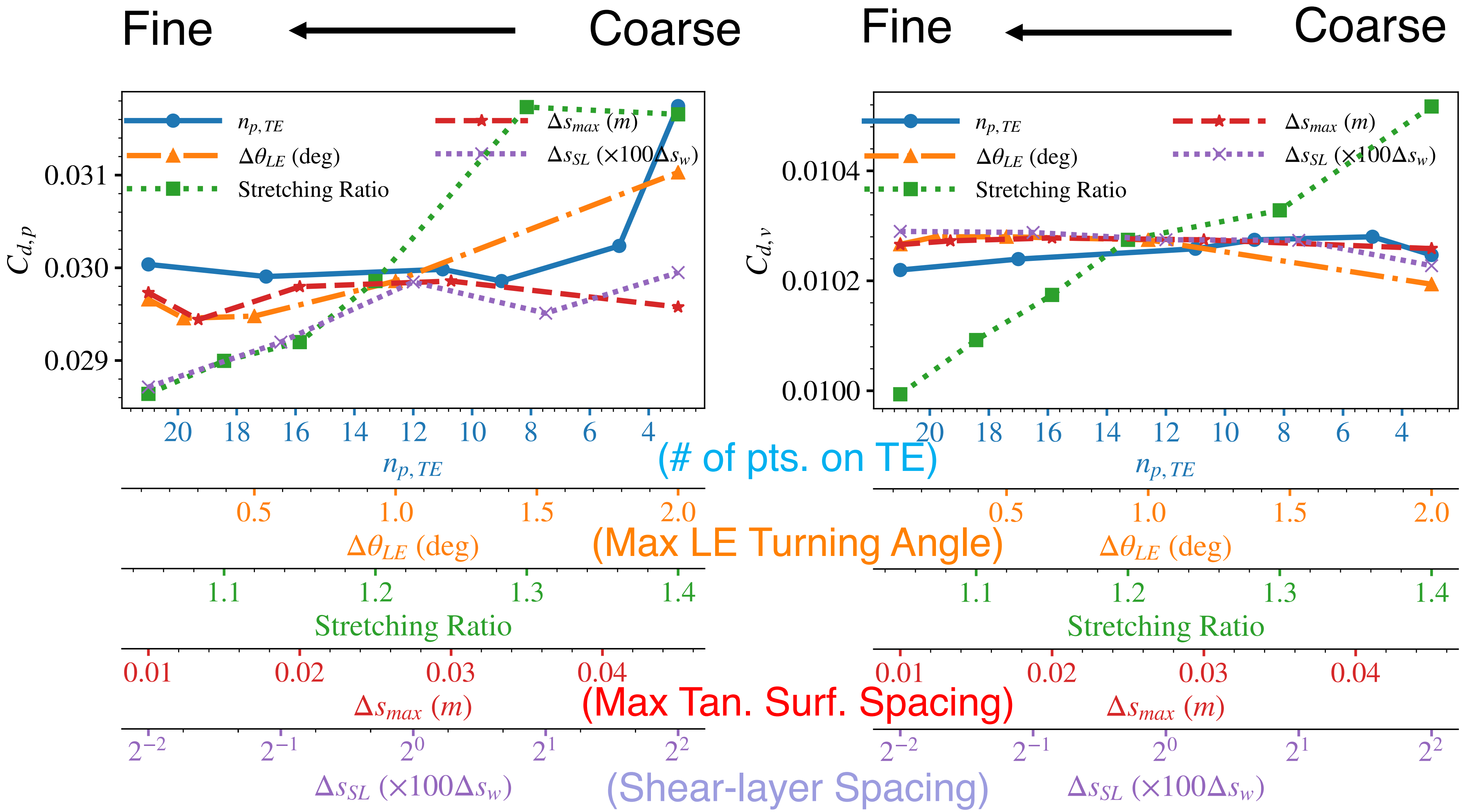

Mesh Convergence Study

- Successive halving of each grid-spacing parameters (except for wall-spacing), SR = 1.15
- $\alpha = 8°, 16°$

Refinement Level	n_{pTE} (# of pts. at T.E.)	$\Delta\theta_{LE}$ (deg) (L.E. Max Turning Angle)	$\Delta s_{\max}\ (\times c_{ref})$ (Max tangential wall spacing)	$\Delta s_{SL}(\times\Delta s_{w})$ (Shear Layer Spacing)	$\Delta s_{wgTE}(\times\Delta s_{w})$ (Wake-grid spacing at T.E.)	Node Count
L1	5	2.0	0.06	200	10	129980
L2	**9**	**1.0**	**0.03**	**100**	**5**	**262209**
L3	17	0.5	0.015	50	2.5	686587
L4	33	0.25	0.0075	25	1.25	2166259

Mesh Adaption Study

- Sensor: second undivided differences in conservative variables (q)
- Adaption performed with 2, 3, and 4 levels of refinement
- Starting mesh : coarse with only BL clustering; sans shear-layer spacing, wake grids

$$S = \max_{i=j,k,l} \left\{ \max_{\vec{Q}} \left[\left(\frac{q_{i-1} - 2q_i + q_{i+1}}{2q_{ref}} \right)^2 \right] \right\}$$

Mesh Parameter	$\Delta s_{\mathrm{w}}\ (\times c_{ref})$	n_{pTE}	$\Delta\theta_{LE}$ (deg)	$\Delta s_{\max}\ (\times c_{ref})$	SR
Value	4.323×10^{-6}	3	2.0	0.045	1.2

Buning, P. G., and Pulliam, T. H., “Cartesian off-body grid adaption for viscous time-accurate flow simulation,” 20th AIAA Computational Fluid Dynamics Conference 2011, 2011. https://doi.org/10.2514/6.2011-3693.
Buning, P. G., and Pulliam, T. H., “Near-body grid adaption for overset grids,” 46th AIAA Fluid Dynamics Conference, American Institute of Aeronautics and Astronautics Inc, AIAA, 2016. https://doi.org/10.2514/6.2016-3326.

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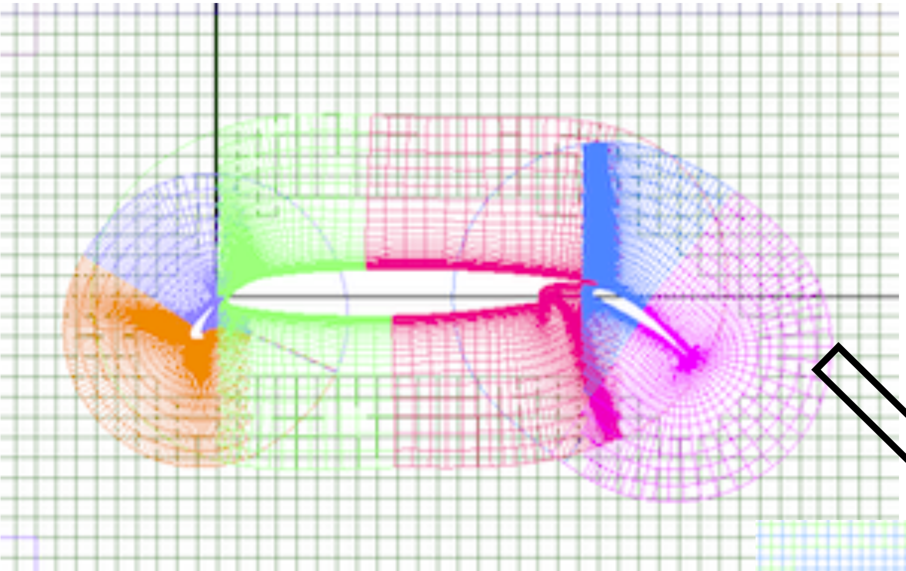
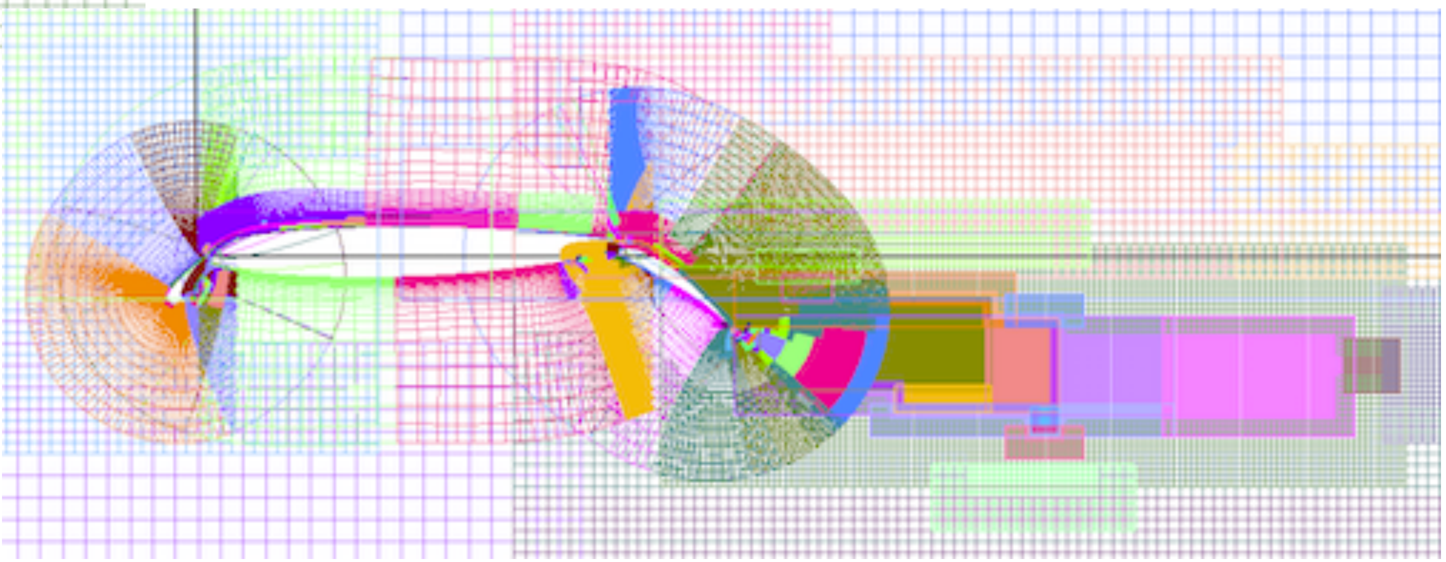
Meshes Generated From Adaption

$(\alpha = 8^{\circ})$



Starting Mesh

Final Mesh with Four Levels of Refinement



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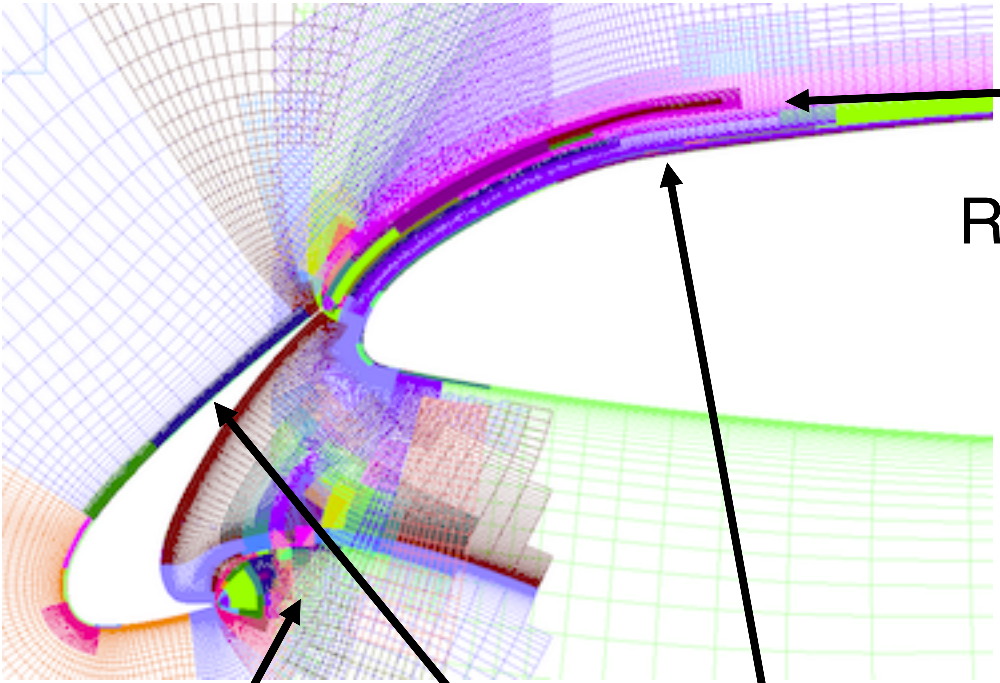
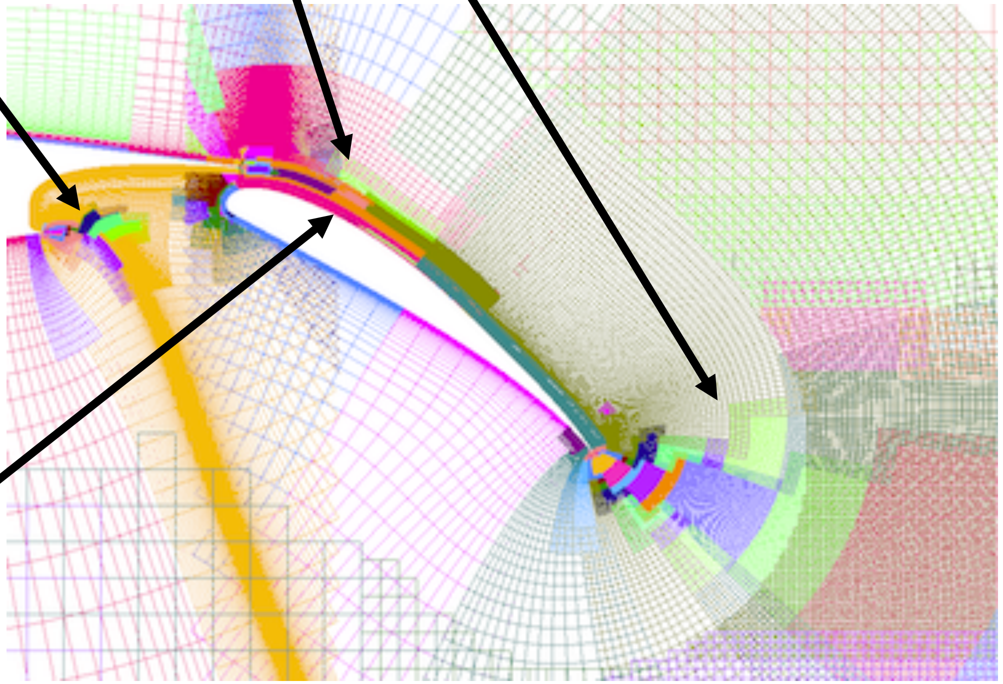
Meshes Generated From Adaption

$(\alpha = 8°)$





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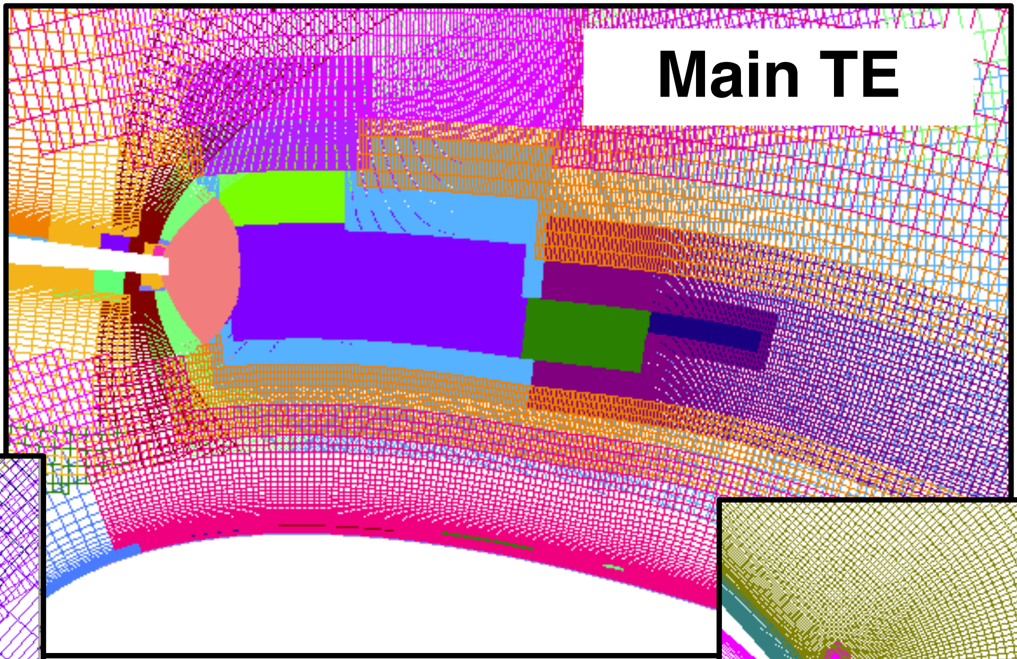
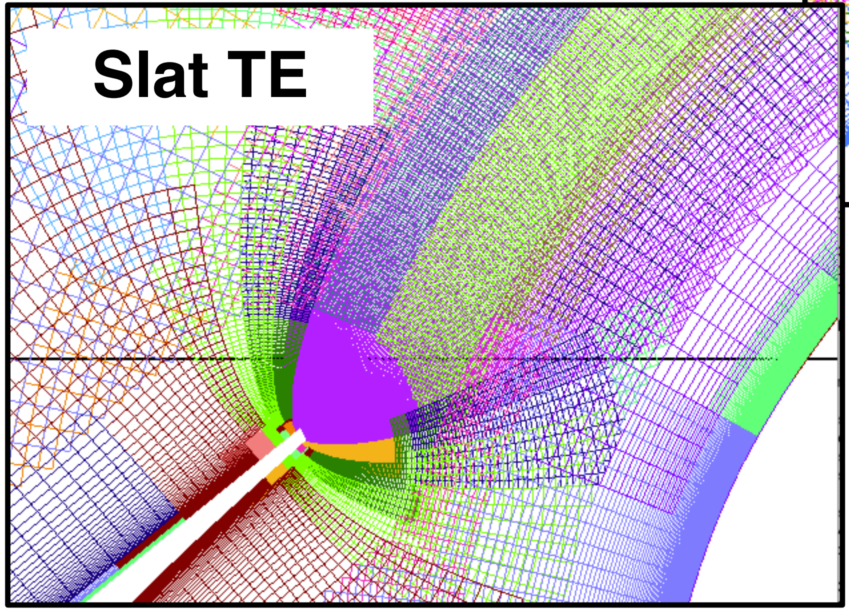
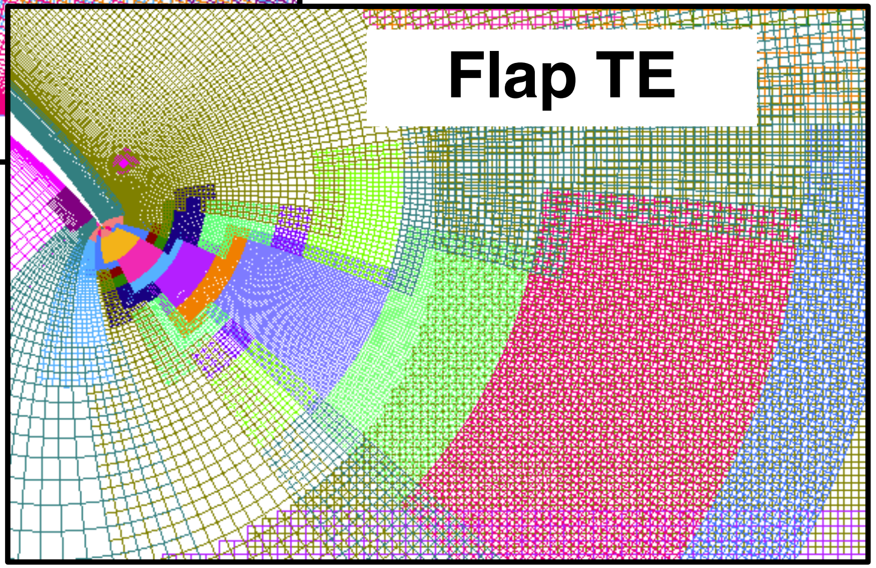
Meshes Generated From Adaption

$(\alpha = 8°)$





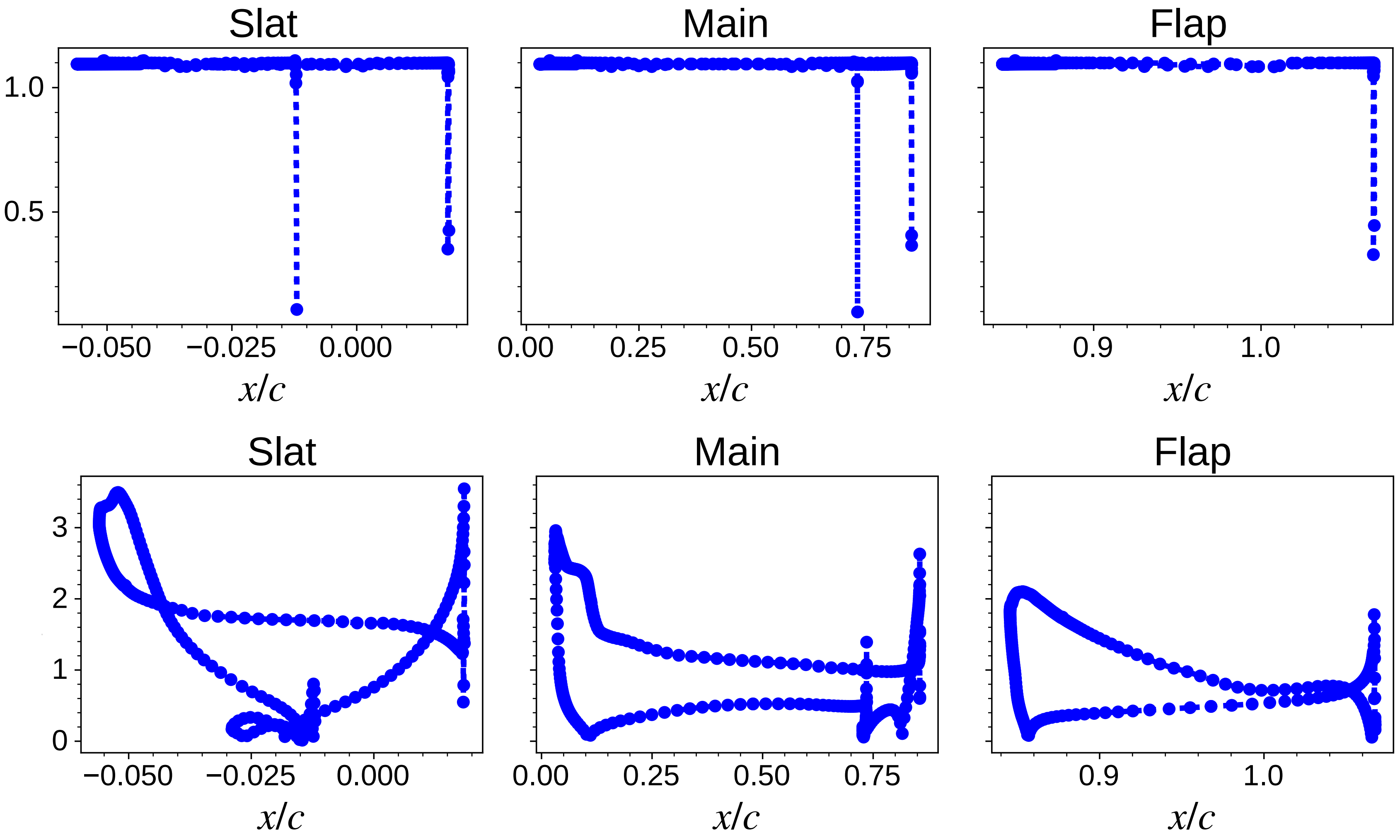


Wall-Normal Spacing

- Specified wall spacing: $\Delta s_w = 4.323\times10^{-6}$ $(y^+ \approx 1)$

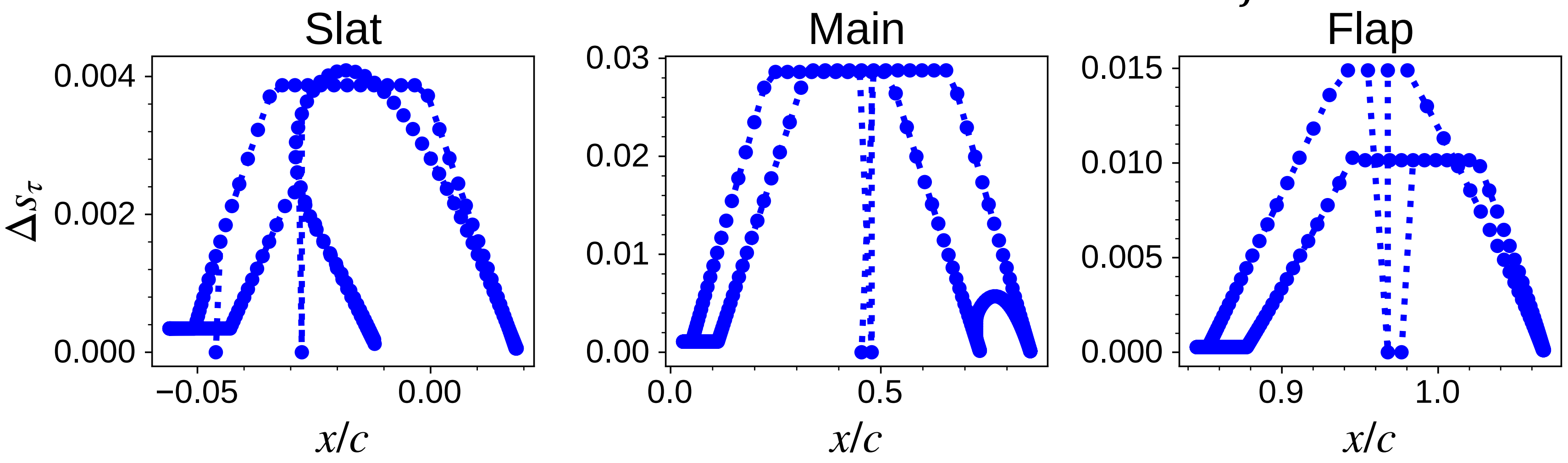
Actual wall spacing $(\times \boldsymbol{\Delta s_w})$

y+ from computed solution

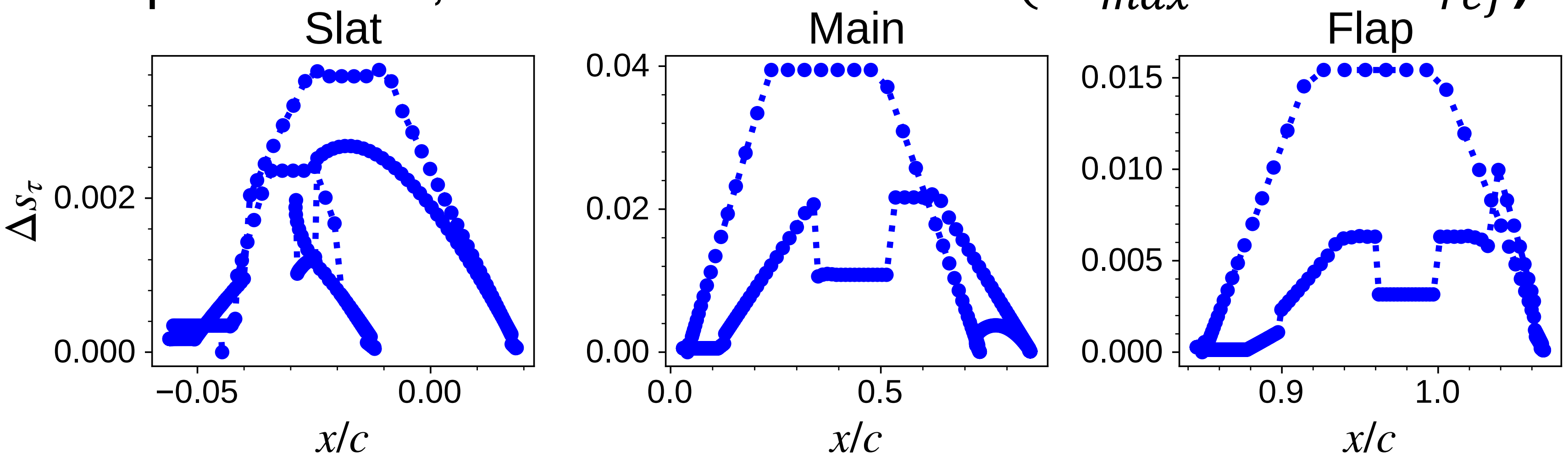


Chordwise Spacing

Best-Practice Mesh ($\Delta s_{max} = 0.03c_{ref}$)

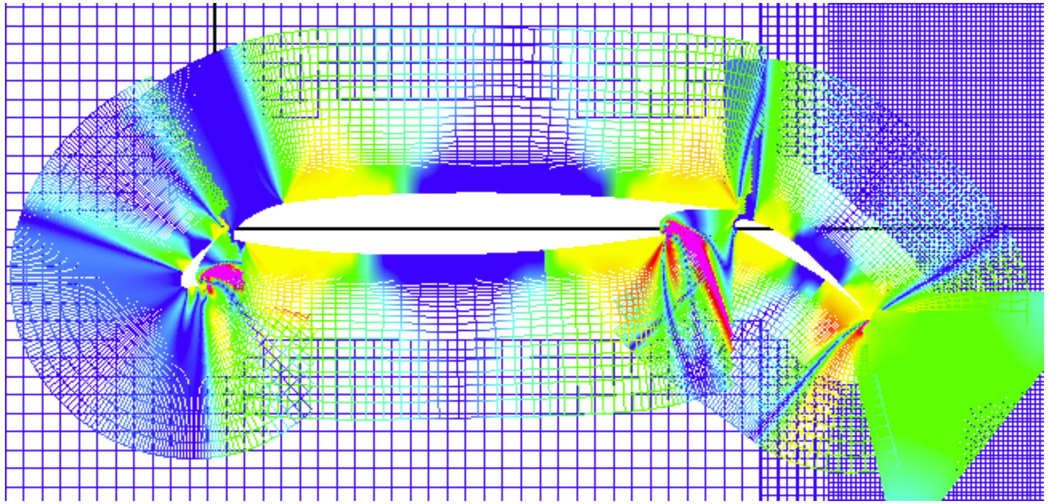


Adaptive Mesh, 2 Refinement Levels ($\Delta s_{max} = 0.045c_{ref}$)

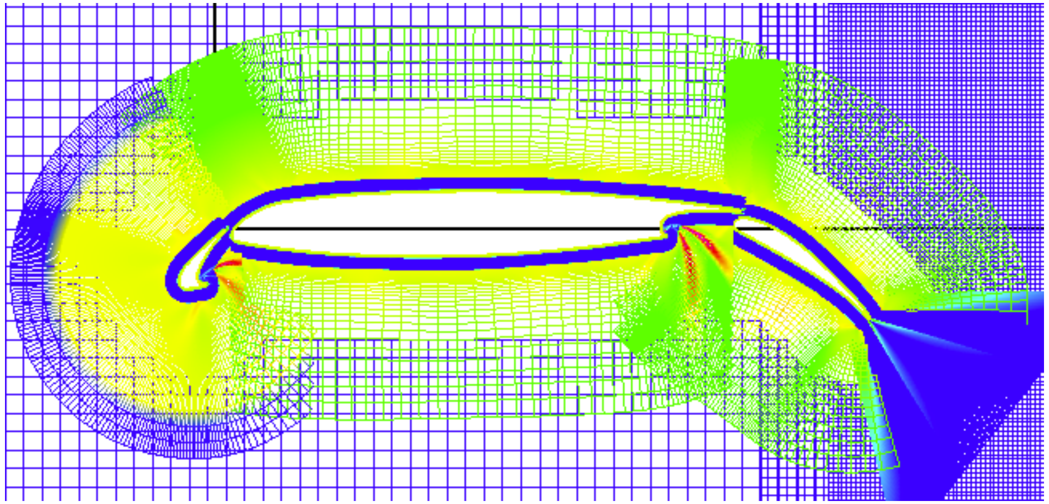


Stretching Ratio

- Specified max $SR = 1.15$



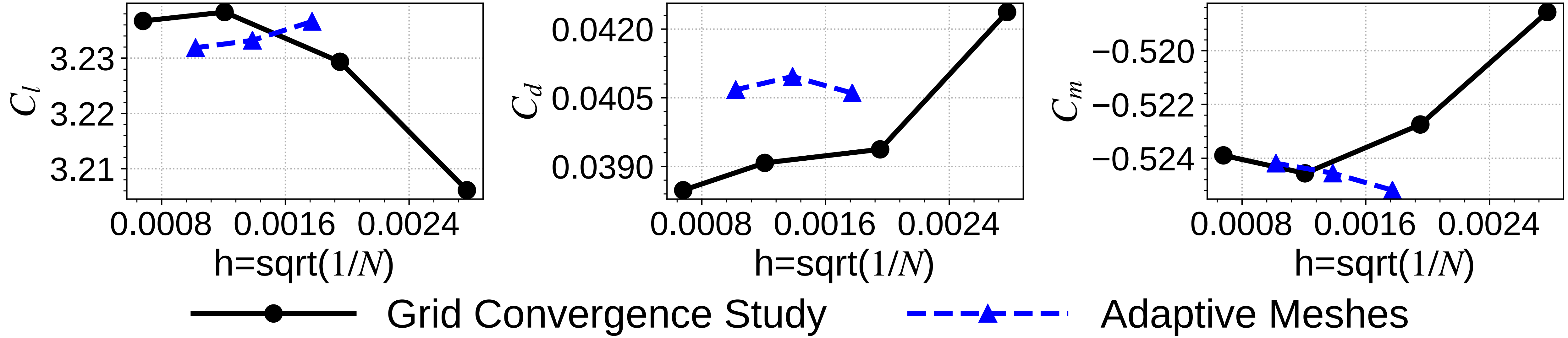
Tangential



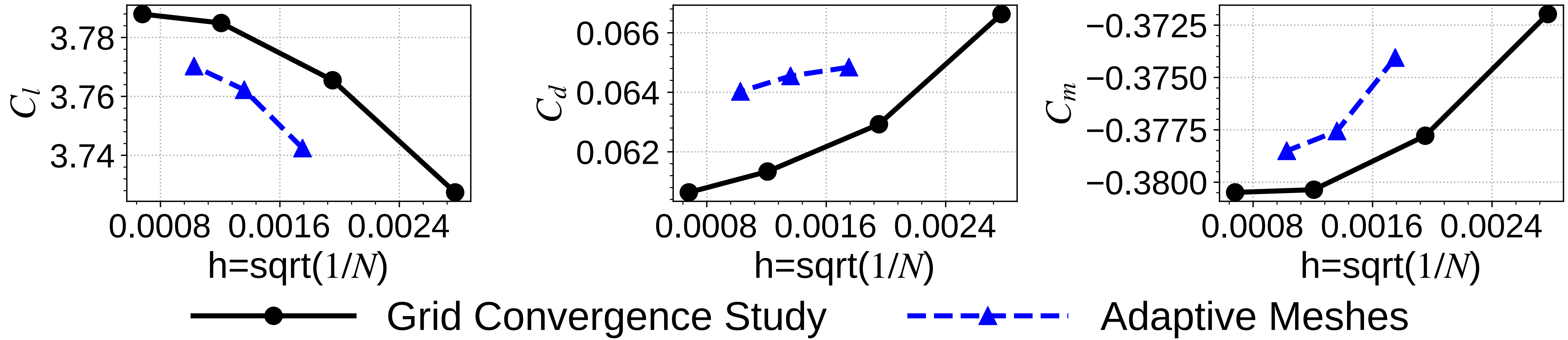
Normal

Convergence of Aerodynamic Coefficients

$\alpha = 8°$

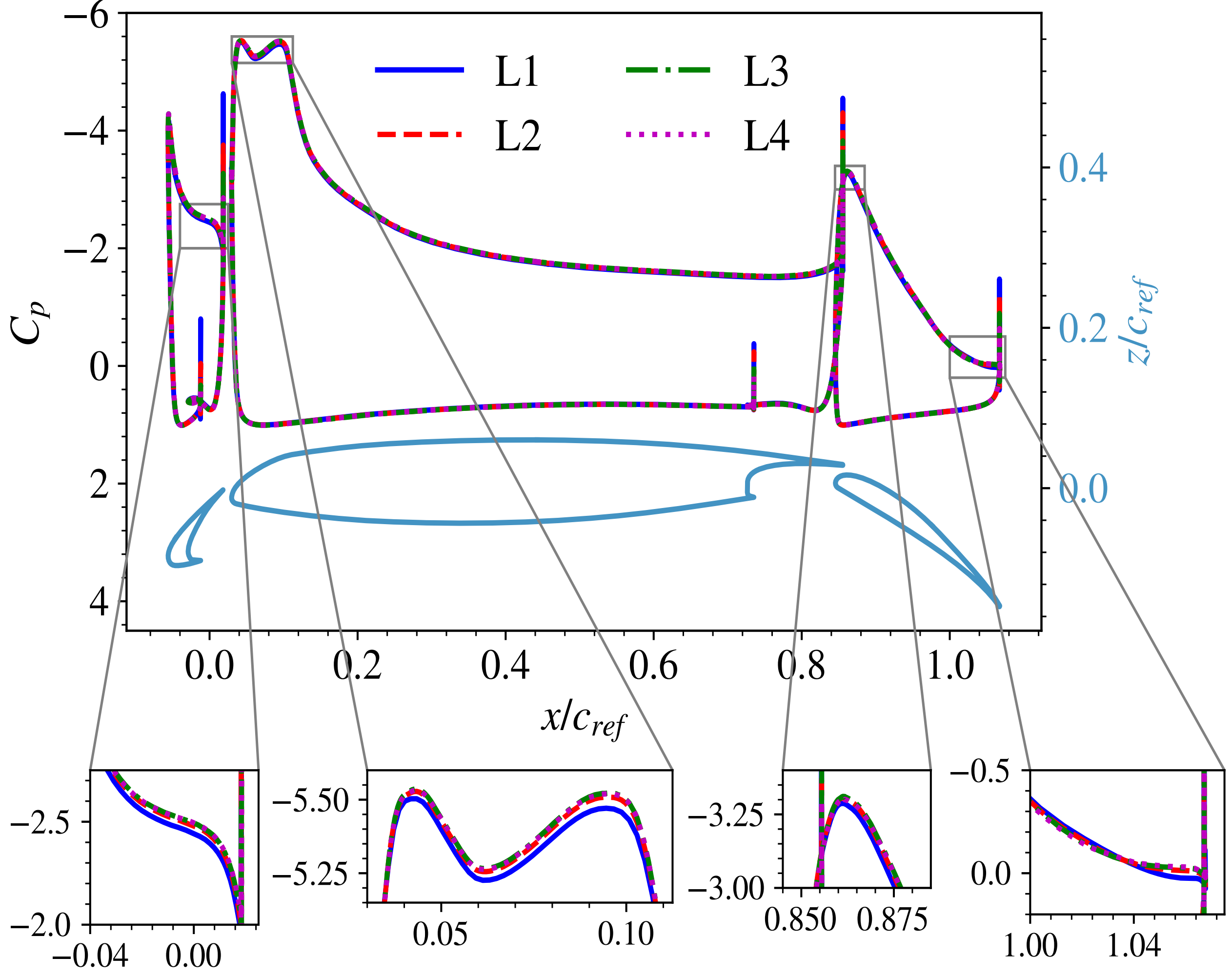


$\alpha = 16°$

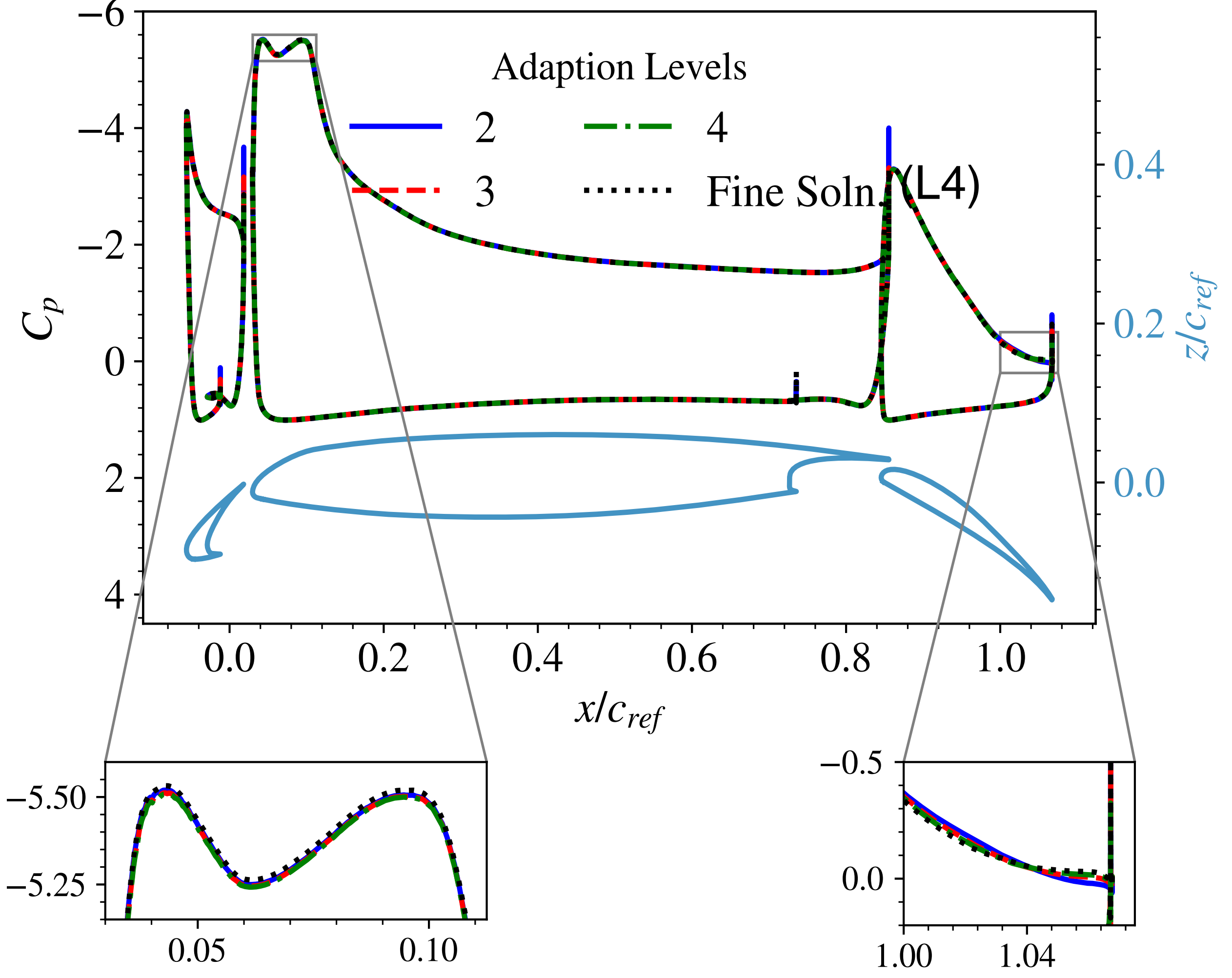


Surface Pressure Coefficient ($\alpha = 8°$)

Grid Convergence Study

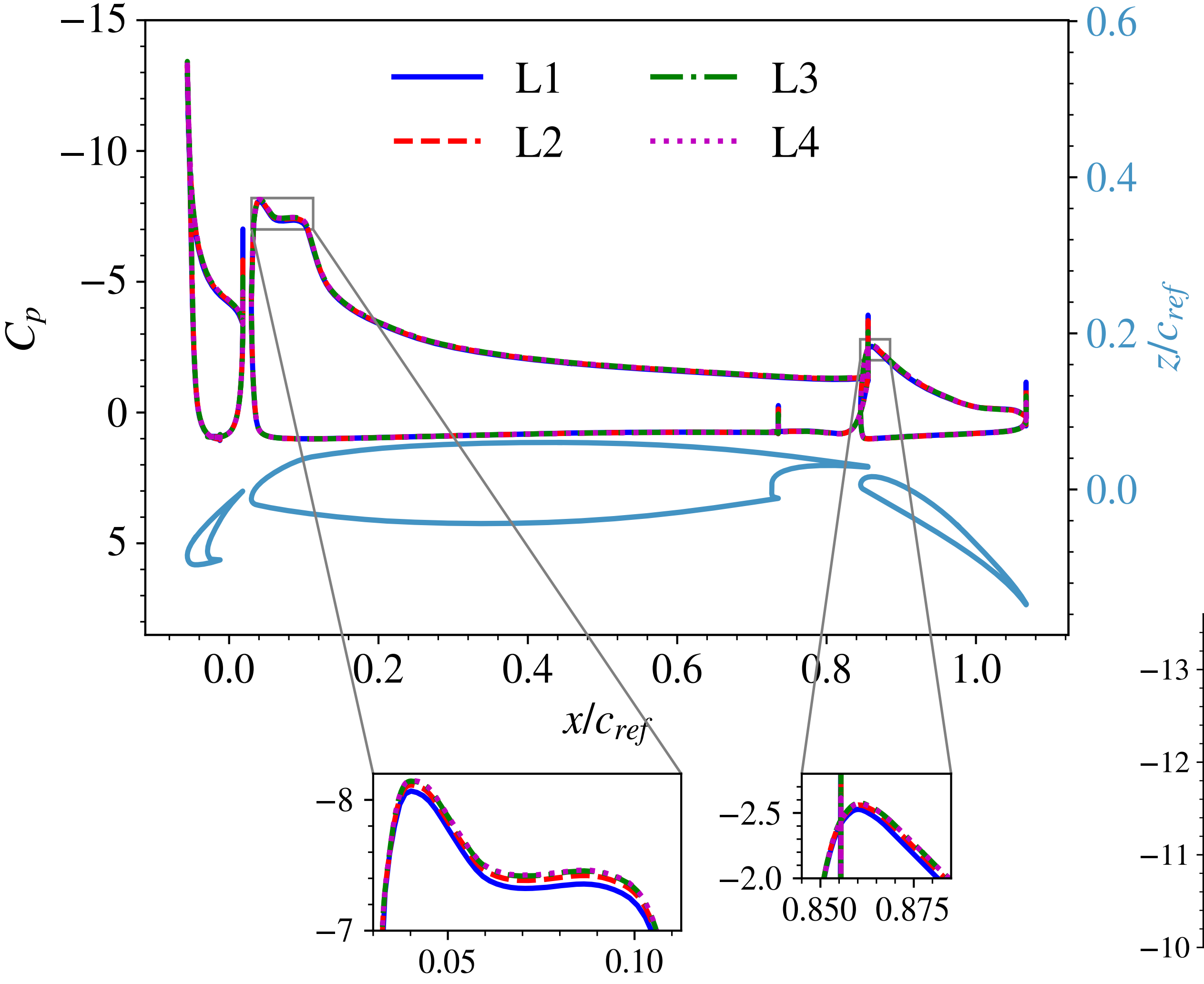


Adaptive Mesh

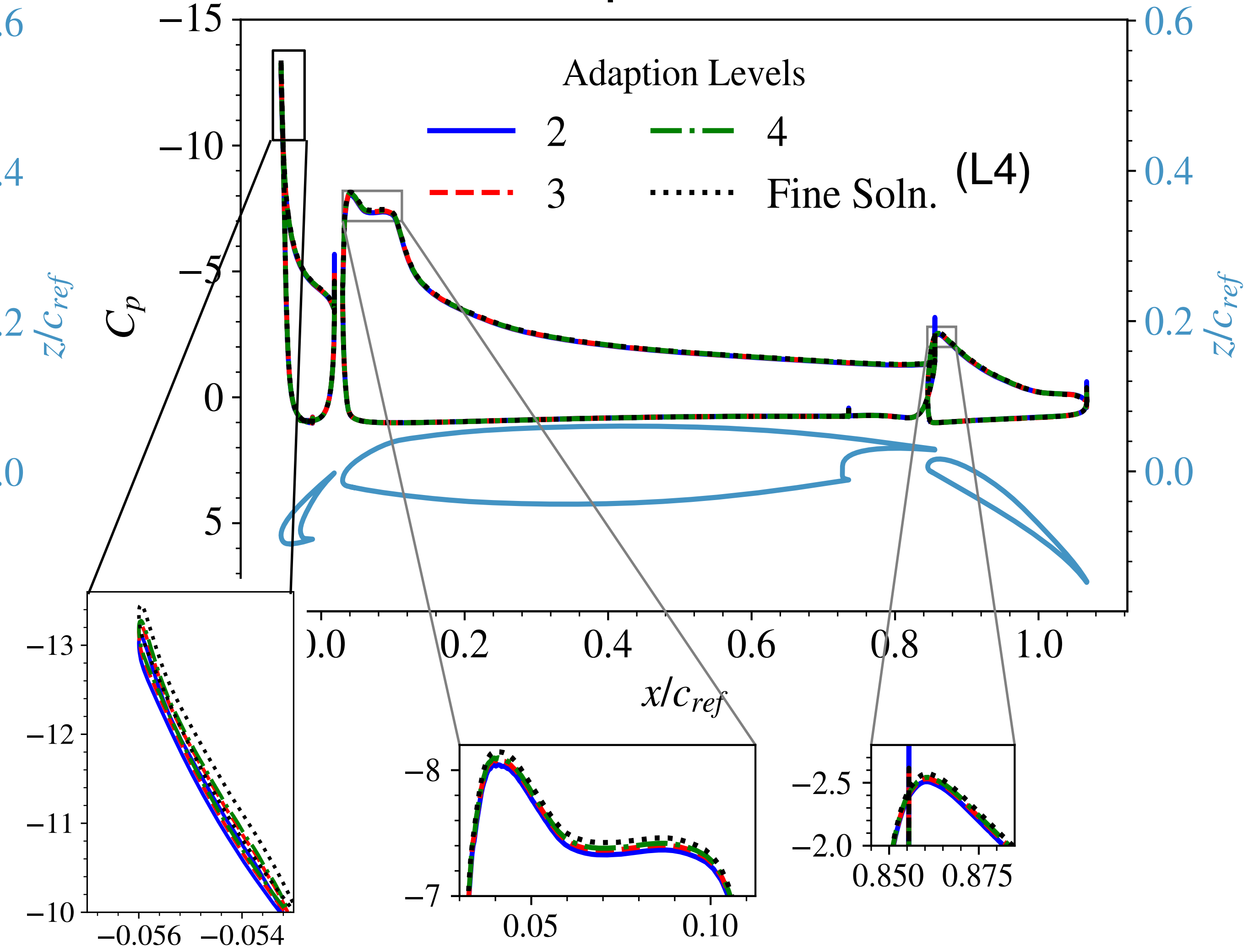


Surface Pressure Coefficient ($\alpha = 16°$)

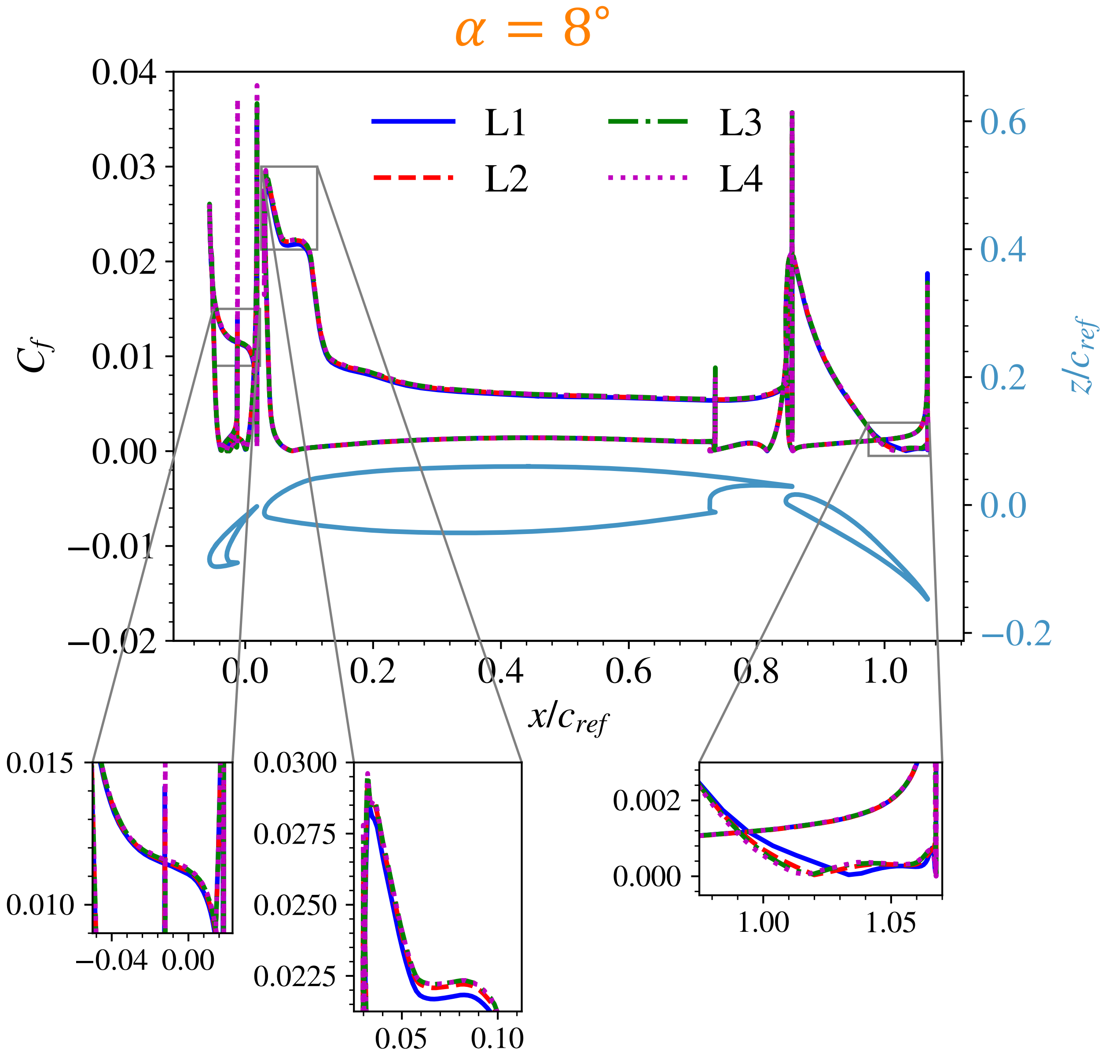
Grid Convergence Study

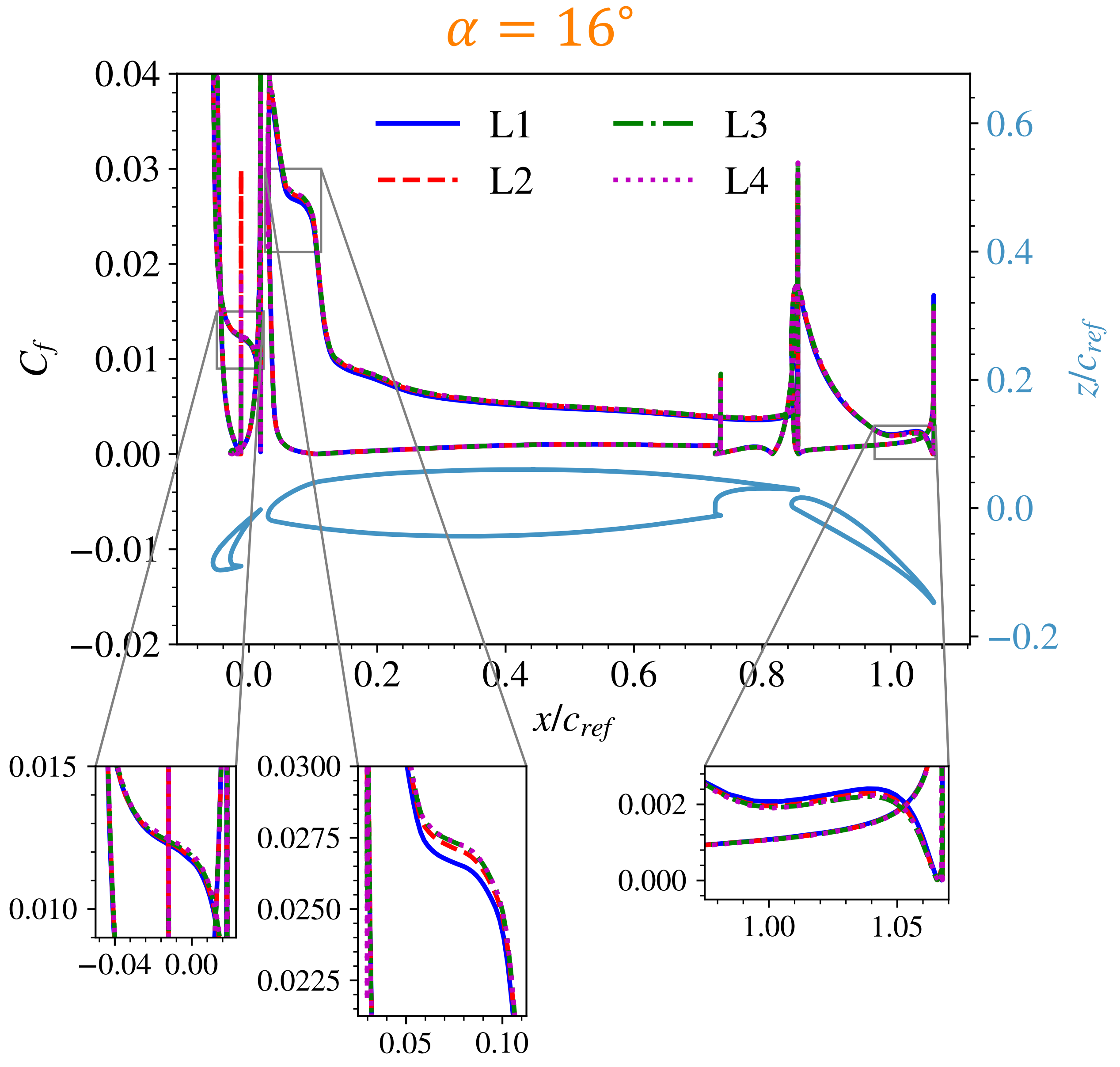


Adaptive Mesh

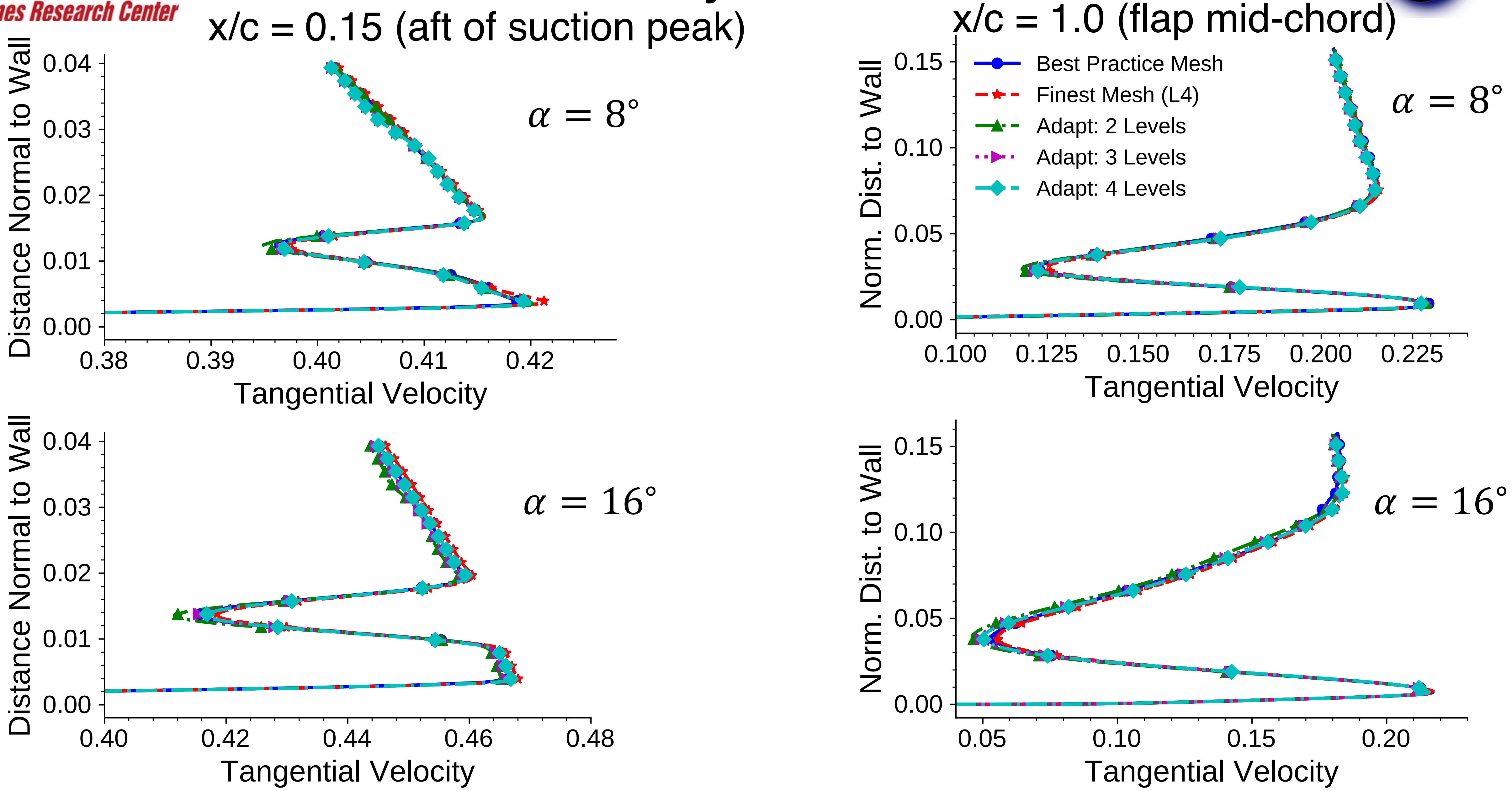


Surface Skin Friction Coefficient

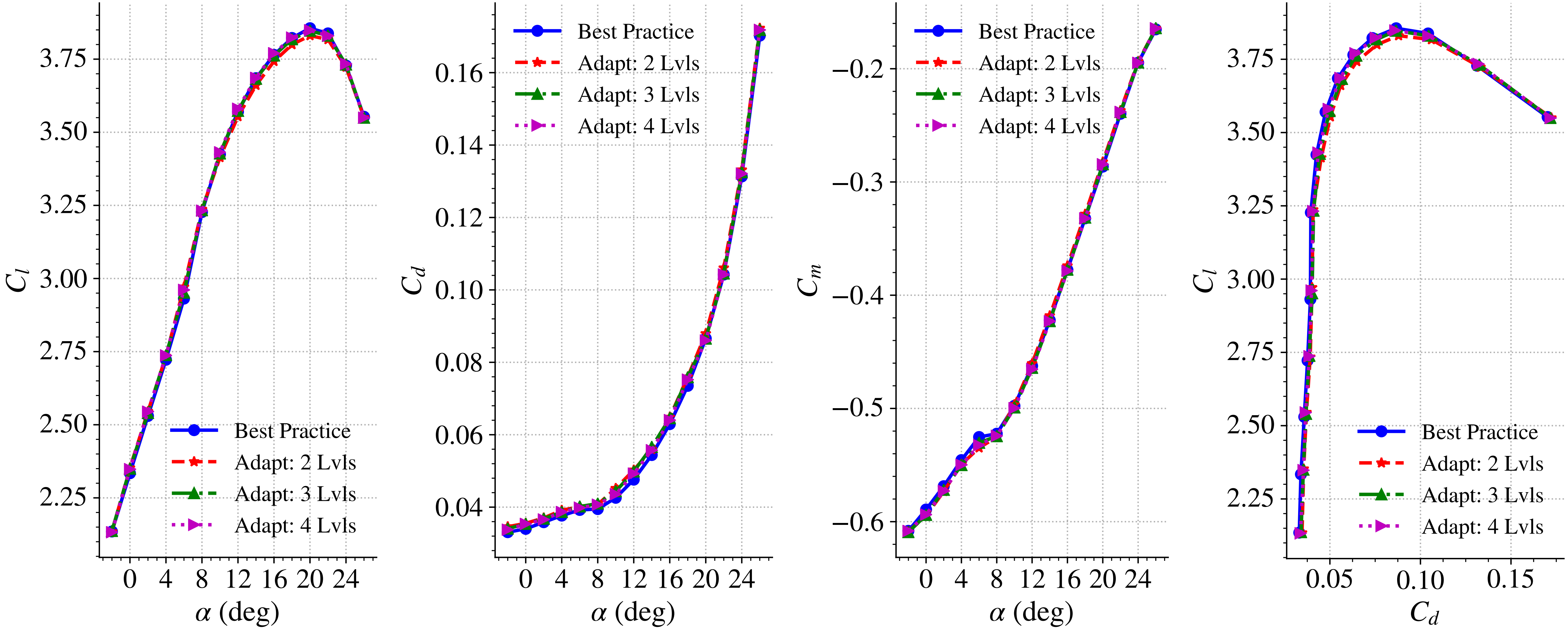




Velocity Profiles

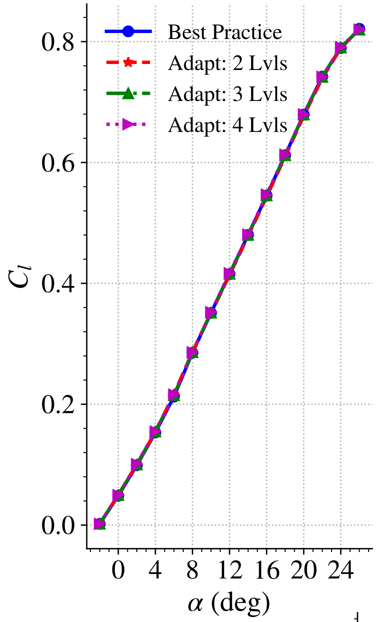


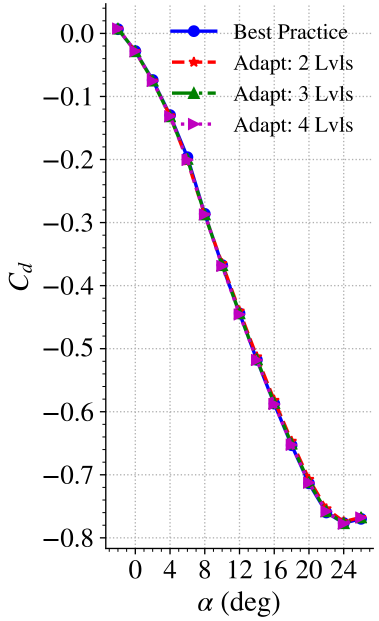
Alpha Sweep — Total

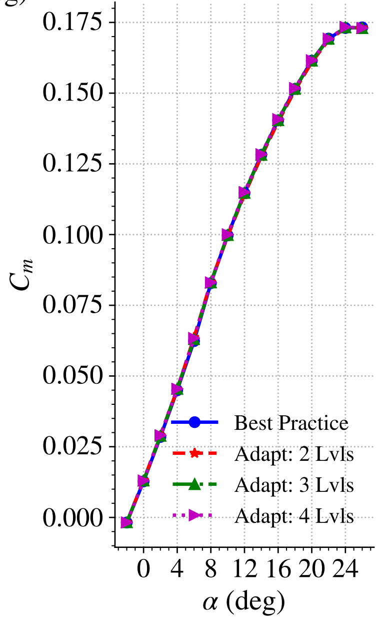


Alpha Sweep

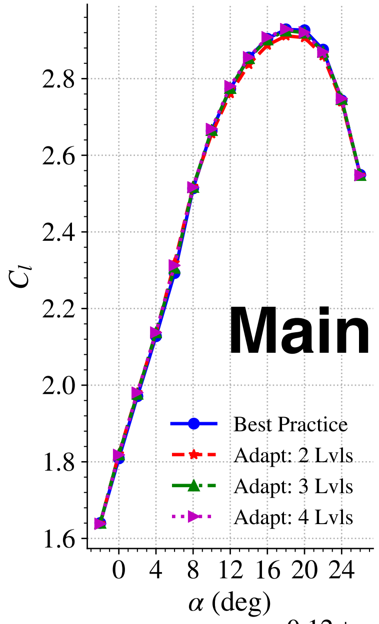
Slat

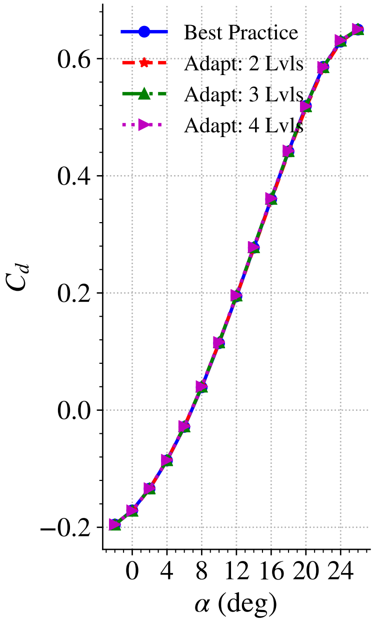


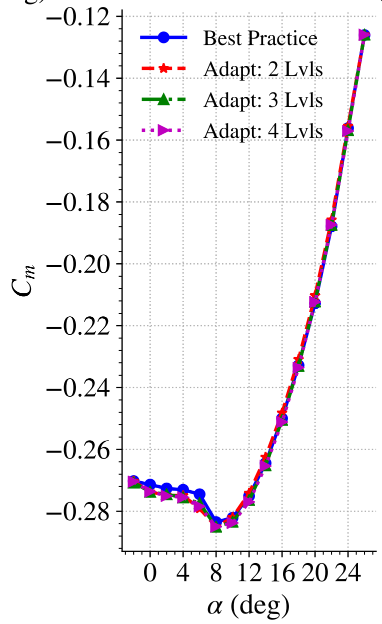




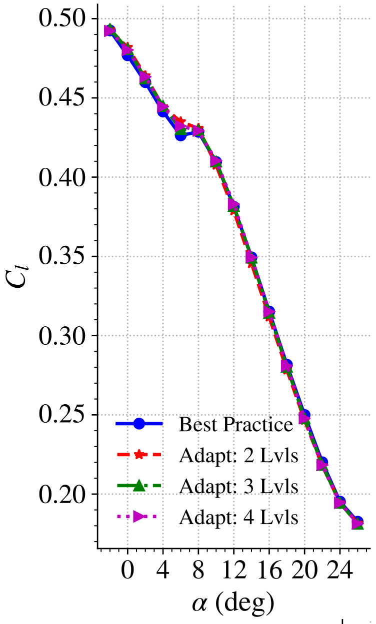
Main

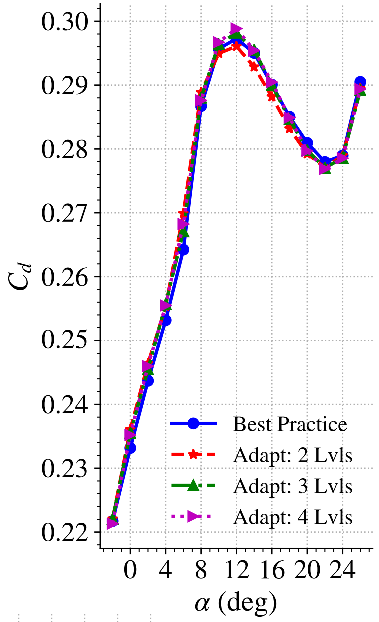


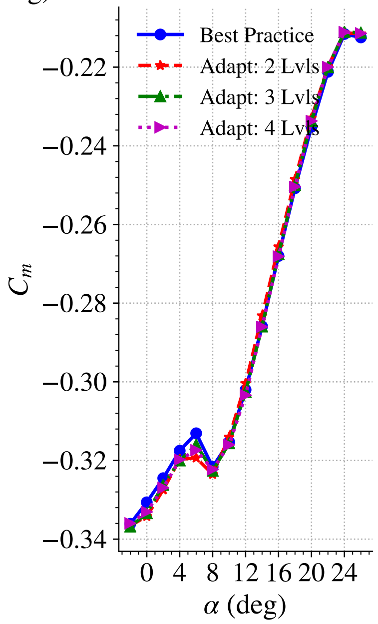




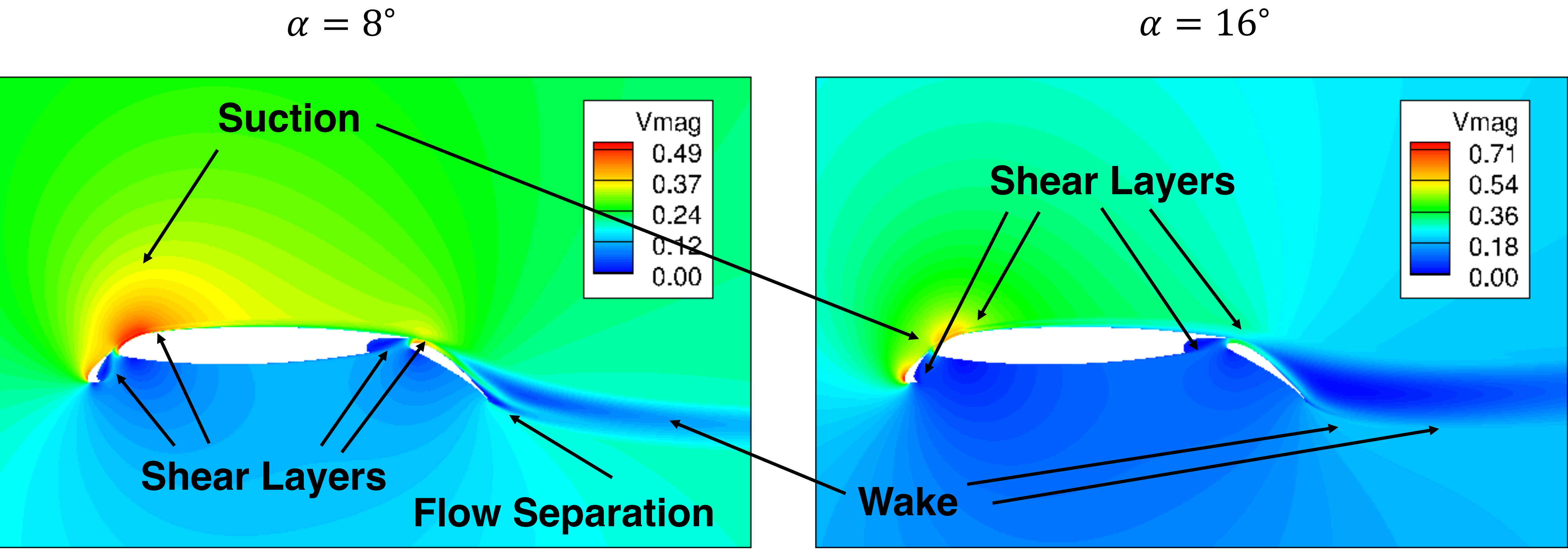
Flap



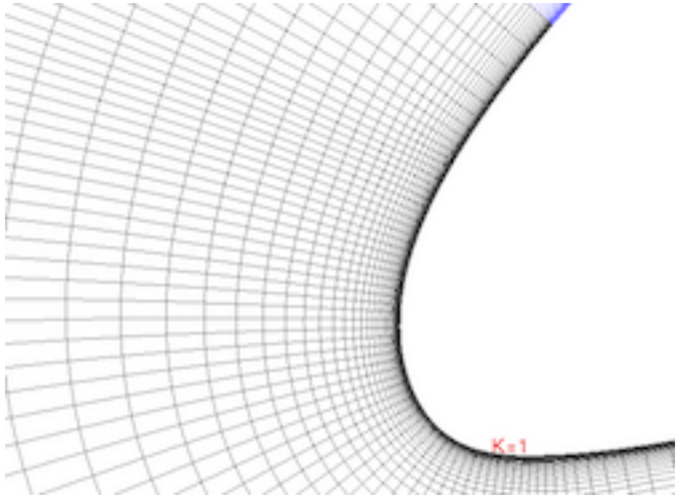




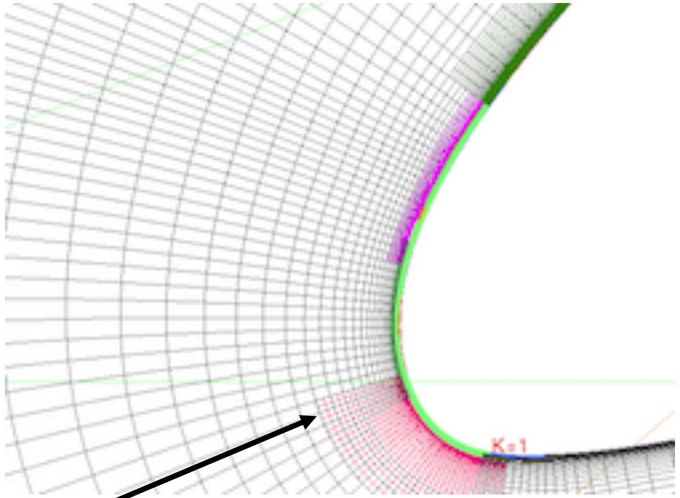
Flow Characteristics



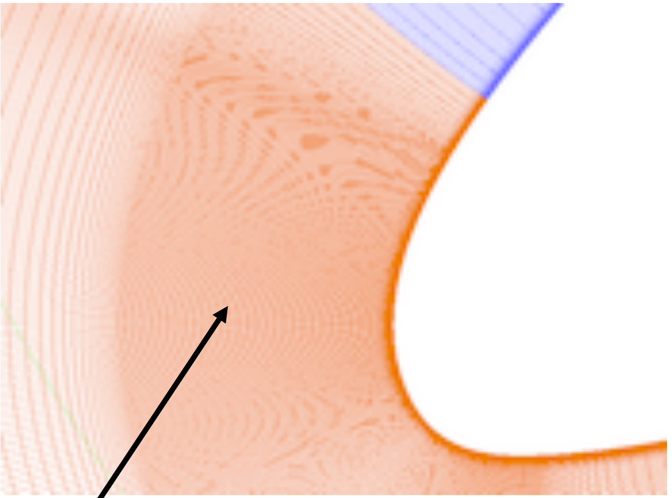
Possible Source of Discrepancies in Adaptive Meshes



Starting Adaptive Mesh



Adaptive Mesh with 4 Levels of Refinement



Level 3 Grid Convergence Mesh

Only BL clustering refined

Spacing is finer in both directions

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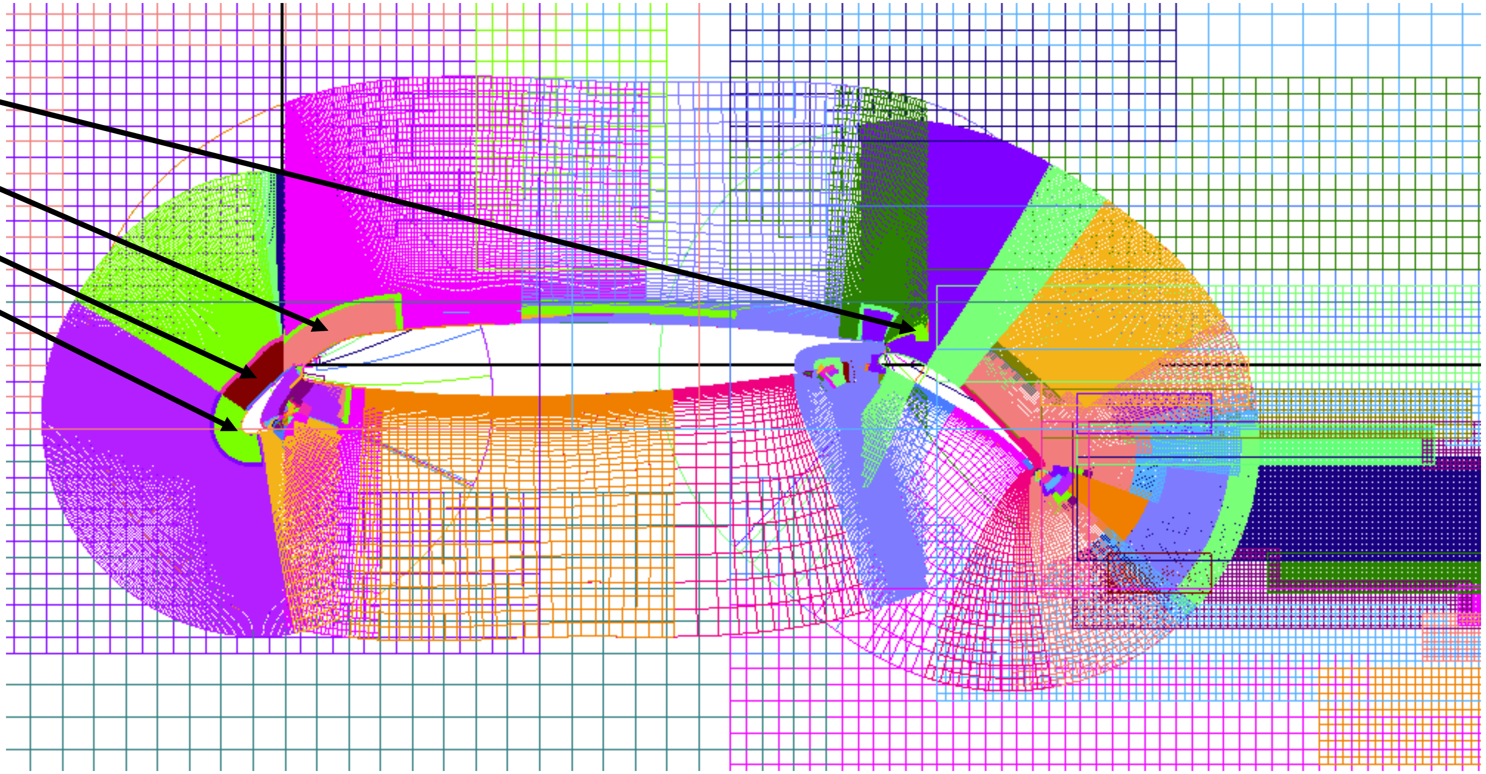
Effect of LE Refinement on Adaptive Meshes

- Two factors to consider
  - Fixed-grid convergence results
  - Other adaption results presented at conference
- Investigated effect of using finer LE tangential spacing ($\Delta\theta_{LE}$) in initial mesh on final solution
  - $\Delta\theta_{LE} = 2.0°, 1.0°, 0.5°, 0.25°$
  - Adaption levels: 2-5
- Also investigated effect of prescribed refinement in LE regions in both tangential and normal directions coupled with adaption
  - $\Delta\theta_{LE} = 2.0°, 1.0°, 0.5°$
  - Adaption levels: 2-4

Adapted Mesh with Prescribed LE Refinement

Prescribed refinement regions



$(\Delta\theta_{LE} = 2.0°, \alpha = 8°, 4\ levels)$

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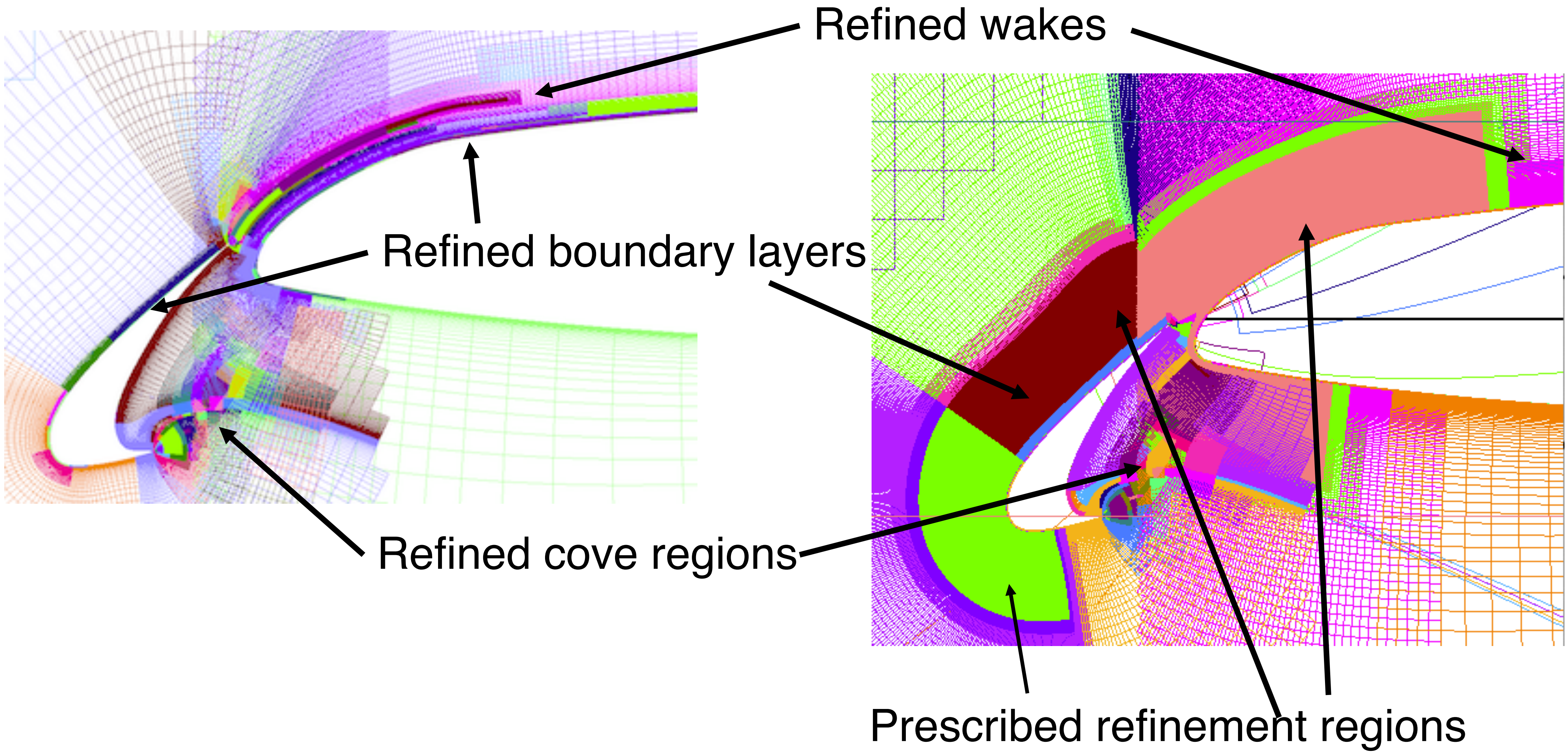
Comparisons of Adaptive Meshes



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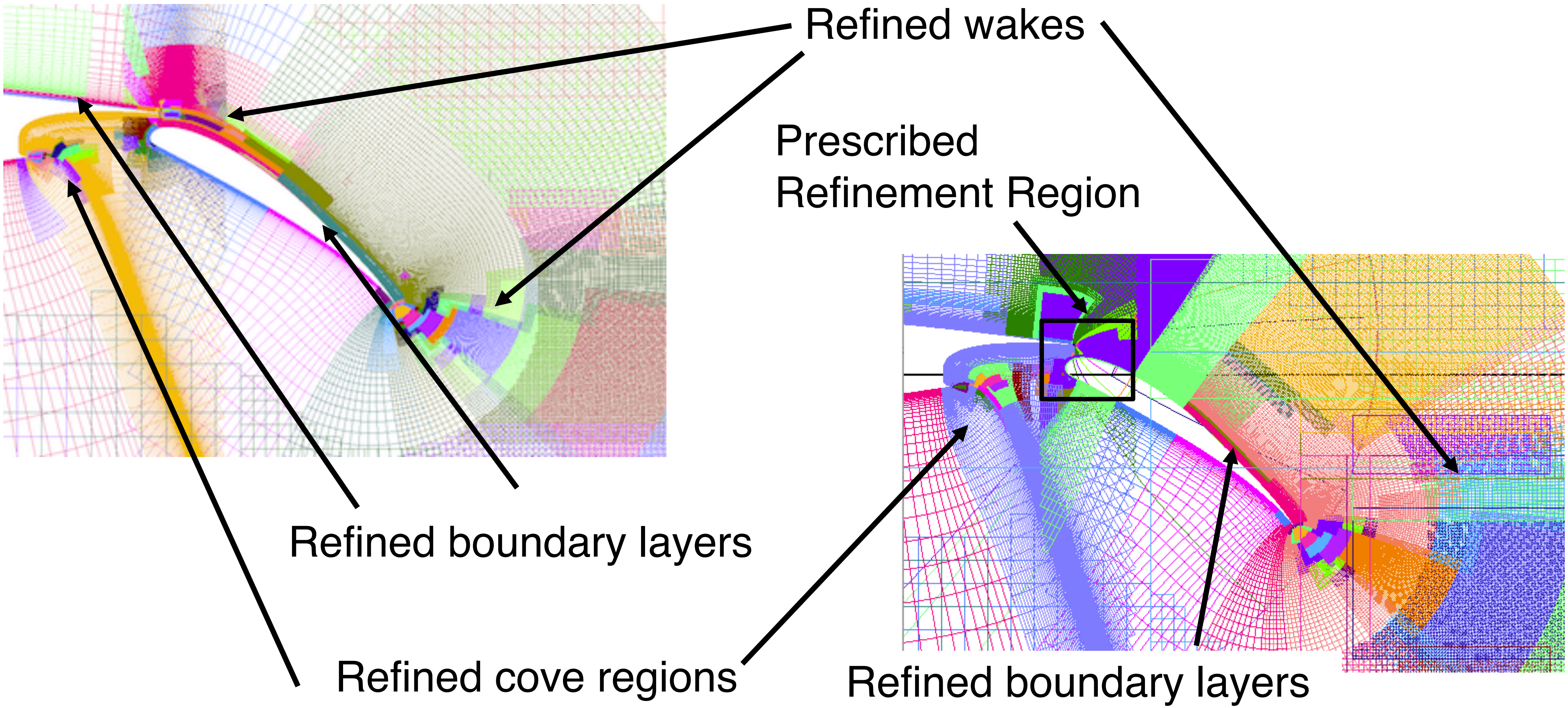
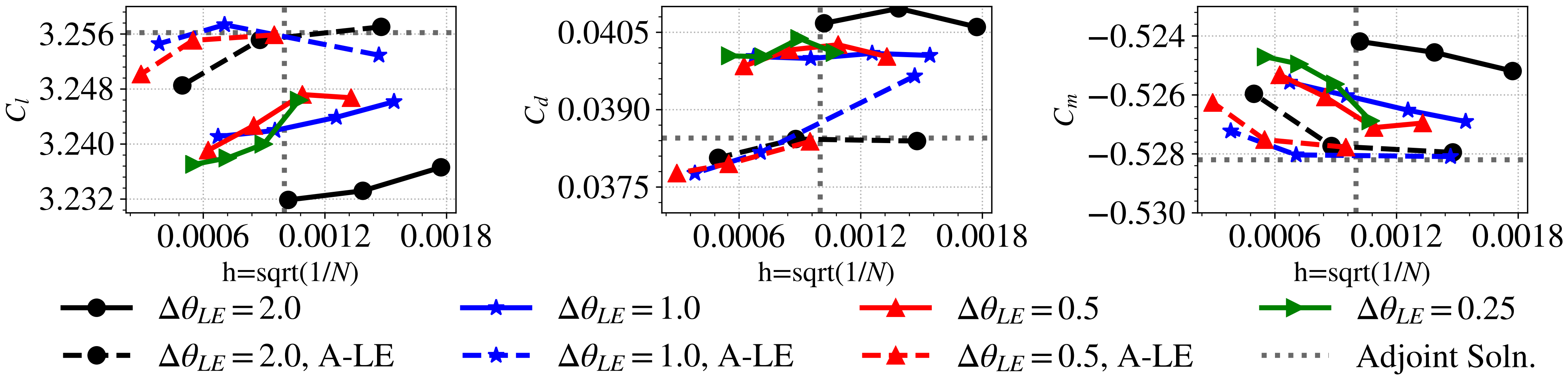
Meshes Generated From Adaption

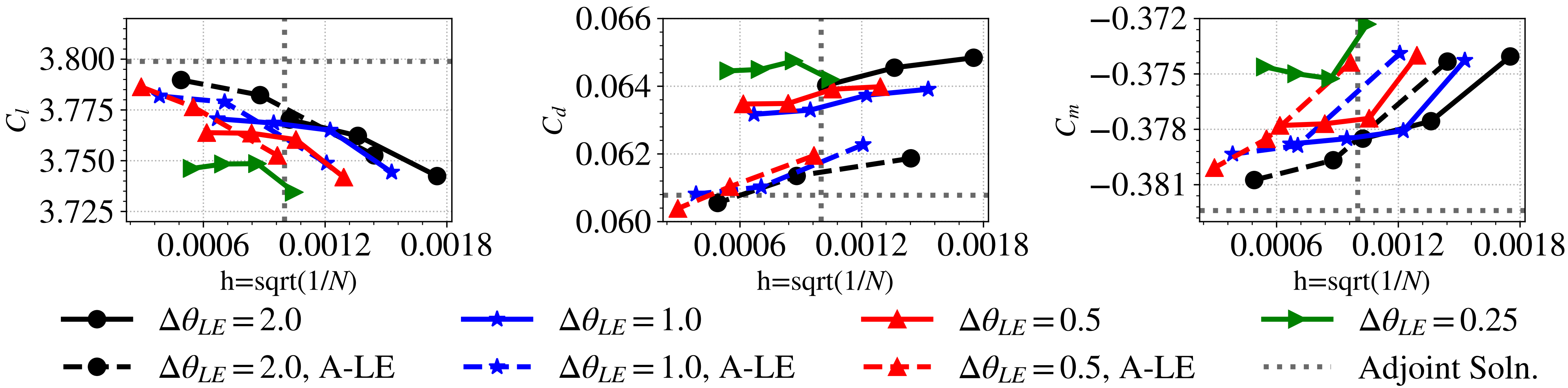


Force Comparisons

α = 8°



α = 16°



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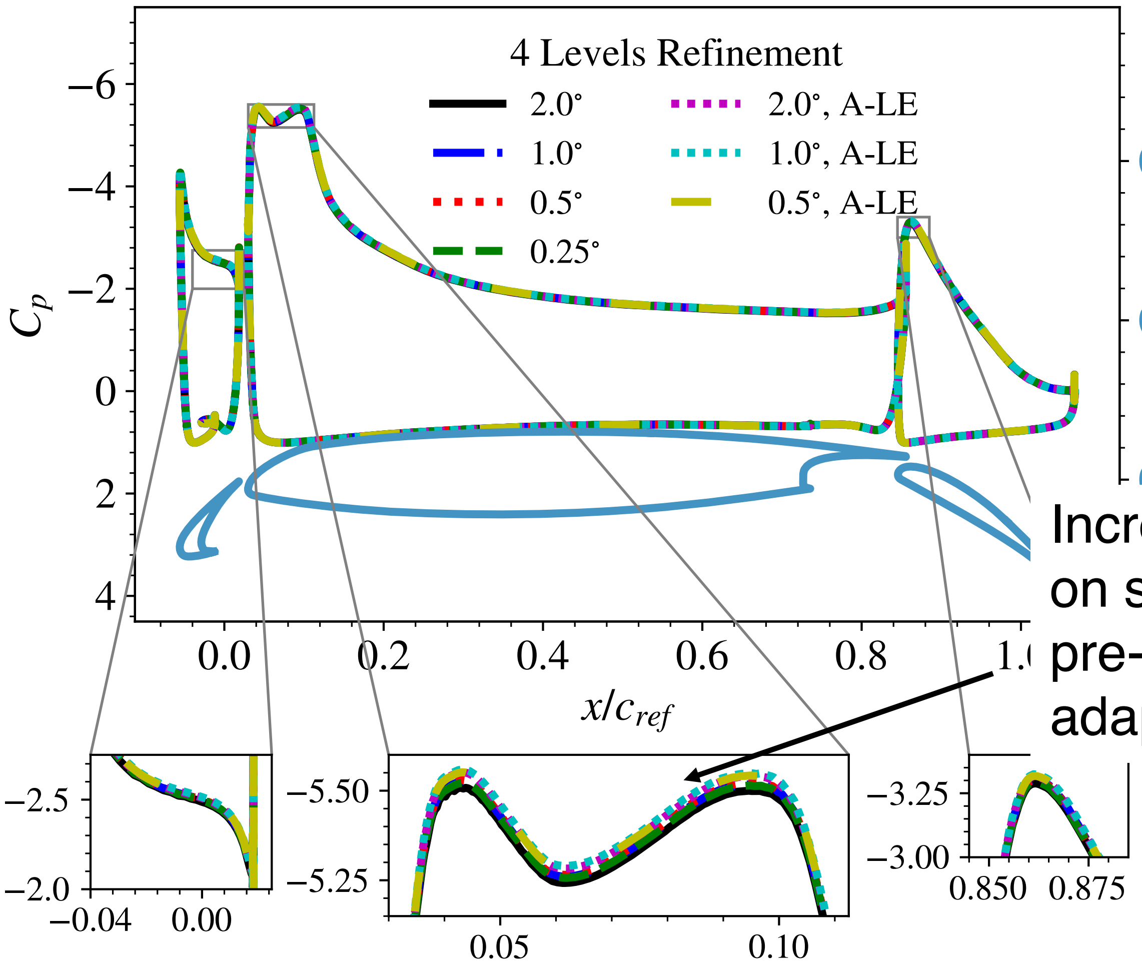
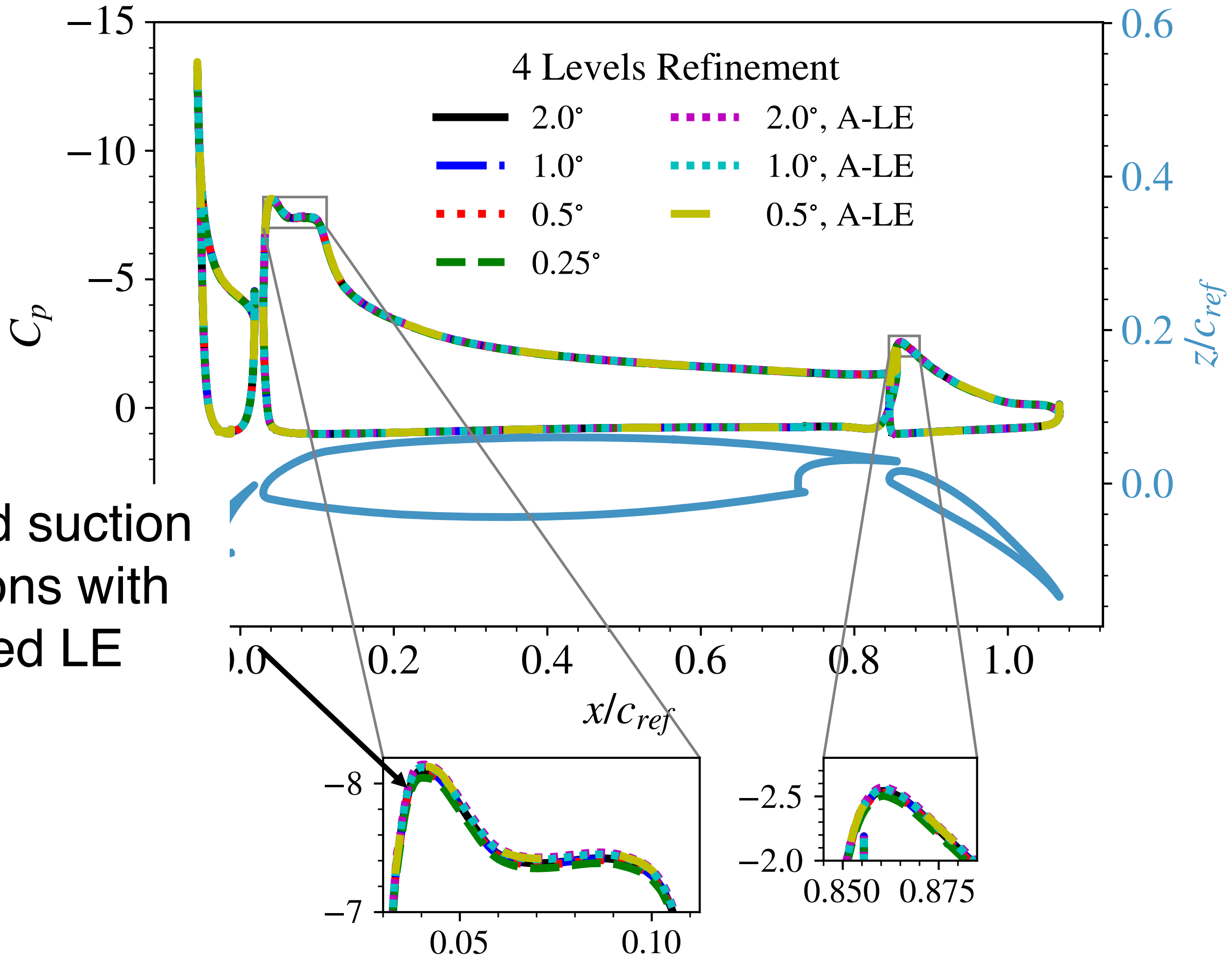
Section Pressure Coefficients

$\alpha = 8°$



$\alpha = 16°$



Increased suction on solutions with pre-scribed LE adaption

Summary and Conclusions

- Lessons learned:
  - Key features to resolve: Shear layers, wakes, suction regions
  - Solutions are sensitive to wake resolution downstream of configuration
  - C mesh and O mesh can produce similar results with proper TE and wake treatment
  - Solutions are sensitive to normal spacing in near body grids, and trailing-edge resolution
    - Difficult to determine best-practice mesh without sufficient reference data
  - Mesh convergence study show solutions converge asymptotically
  - Prescribing leading-edge refinement can assist with accuracy of adaptive solutions in OVERFLOW

Summary and Conclusions

- Recommended Best Practices
  - Use fine normal spacing to resolve wakes/shear layers from upstream elements
  - Wake should be refined up to a certain distance downstream of configuration
  - May be beneficial to explicitly refine LE in adaption solutions
  - Add wake grids if using O grid for near body meshes
- Future Investigations
  - Discrepancies in current best-practice mesh and adjoint-based result presented at conference
  - Determine what is a sufficiently defined wake

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