Results from HPCMP CREATE^{TM}-AV Kestrel Component COFFE for the 6th Drag Prediction Workshop Cases

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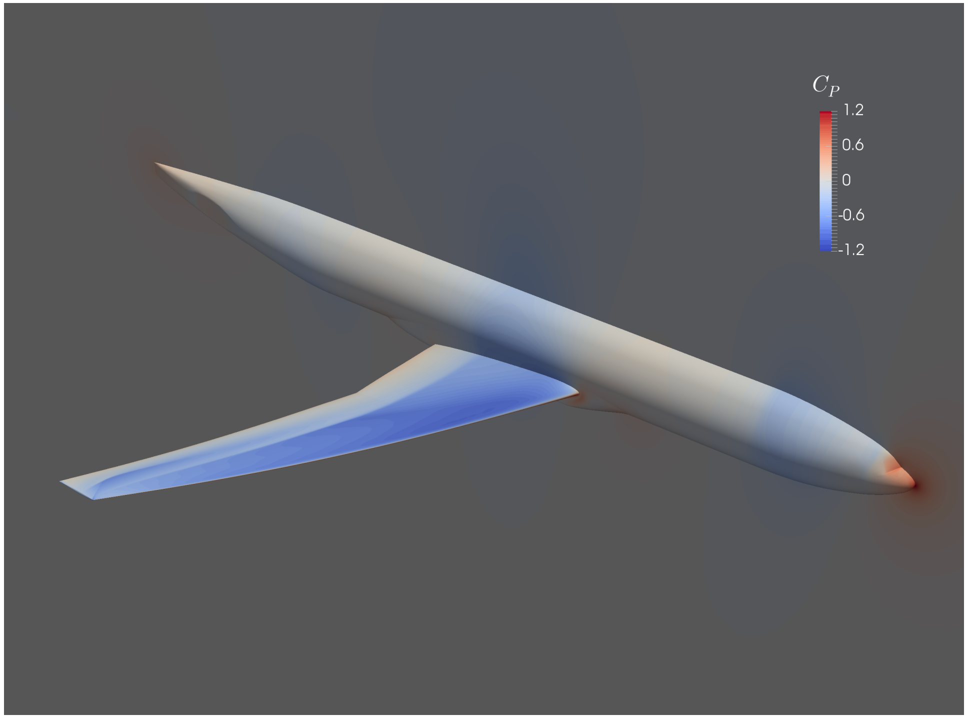
DOD HPC MODERNIZATION PROGRAM

5th Higher Order Workshop January 2018

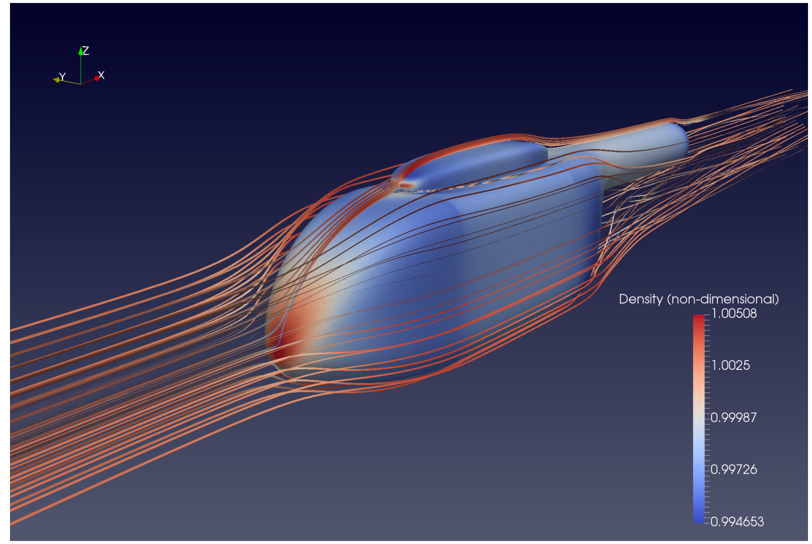
Outline – COFFE DPW6

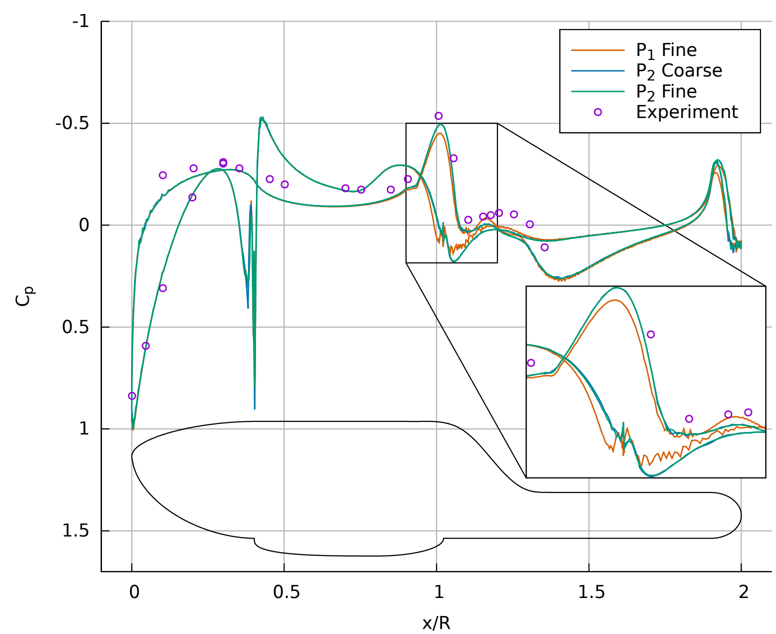
- **Kestrel Component COFFE Availability**
- **CFD Verification and Validation Effort**
- **COFFE Solver Discretization Update**
- **DPW6 Results**
  - NACA0012
  - 3D Mesh Convergence -- Drag
    - Wing Body (WB)
    - Wing Body Nacelle Pylon (WBNP)
  - Alpha Sweep for Wing Body
- **Conclusions**
- **Acknowledgments**



CFD Verification & Validation Effort

- **Extensive V&V Effort**
- **Verification**
  - MMS
  - Joukowski airfoil
- **Validation**
  - **DPW6**
  - HLPW3
  - Robin Fuselage (shown here)
  - Laminar Sphere
  - 2D Supersonic Base-flow
  - NASA TMR Cases
    - NACA0012
    - ONERA-M6
    - 3D Bump
    - Hemisphere Cylinder





Solver Discretization Update

- **The SU/PG discretization utilized in COFFE is outlined here:**
  - Ryan S. Glasby, J. Taylor Erwin, Douglas L. Stefanski, Steven R. Allmaras, Marshall C. Galbraith, W. Kyle Anderson, and Robert H. Nichols. "Introduction to COFFE: The Next-Generation HPCMP CREATE™-AV CFD Solver", 54th AIAA Aerospace Sciences Meeting, AIAA SciTech, (AIAA 2016-0567).
- **For these calculations, the SU/PG stabilization term, and the shock indicator are defined as:**

$$\sum_i \iiint \left[\nabla\phi_i \bullet \frac{\partial F_c(u_h)}{\partial u_h} \right] [\tau] \left[PDE_{StrongForm} \right]$$

$$[\tau]^{-1} = \sum_i \left(\left| \nabla\phi_i \bullet \frac{\partial F_c(u_h)}{\partial u_h} \right| + \nabla\phi_i \bullet \frac{\partial F_v(u_h, \nabla u_h)}{\partial(\nabla u_h)} \bullet \nabla\phi_i \right)$$

$$\varepsilon_{shock} = \frac{(u \bullet \nabla p) h}{(u \bullet \nabla p) h + \kappa_{shock} c p}, \ if \ u \bullet \nabla p > 0, \ \varepsilon_{shock} = 0, \ if \ u \bullet \nabla p <= 0$$

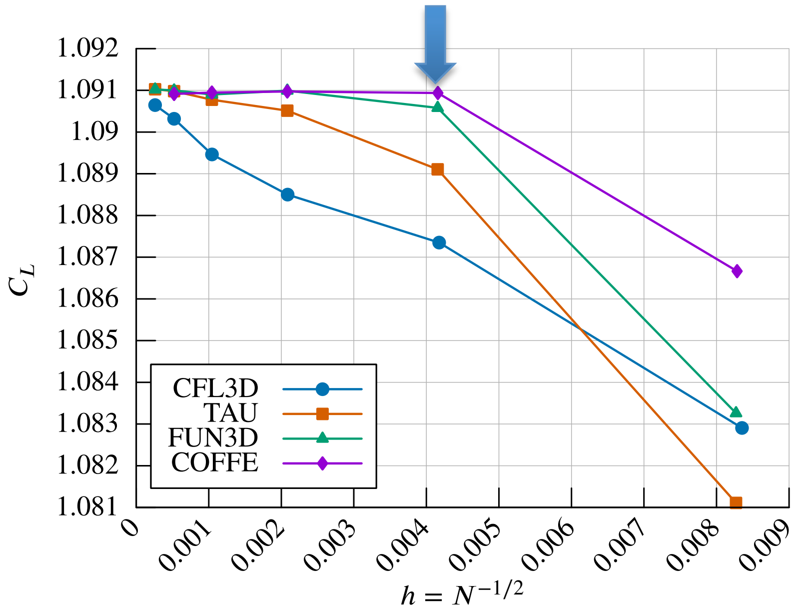
DPW6 Task 1 – NACA0012

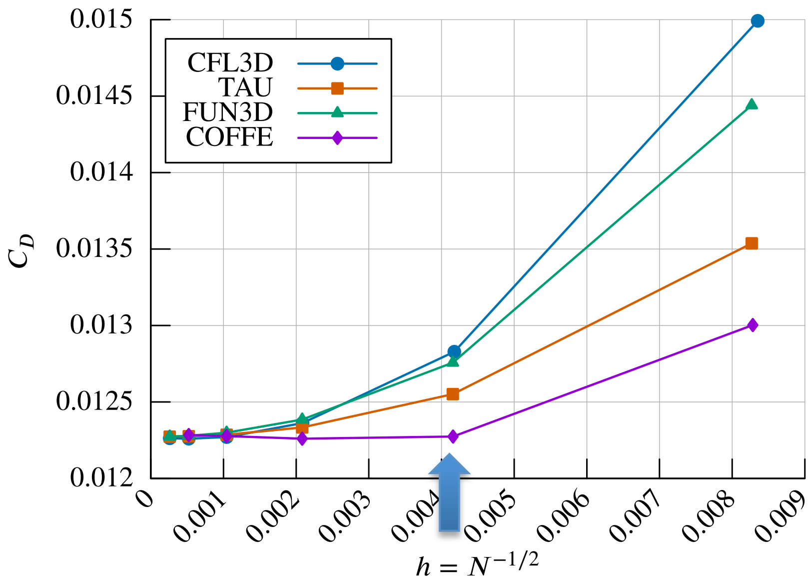
- **2D NACA0012 Airfoil from the Turbulence Modeling Resource (TMR)**
  http://turbmodels.larc.nasa.gov/
- **Flow conditions: Mach = 0.15, Re_C = 6 million, angle-of-attack = 10 degrees**
- **Far-field boundary condition at 500 chords**
- **Grids: http://turbmodels.larc.nasa.gov/naca0012numerics_grids.html**
- **Expected C_L = 1.0909 - 1.0911, C_D = 0.012270 - 0.012275**
- **COFFE Forces calculated:**

6. Family II 225 x 65	**C_L = 1.0866643, C_D = 0.01300284**
5. Family II 449 x 129	**C_L = 1.0909380, C_D = 0.01227414**
4. Family II 897 x 257	**C_L = 1.0909723, C_D = 0.01225952**
3. Family II 1793 x 513	**C_L = 1.0909464, C_D = 0.01227657**
2. Family II 3585 x 1025	**C_L = 1.0909141, C_D = 0.01228354**

- **Density residual converged to 10^-15, SA-neg turbulence model**

NACA0012 – C_L, C_D

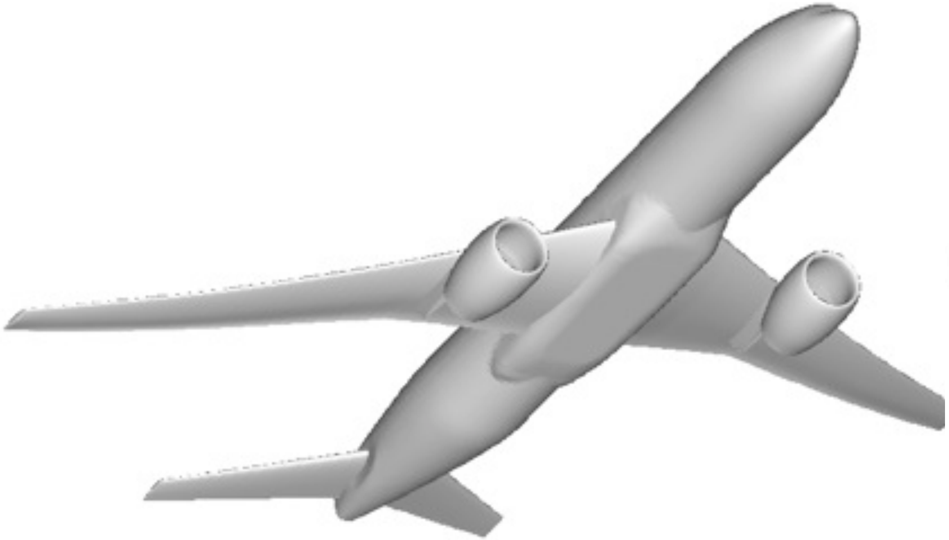


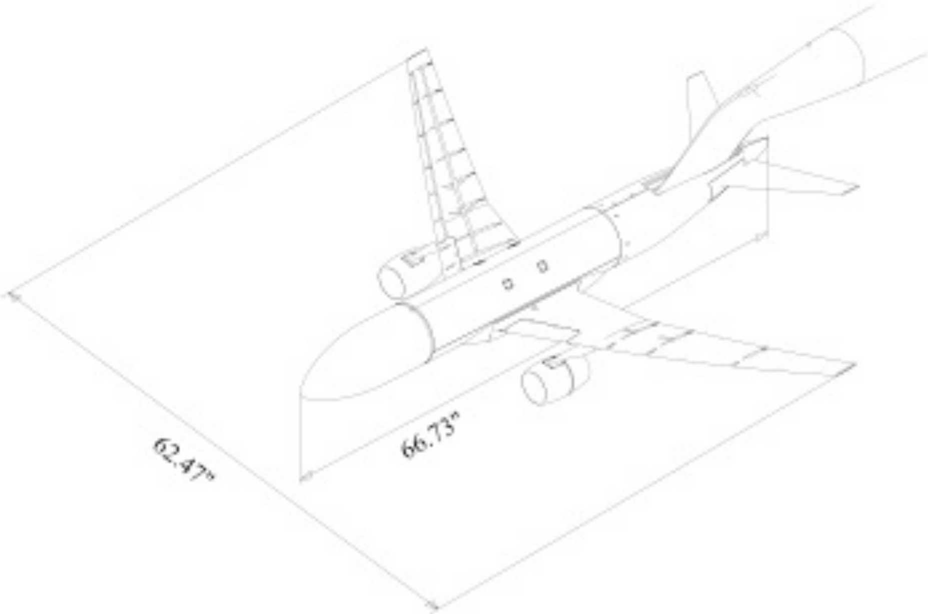


	Nodes required to reach target range
Grid 5, 57,824 nodes:	
COFFE C_L = 1.0909380, C_D = 0.01227414	57,824
CFL3D C_L = 1.0873493, C_D = 0.01282844	14,680,064
FUN3D C_L = 1.0905788, C_D = 0.01275673	3,674,625
Tau C_L = 1.0891050, C_D = 0.01255115	3,674,625

DPW6 Task 2 – CRM Description

- **NASA Common Research Model**
- **Vassberg et. al., AIAA 2008-6916**
- **Reference:**
  - Area, S = 594,720.0 in^2
  - Chord, c = 275.8 in
  - Span, b = 2,313.50 in





Task 2 – CRM Mesh Convergence

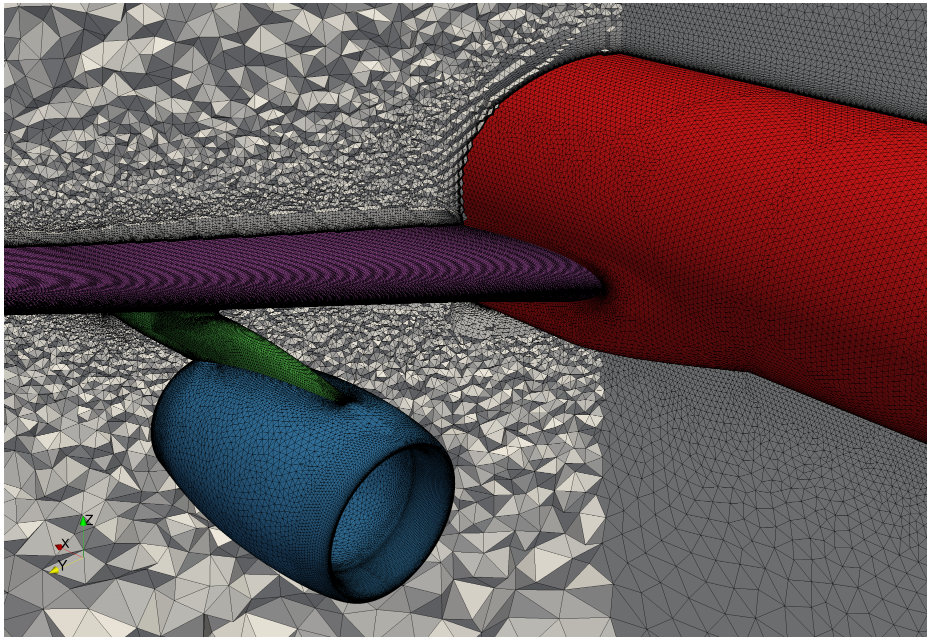
- **Conditions: Mach = 0.85, Re_{MAC} = 5 million, target C_L = 0.5**
- **Meshes made of only tetrahedral elements with a maximum angle < 176 degrees**
- **P1 WB meshes, alpha 2.75 geometry**

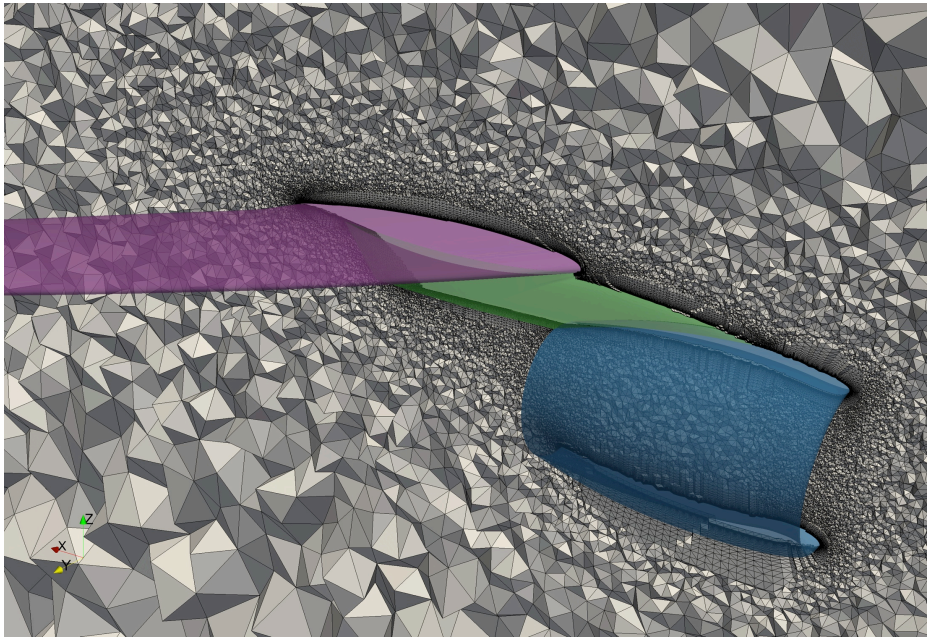
level	initial wall spacing	growth factor	cells	nodes
Coarse	1.285×10^{-3}	1.2	26,780,170	4,533,286
Medium	1.118×10^{-3}	1.2	36,108,376	6,095,629
Fine	9.72×10^{-4}	1.2	47,905,028	8,080,127
Extra Fine	8.45×10^{-4}	1.2	61,454,600	10,362,607

- **P1 WBNP meshes, alpha 2.75 geometry**

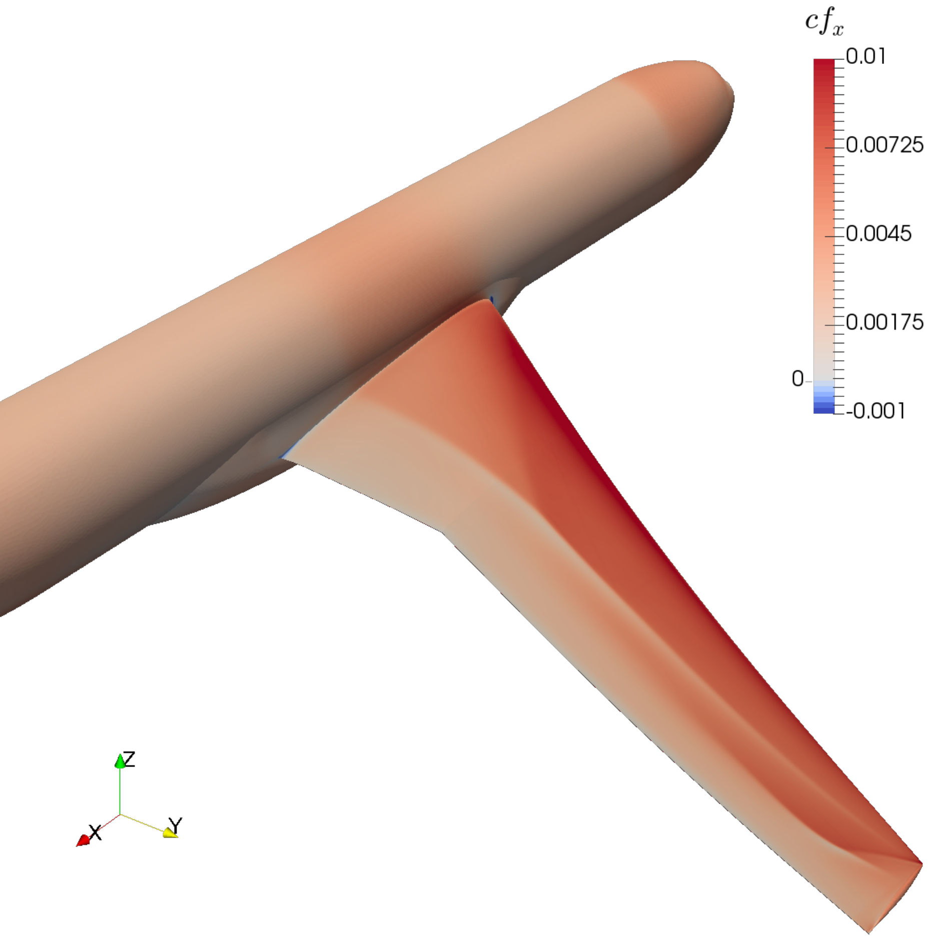
level	initial wall spacing	growth factor	cells	nodes
Coarse	1.285×10^{-3}	1.2	42,101,763	7,101,719
Medium	1.118×10^{-3}	1.2	54,273,284	9,146,625
Fine	9.72×10^{-4}	1.2	70,854,330	11,935,490
Extra Fine	8.45×10^{-4}	1.2	95,124,160	16,015,360

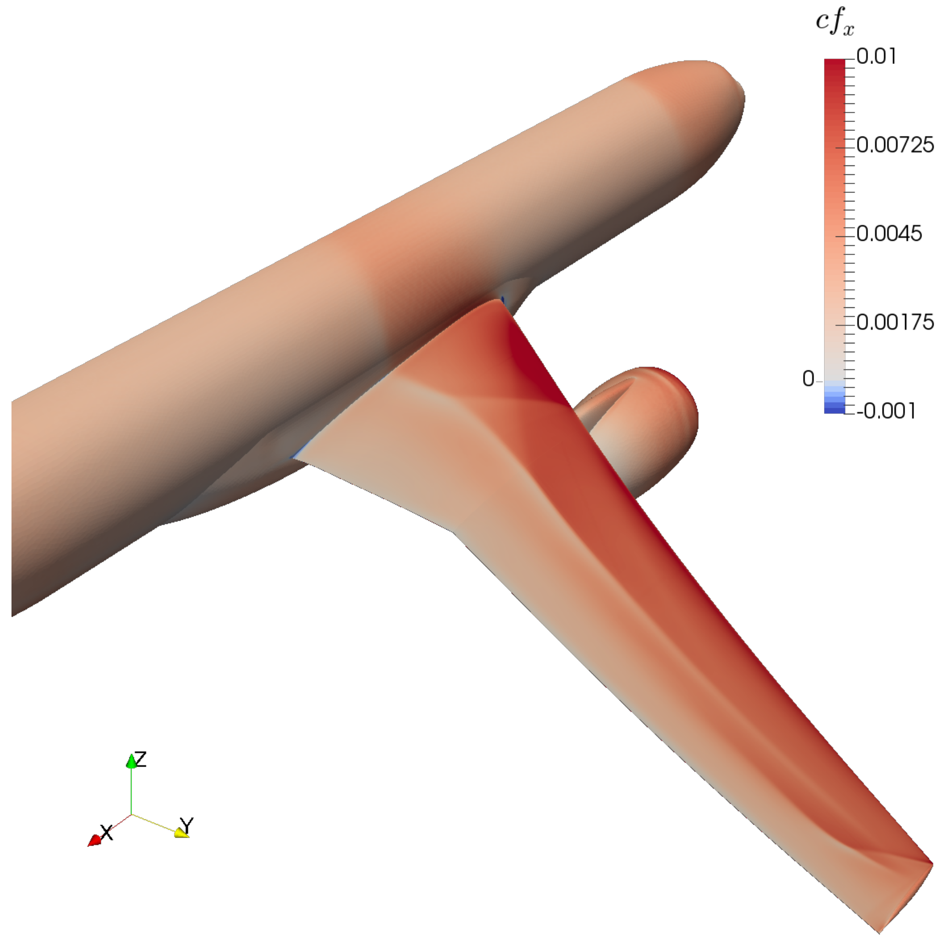
P1 FINE mesh WBNP





WB/WBNP Cf_x Contours P1 FINE Mesh





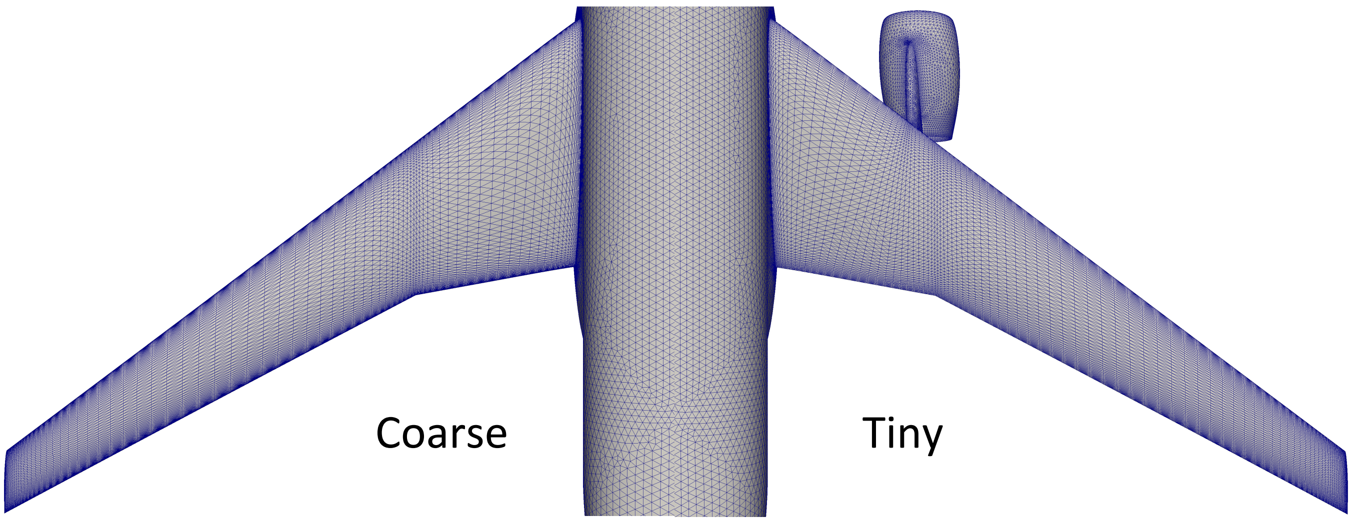
Task 2 – P2 Meshes – 3rd Order

- **P2 WB meshes, alpha 2.75 geometry**

level	initial wall spacing	growth factor	cells	nodes
Coarse	3.354×10^{-3}	1.5	2,763,020	3,752,826
Medium	2.236×10^{-3}	1.5	5,795,210	7,845,870
Fine	$1.490\,67 \times 10^{-3}$	1.4	13,906,580	18,773,425

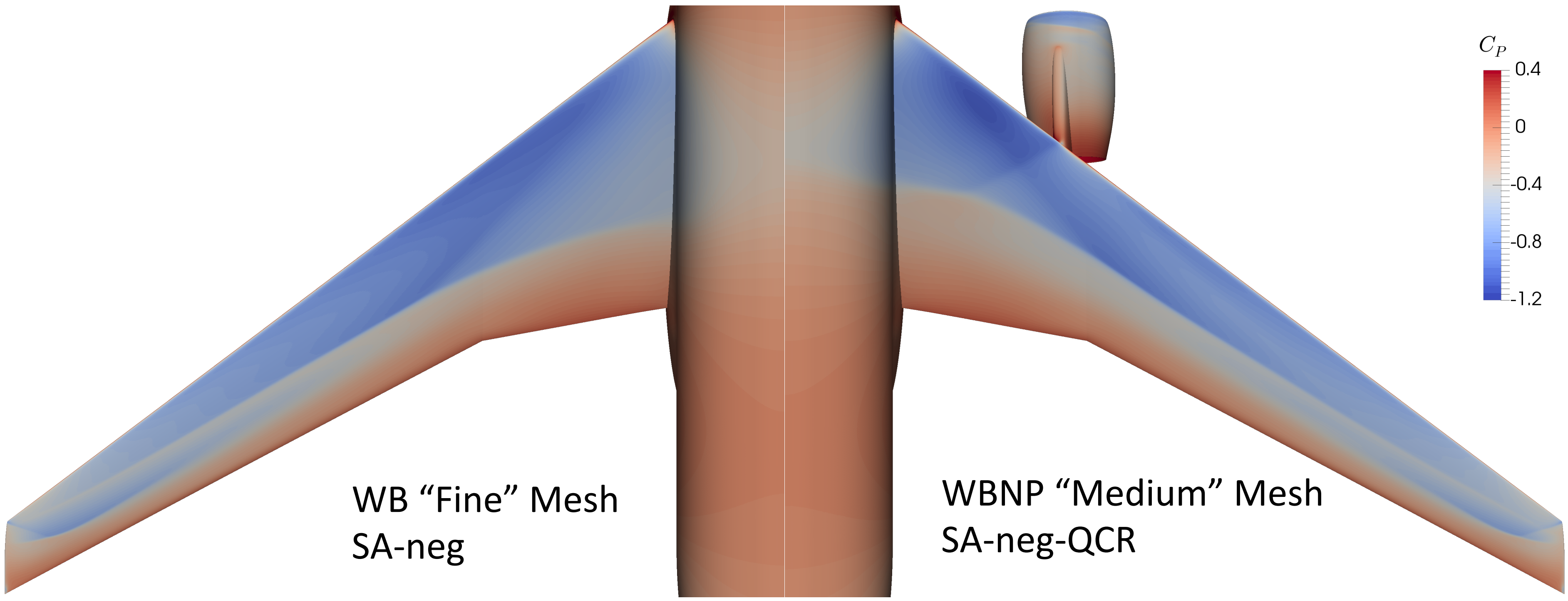
- **P2 WBNP meshes, alpha 2.75 geometry**

level	initial wall spacing	growth factor	cells	nodes
Tiny	4.5×10^{-3}	1.3	6,117,384	8,257,688
Coarse	3×10^{-3}	1.5	7,384,729	9,988,320
Medium	2×10^{-3}	1.5	16,307,305	22,008,177

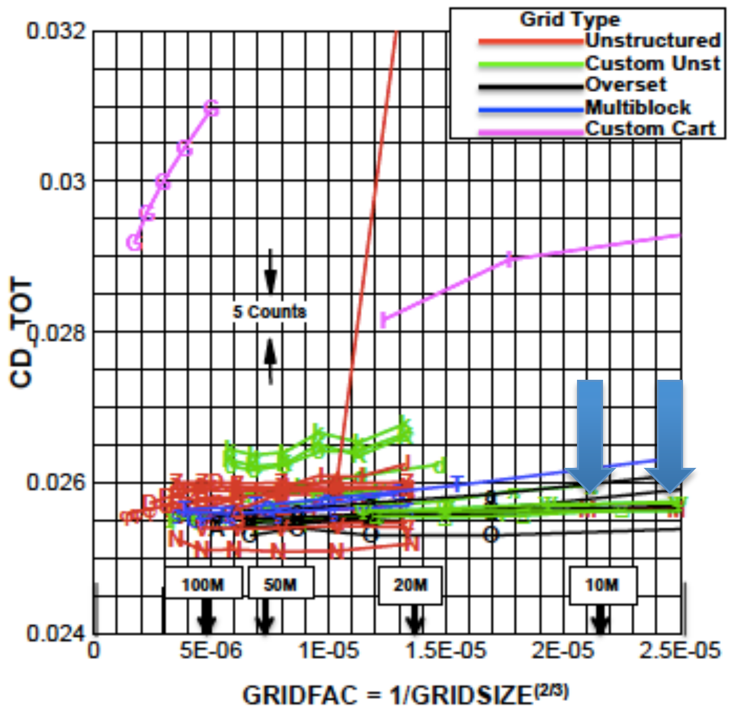


P2 Surface Coefficient of Pressure

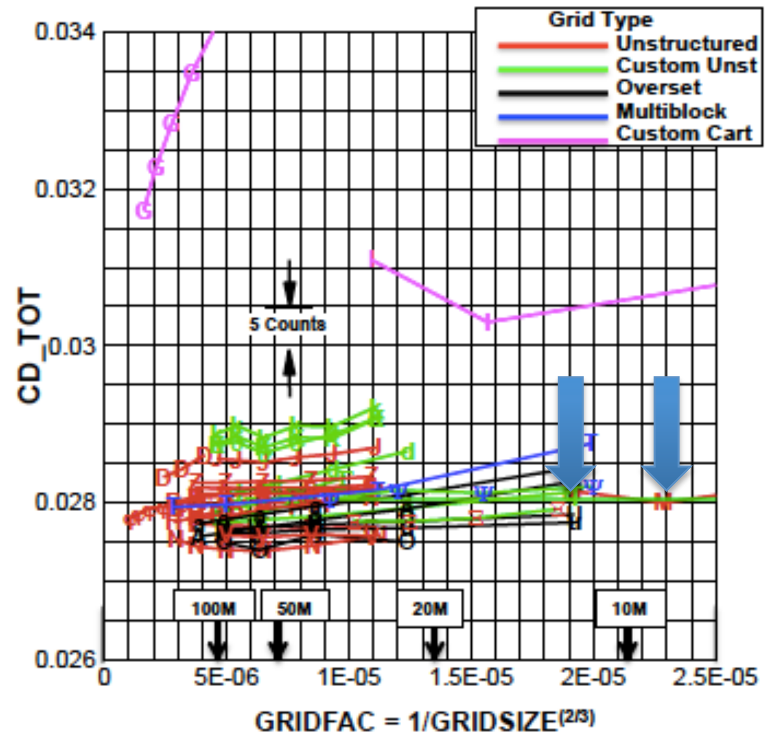
- Well resolved Lambda Shock at wing tip
- X pattern on upper wing surface of WBNP
- Shock located slightly upstream for WBNP



Task 2 – Mesh Convergence WB/WBNP



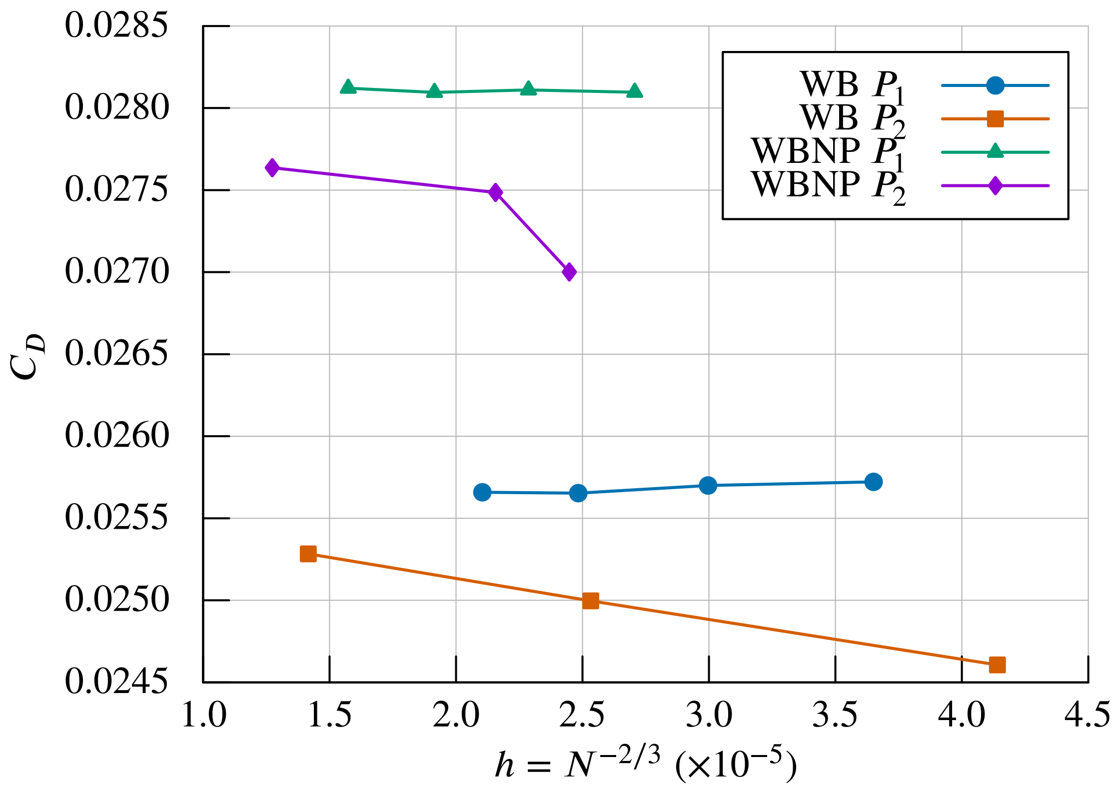
WB



WBNP

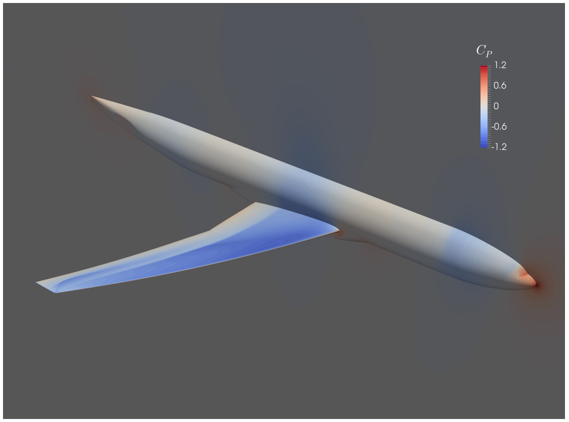
- https://aiaa-dpw.larc.nasa.gov/Workshop6/presentations/2_10_DPW6_Summary-Draft-ET.pdf
- **COFFE P1 results are designated as M**
- **C_D within spread with fully tetrahedral meshes with <10 million DOFs**

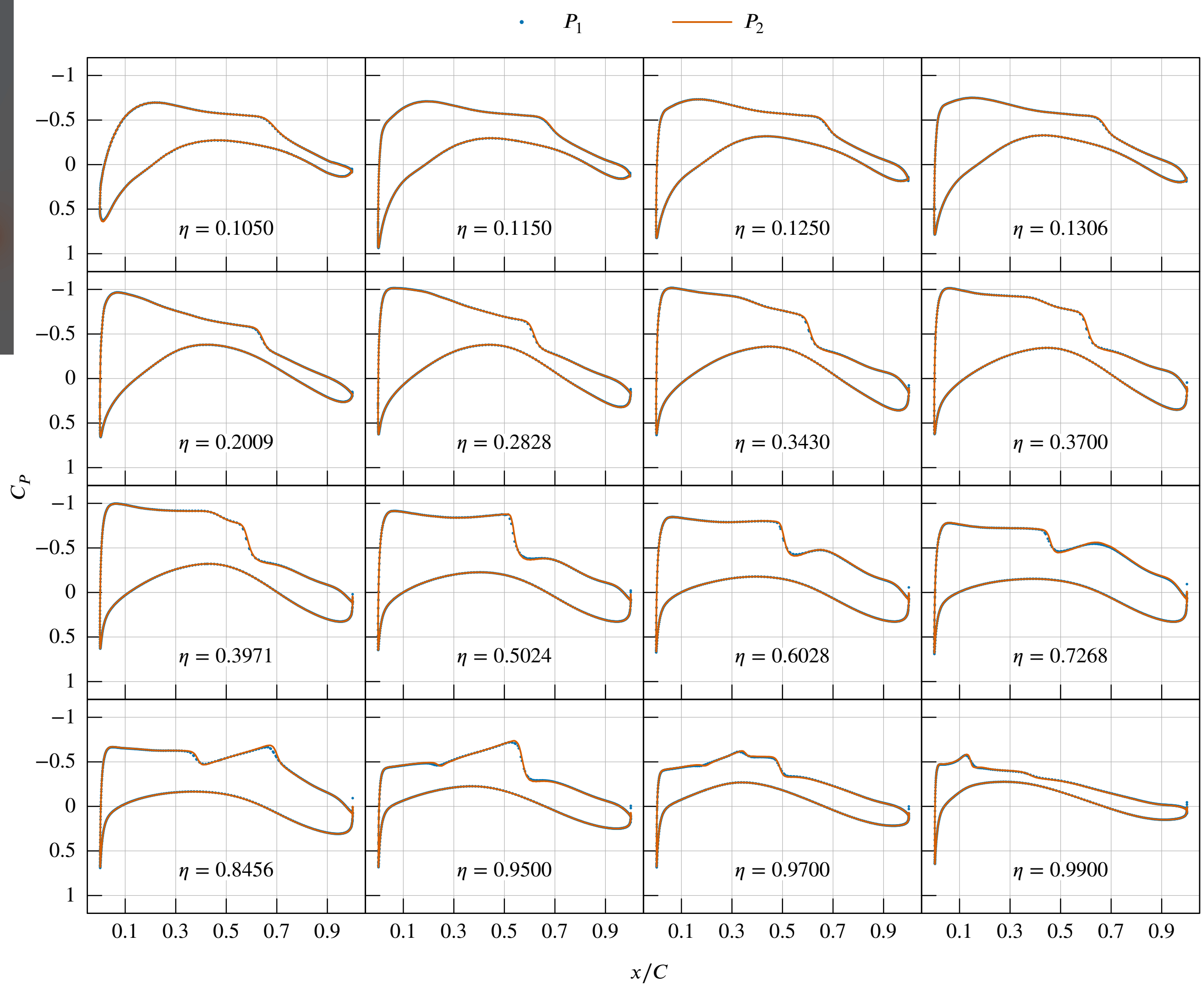
Task 2 – Mesh Convergence WB/WBNP



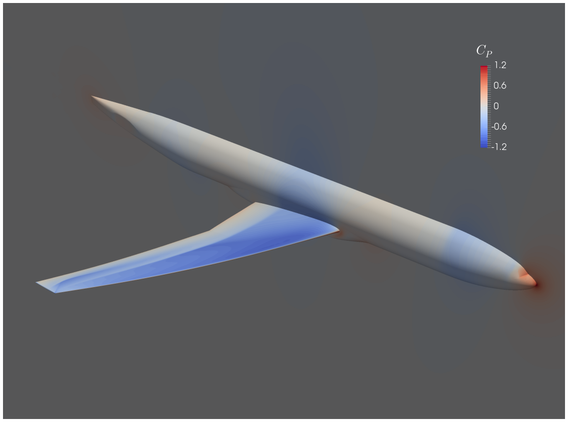
- SA-neg WB, SA-neg-QCR WBNP
- C_L = 0.5 +/- 0.0001
- **Difference in P2 mesh converged C_D for WB and WBNP ~ 0.0023**
- **Wind tunnel Δ C_D ~ 0.00215 – 0.0024**

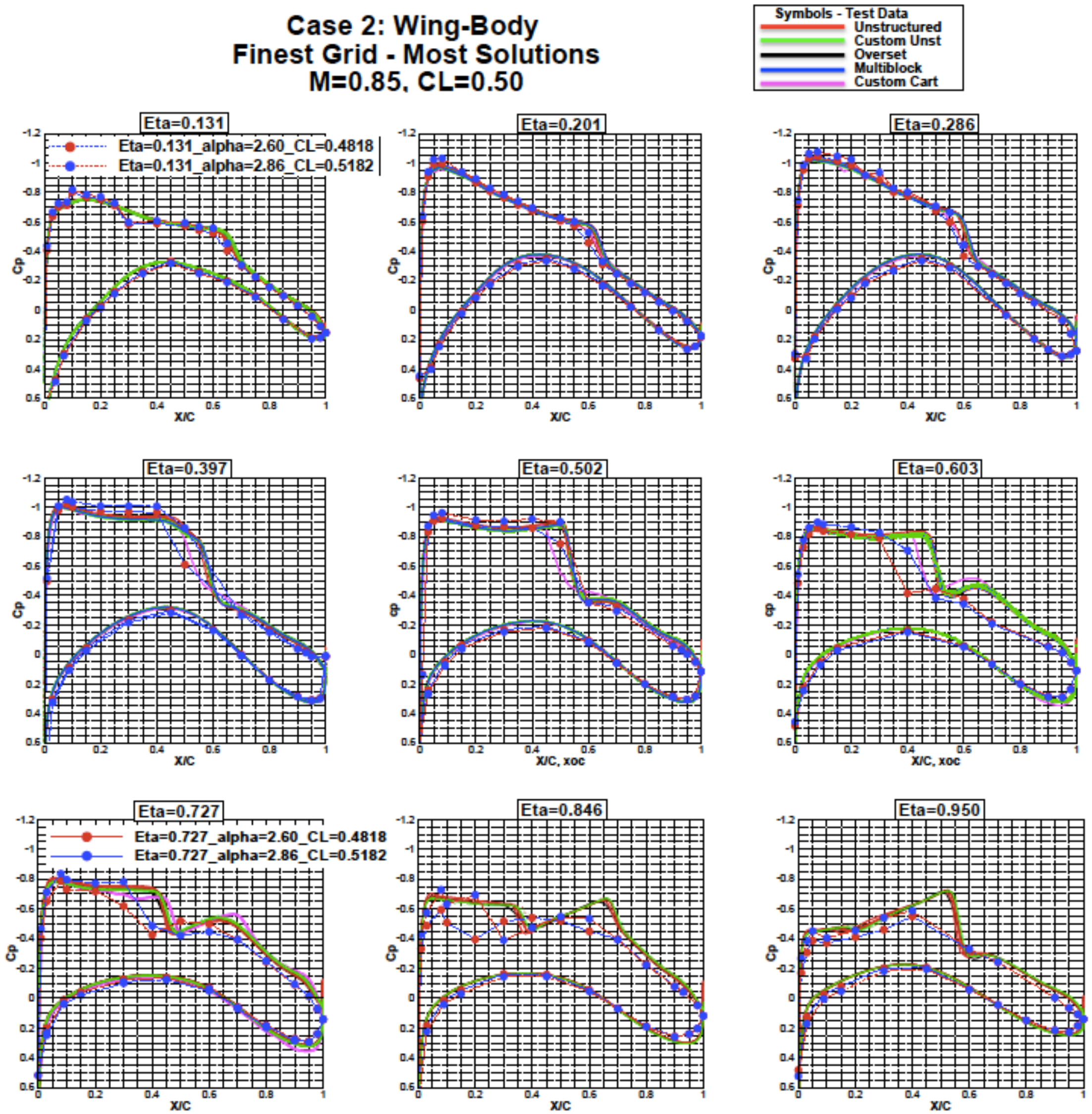
Surface Coefficient of Pressure Span-wise Cuts WB – Finest Meshes COFFE





Surface Coefficient of Pressure Span-wise Cuts WB – Finest Meshes Workshop Solutions





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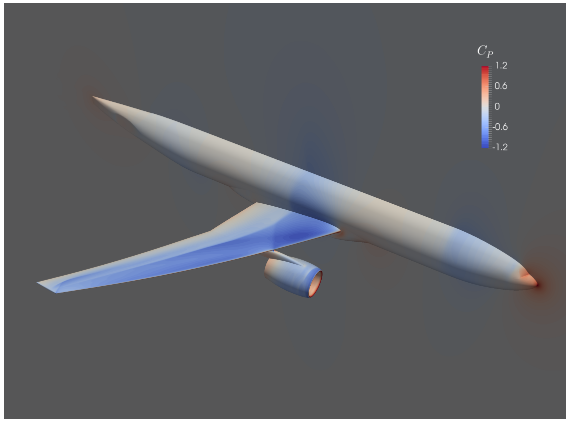
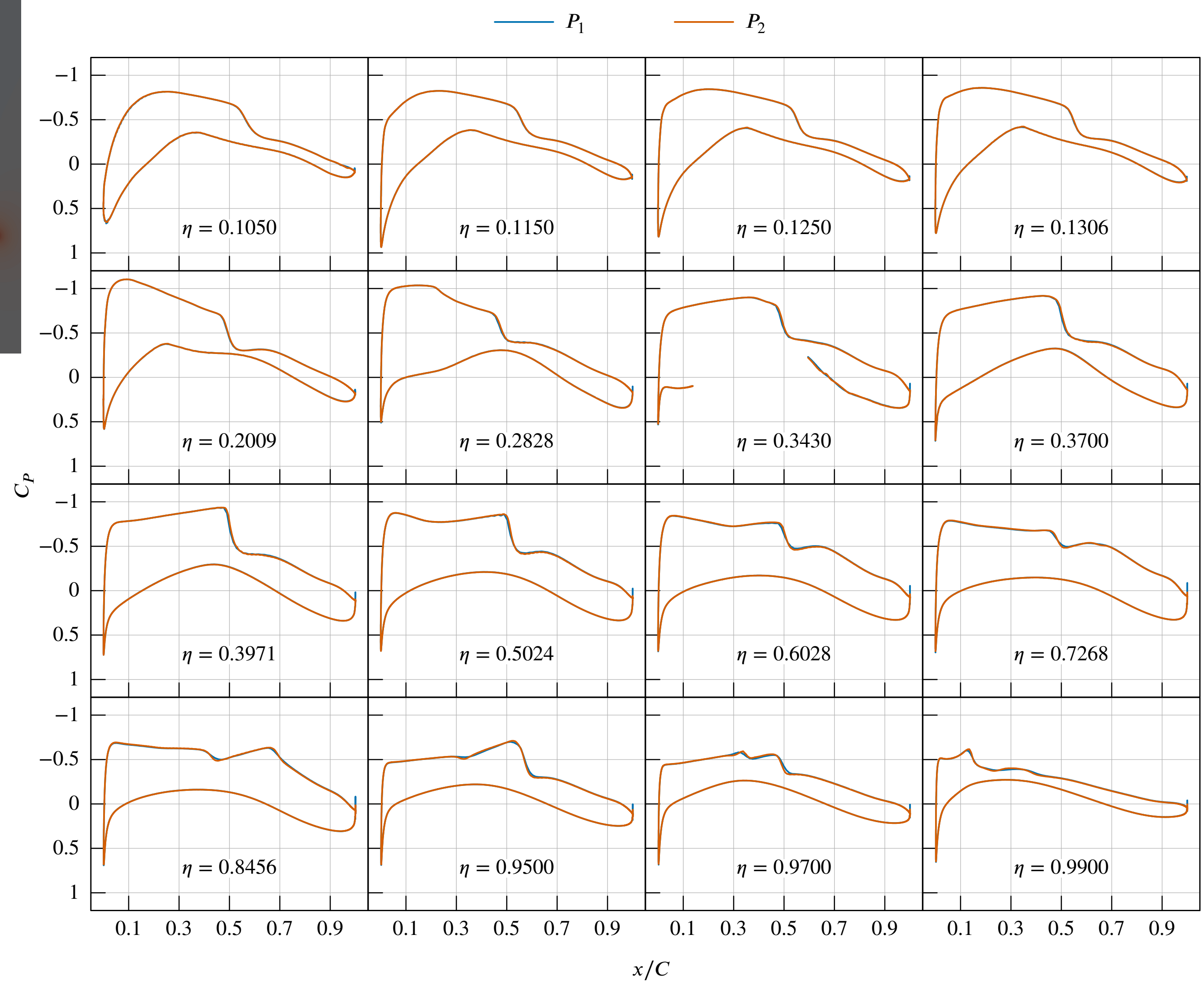
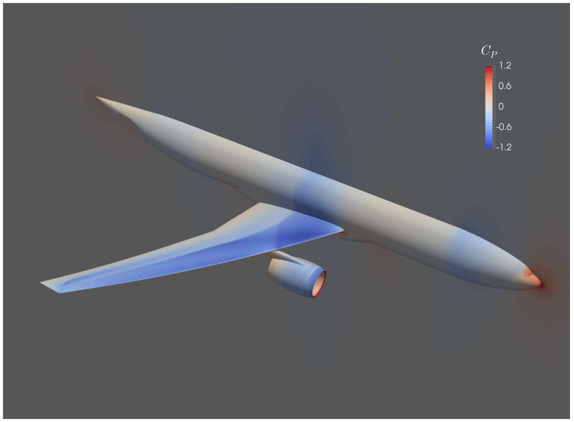
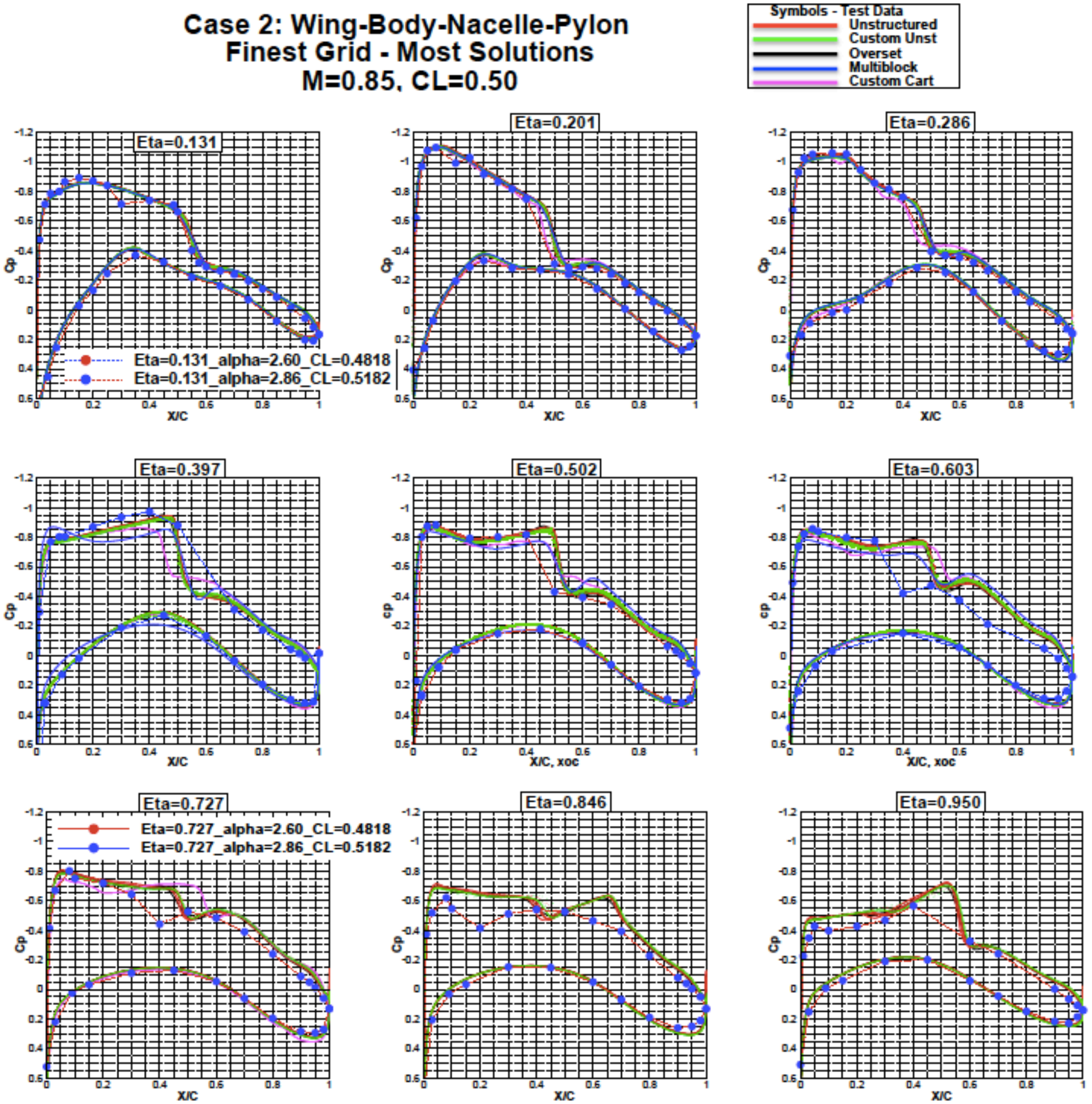
Surface Coefficient of Pressure Span-wise Cuts WBNP – Finest Meshes COFFE





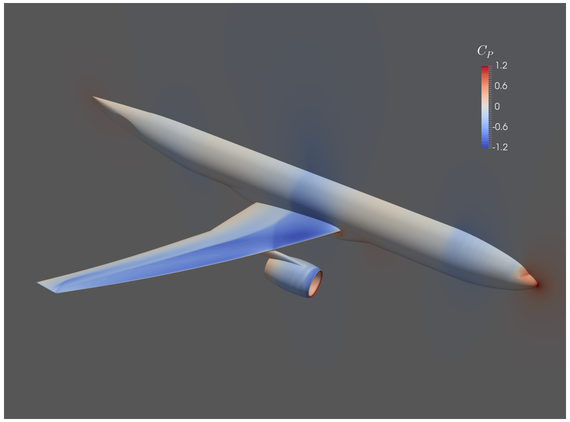
Surface Coefficient of Pressure Span-wise Cuts WBNP – Finest Meshes Workshop Solutions

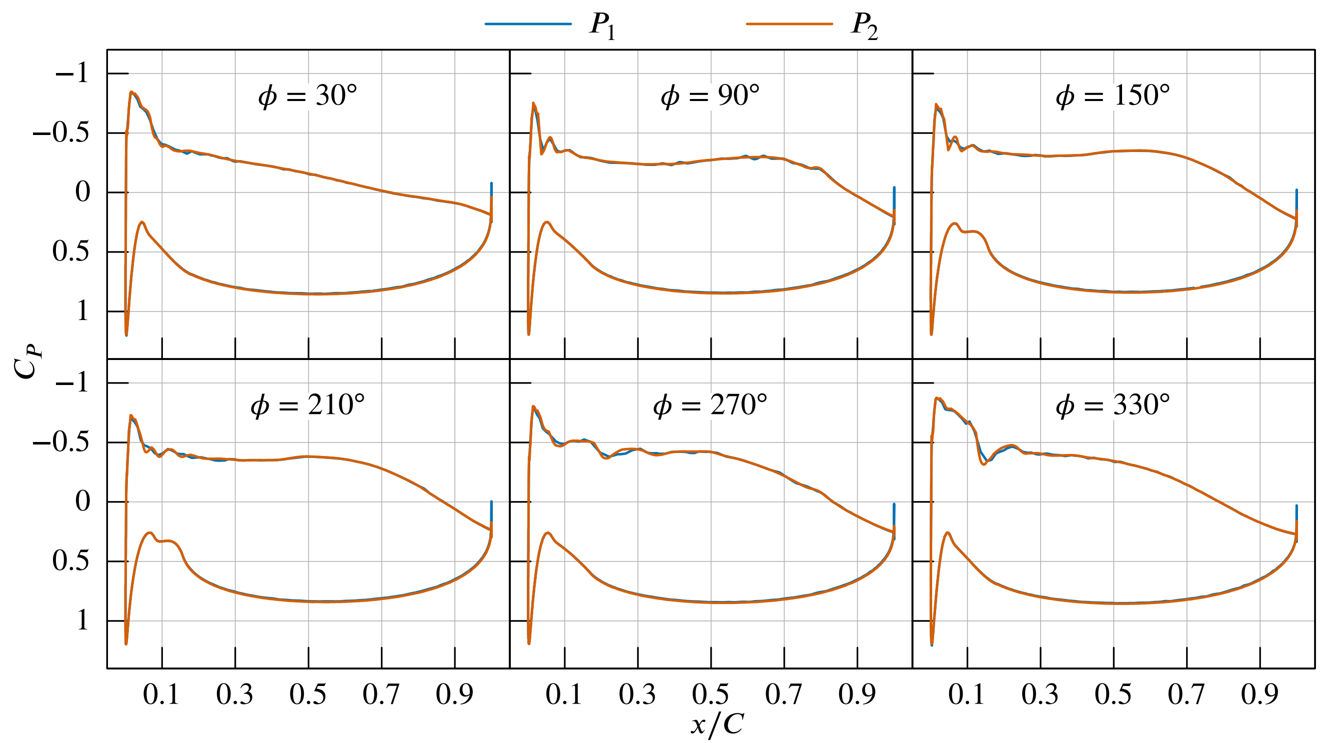




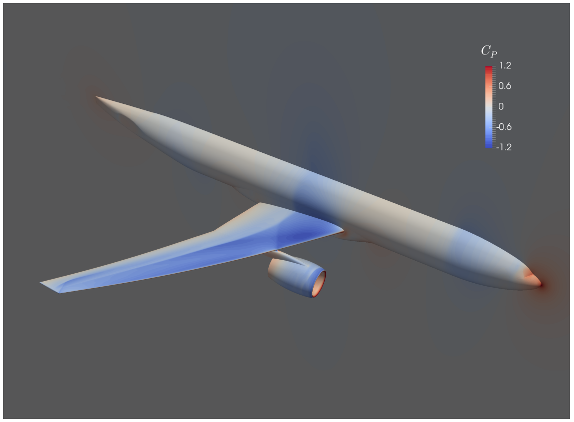
- https://aiaa-dpw.larc.nasa.gov/Workshop6/presentations/2_10_DPW6_Summary-Draft-ET.pdf

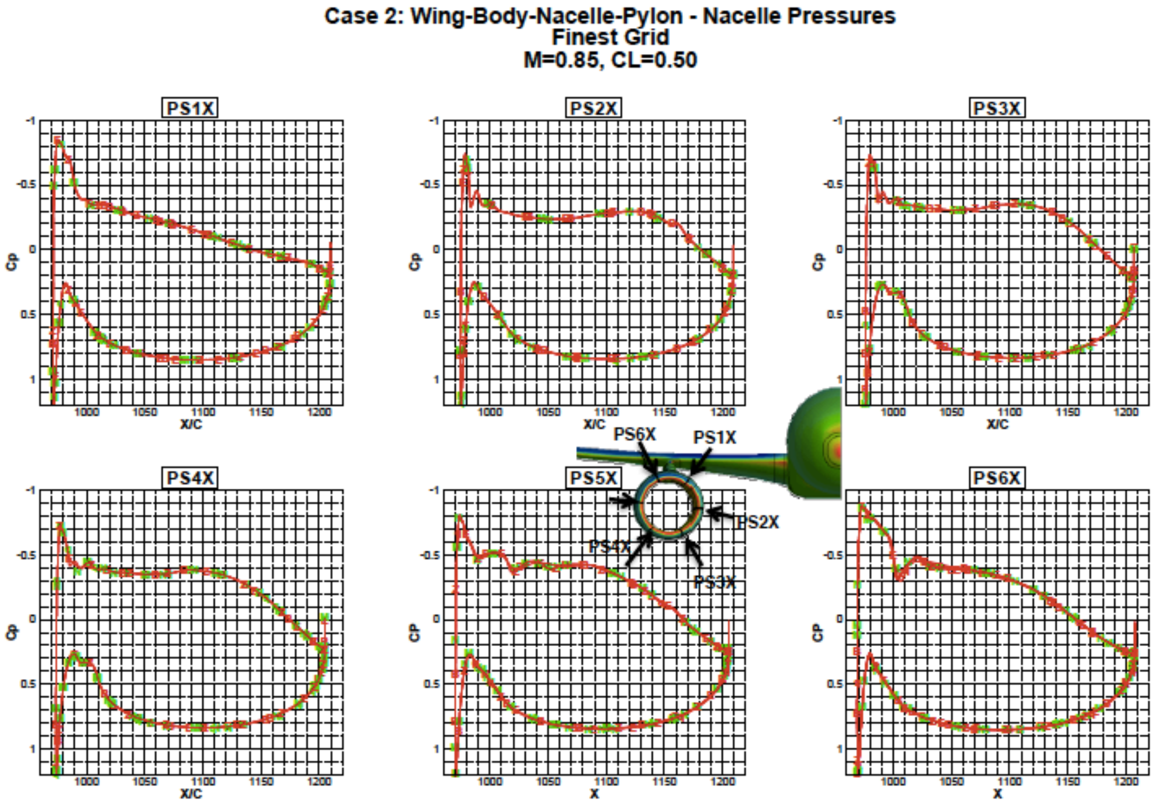
Surface Coefficient of Pressure Nacelle Cuts WBNP– Finest Meshes COFFE





Surface Coefficient of Pressure Nacelle Cuts WBNP – Finest Meshes Workshop Solutions





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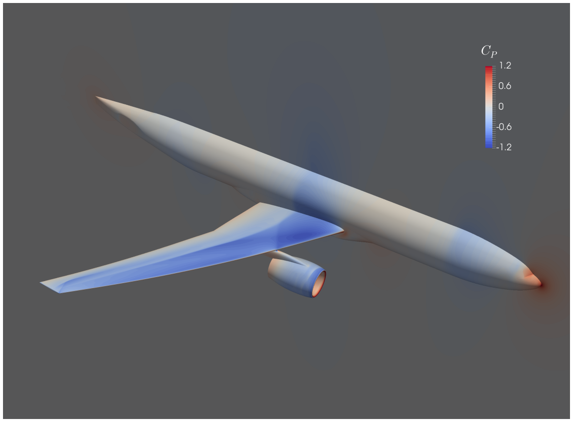
DPW6 Task 2 Summary -- COFFE

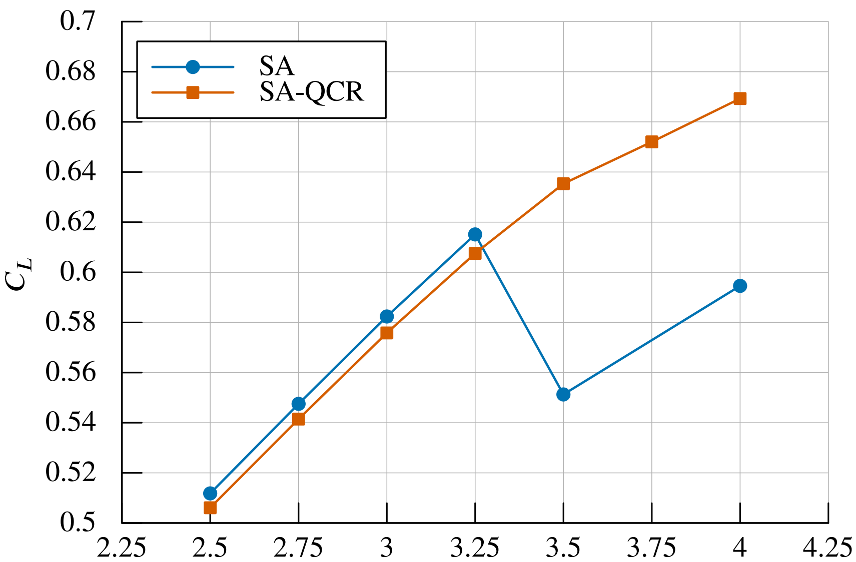


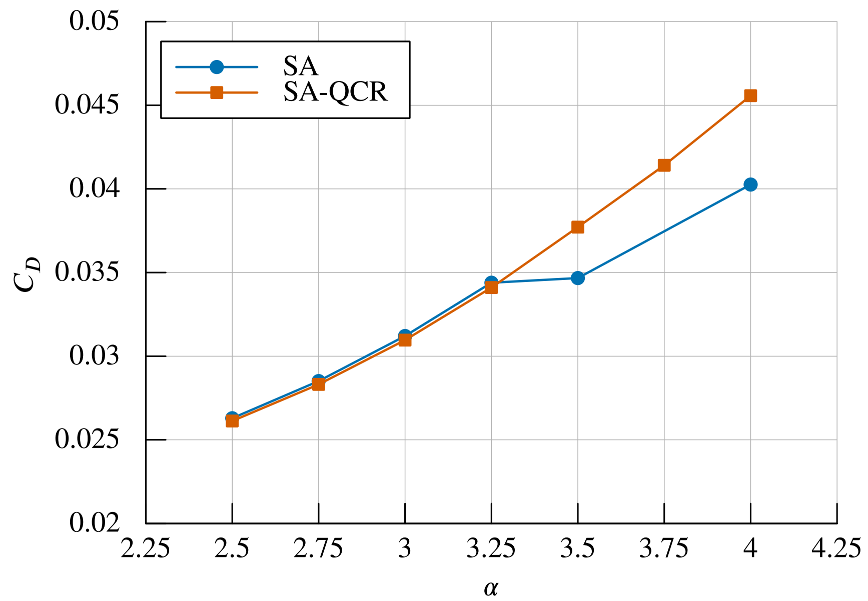
- **Capable of computing accurate forces with minimal degrees of freedom – higher order solution**
- **SU/PG – 3-D discretization**
- **No:**
  - Face based upwinding or Riemann problem – 1D
    - Riemann problem assumes piecewise constant UL and UR
  - Face duplication – significant duplication of DOFs
  - Stencil extension
  - Gradient reconstruction – 1D in the BL
  - Explicit limiting
  - Partial linearization
  - Partial non-linear convergence
- **Capable of utilizing fully tetrahedral meshes**
  - Eases mesh generation
  - Enables anisotropic adaptation
- **Robust shock capturing with no mesh shock-alignment**
- **Extremely efficient automated non-linear path**

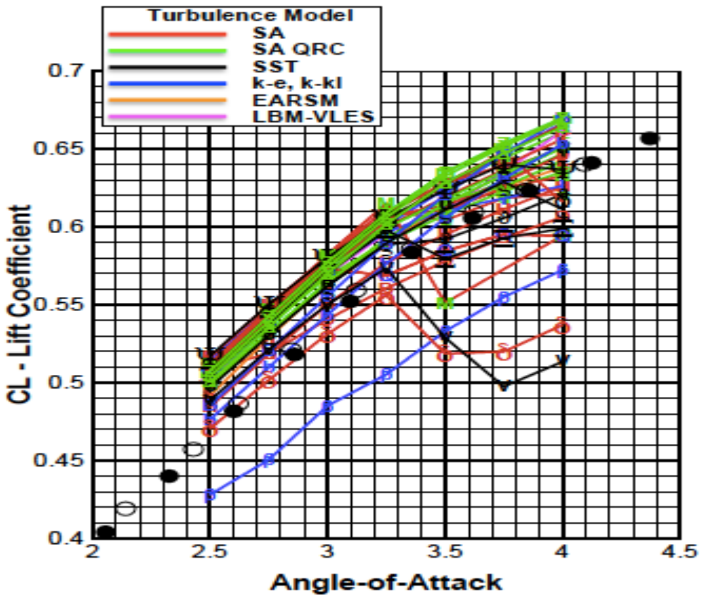
DPW6 Task 3 – Alpha Sweep

- **Conditions: Mach = 0.85, Re_{MAC} = 5 million, angle-of-attack = 2.5, 2.75, 3.0, 3.25, 3.5, 3.75, and 4.0 degrees**
- **Different geometry for each angle-of-attack – loaded wind tunnel model**
- **Meshes made of only tetrahedral elements with a maximum angle < 176 degrees**
- **MEDIUM P1 WB meshes, ~6,000,000 nodes per geometry**
- **Density residual converged to 10^-15**
- **SA-neg and SA-neg QCR-2000**

Task 3 – Alpha Sweep – Forces







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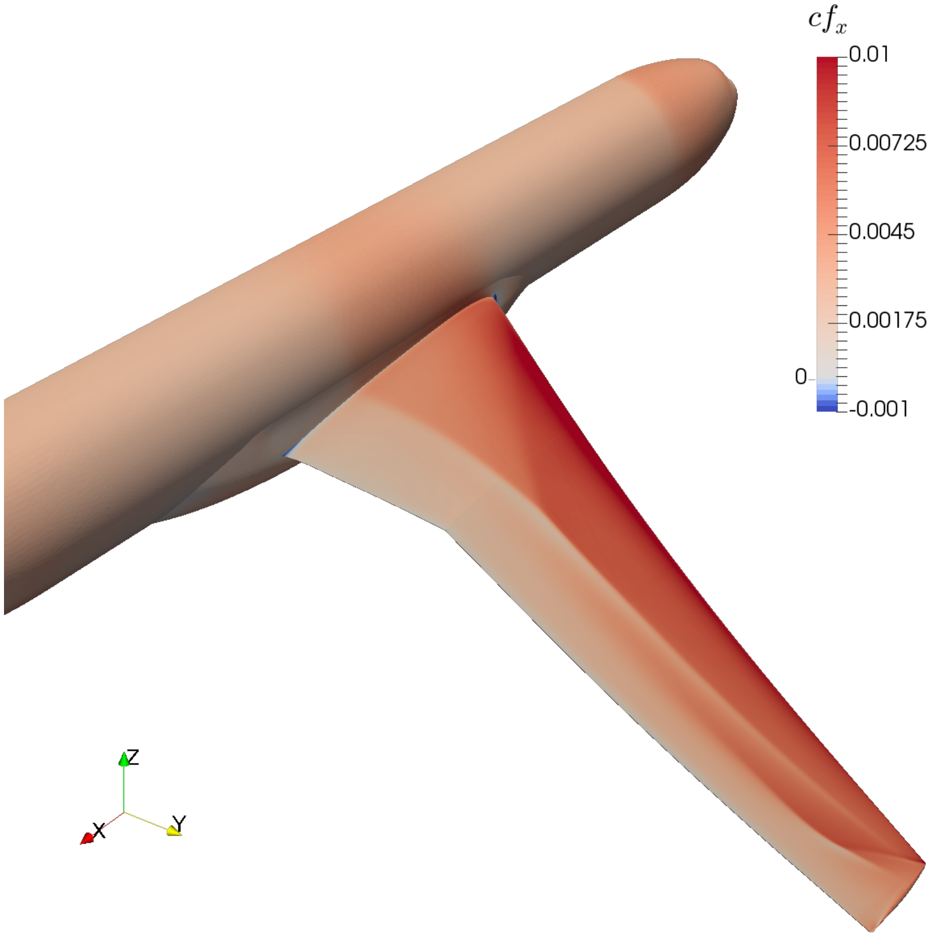
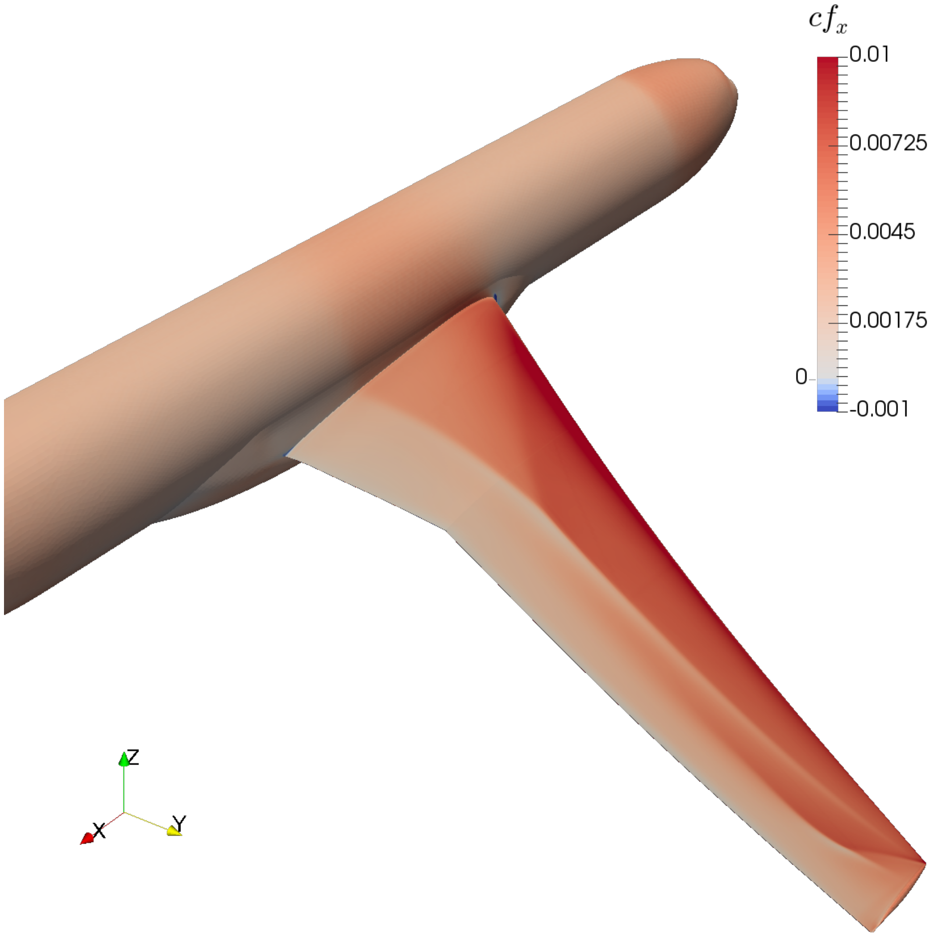
COFFE Results – Alpha 2.5, Cf_x

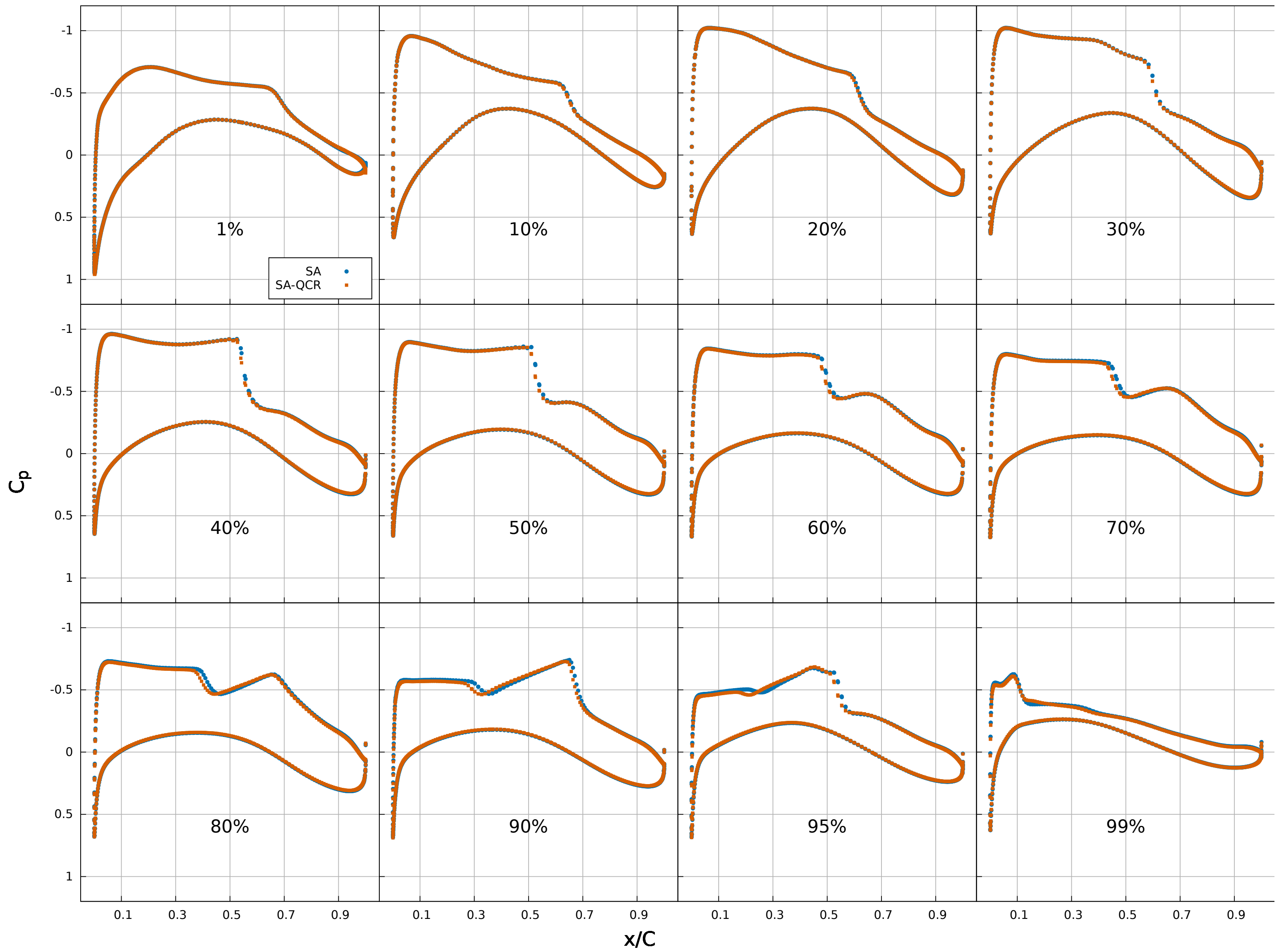


SA

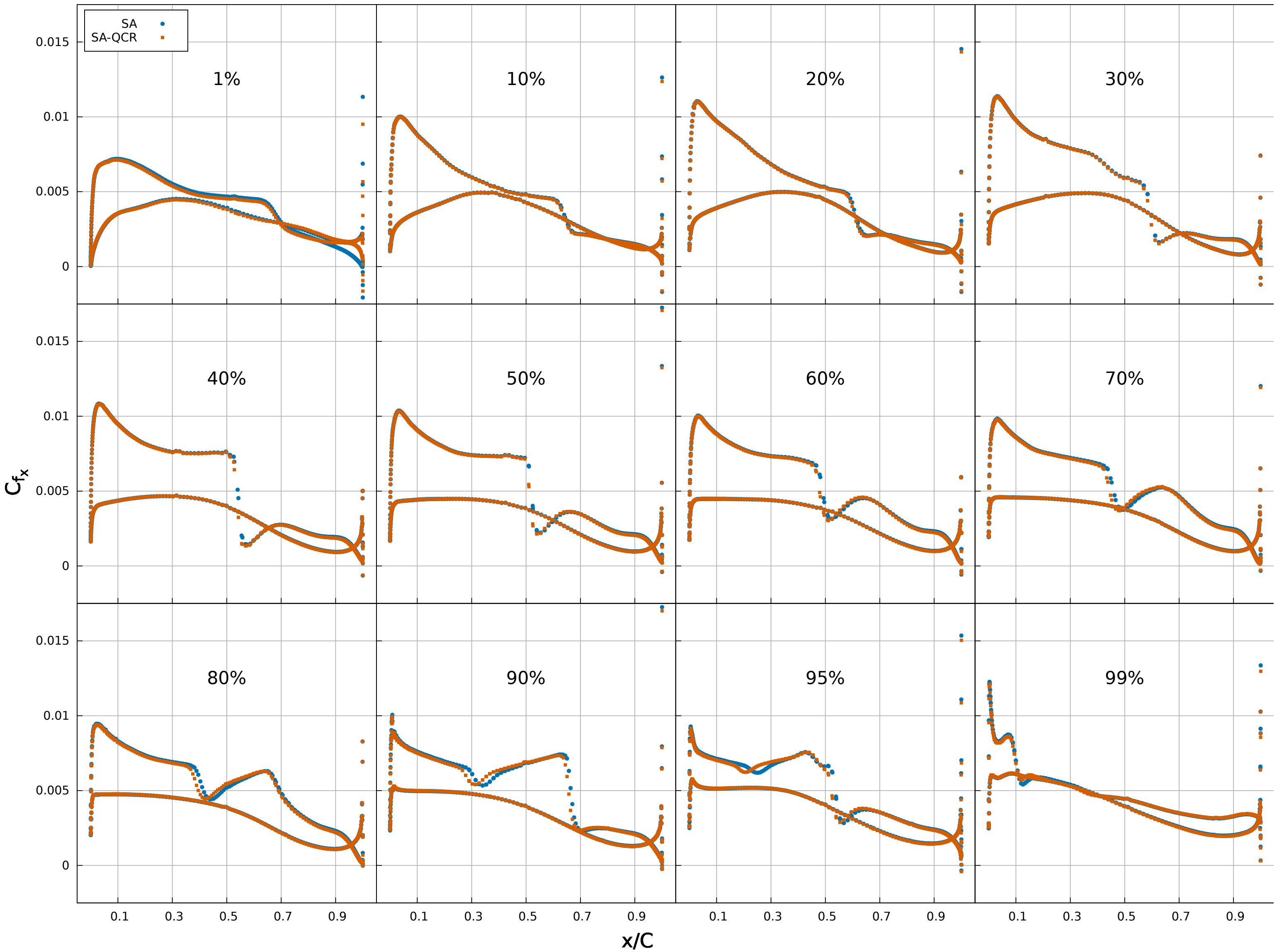


SA - QCR

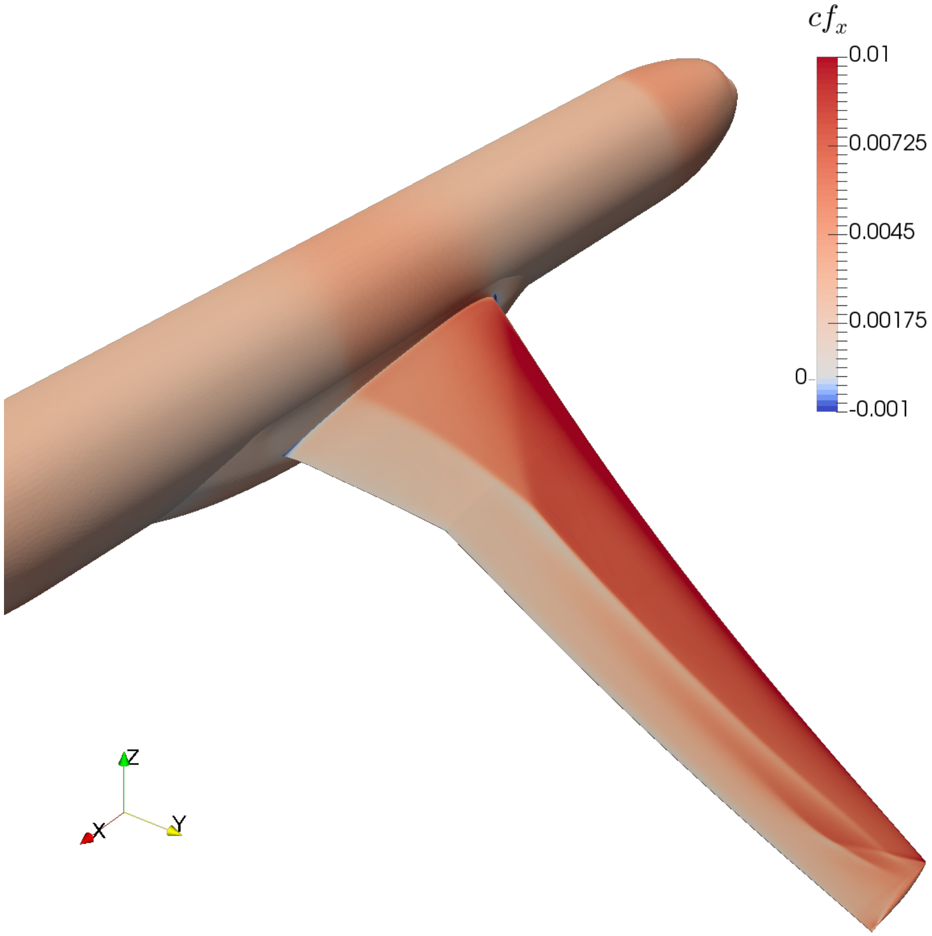
COFFE Results – Alpha 2.5, Cp



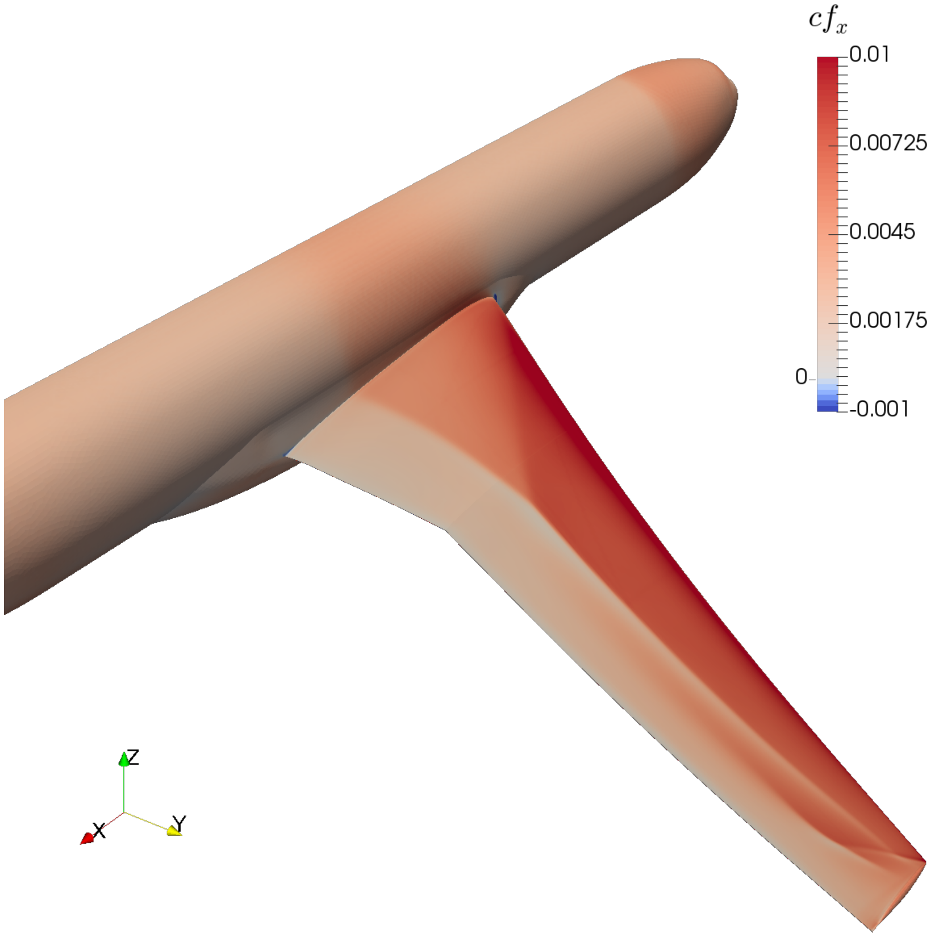
COFFE Results – Alpha 2.5, Cf_x



COFFE Results – Alpha 2.75, Cf_x

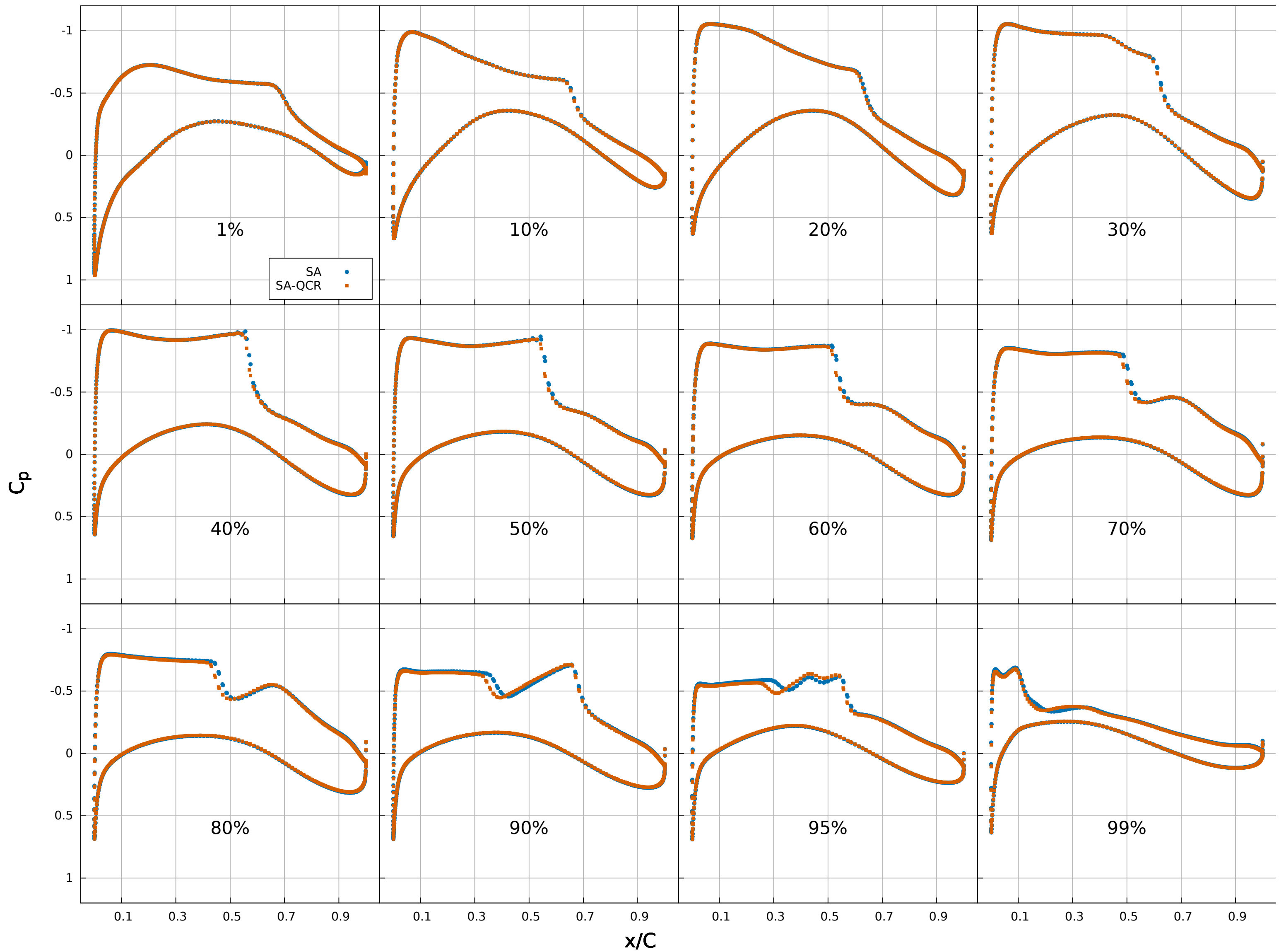


SA

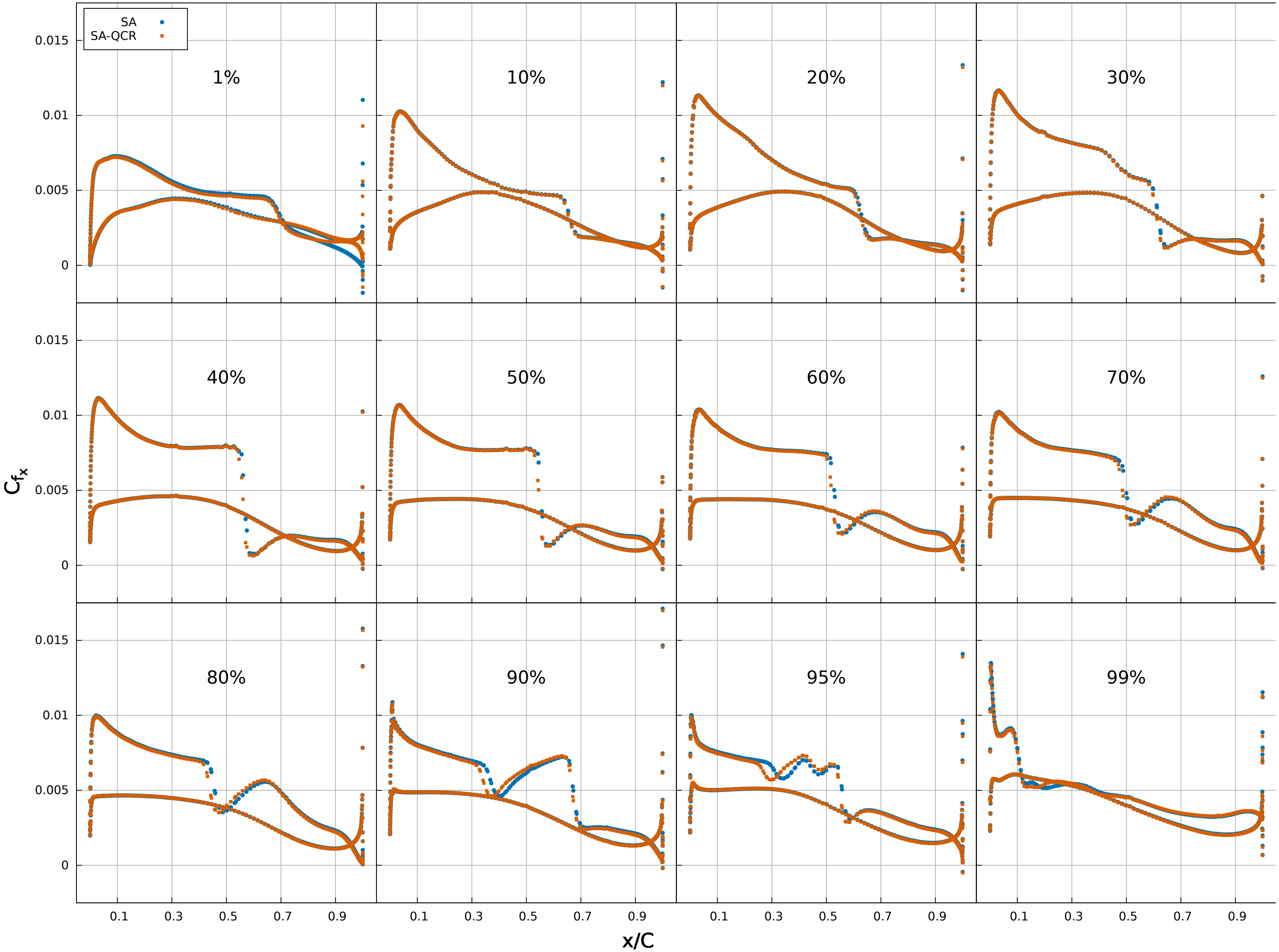


SA - QCR

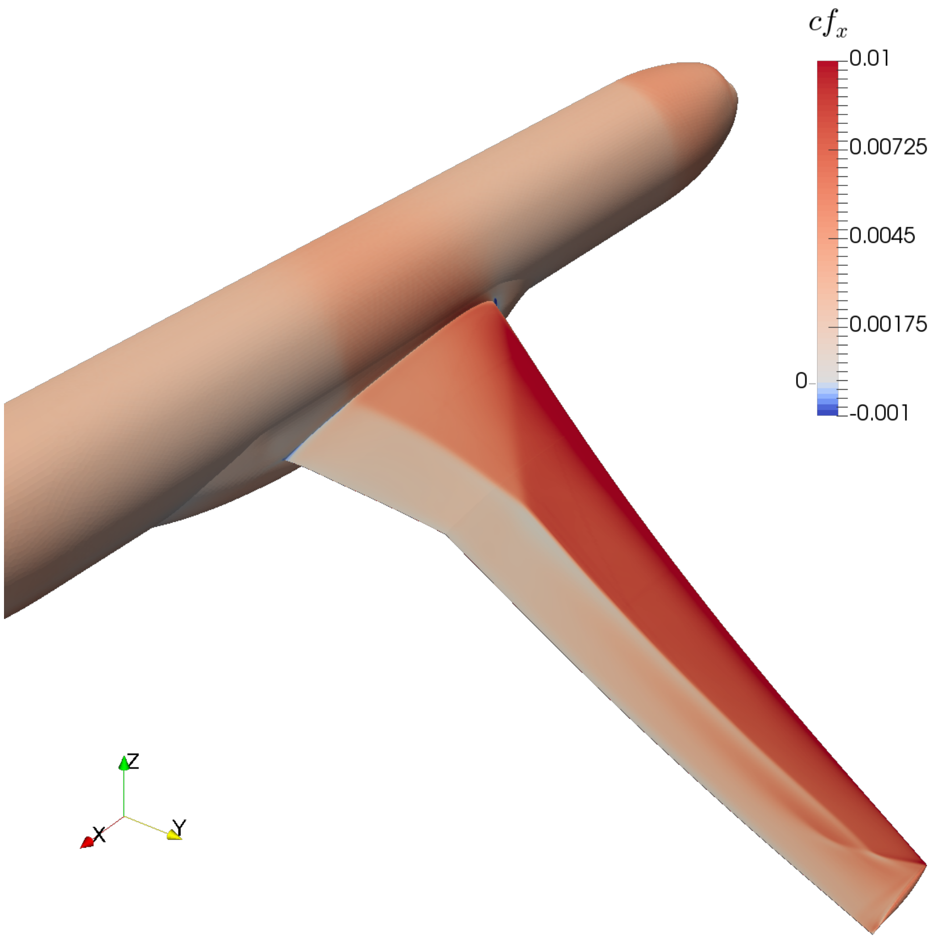
COFFE Results – Alpha 2.75, Cp



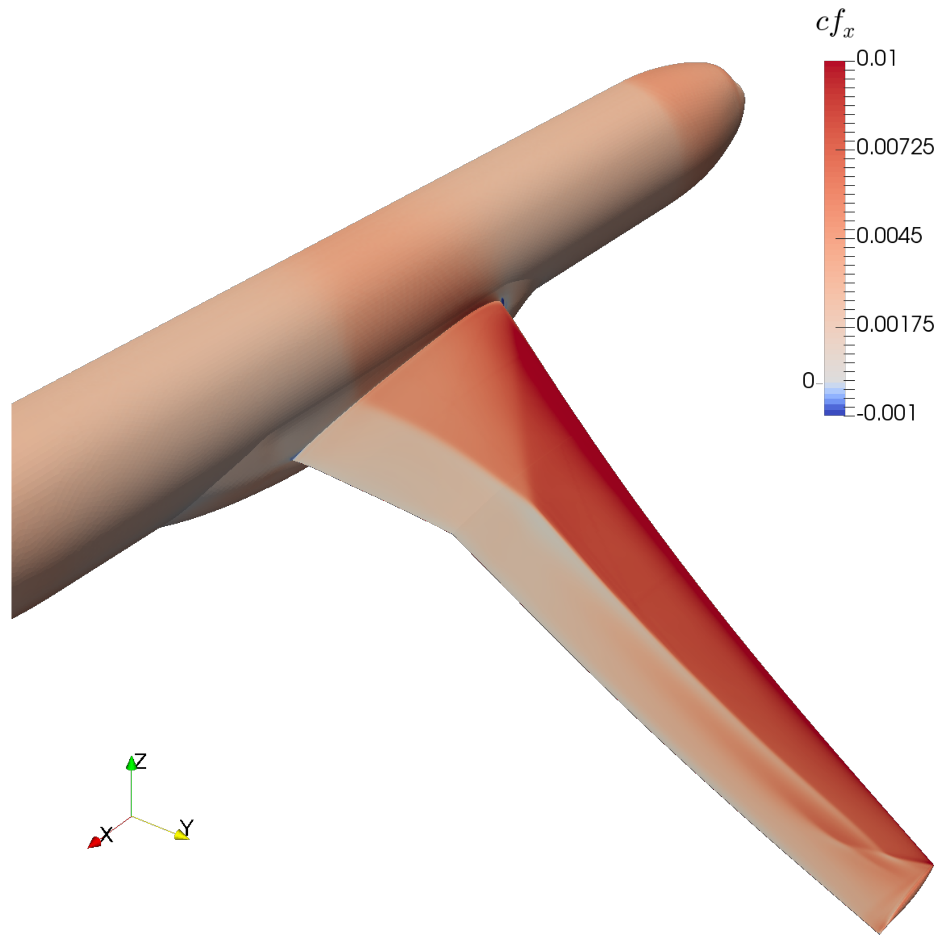
COFFE Results – Alpha 2.75, Cf_x



COFFE Results – Alpha 3.0, Cf_x

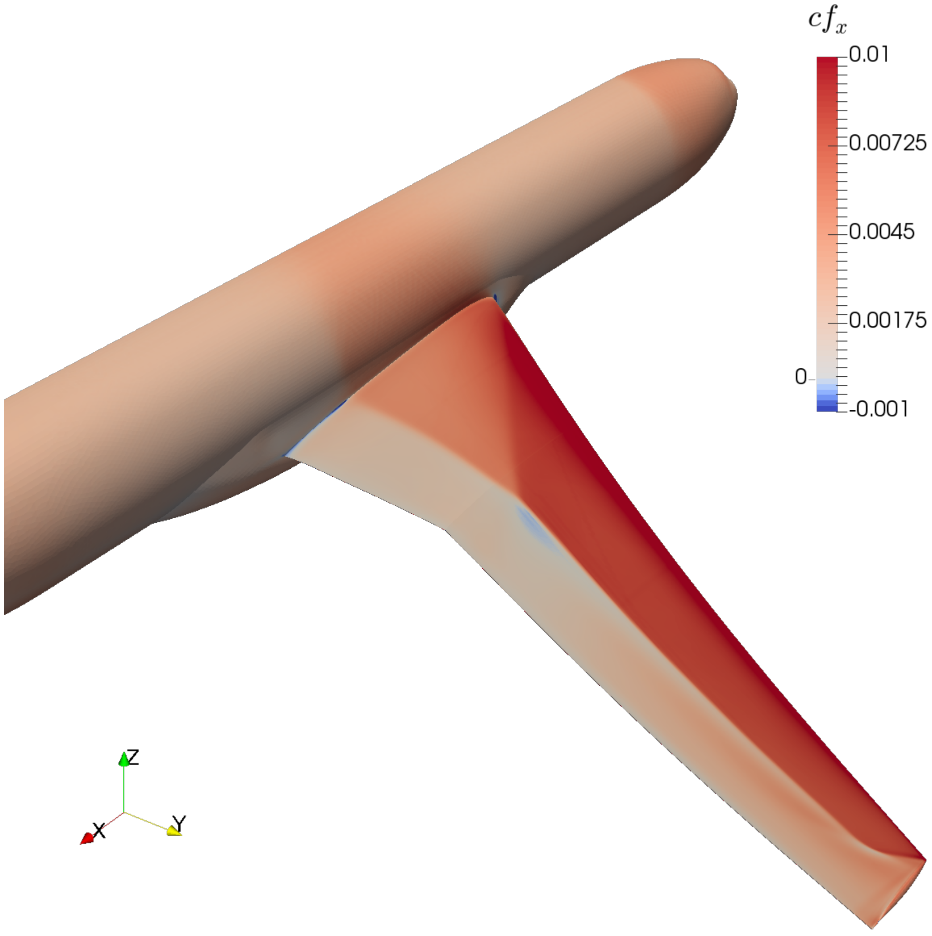


SA



SA - QCR

COFFE Results – Alpha 3.25, Cf_x



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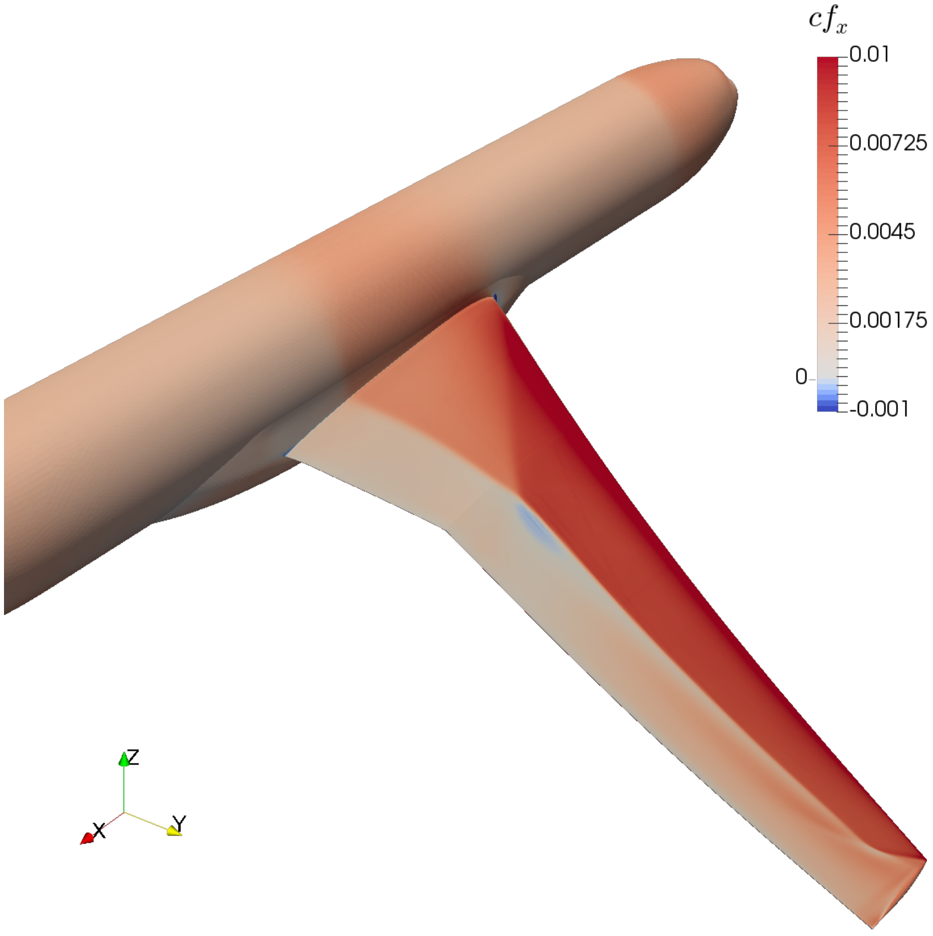
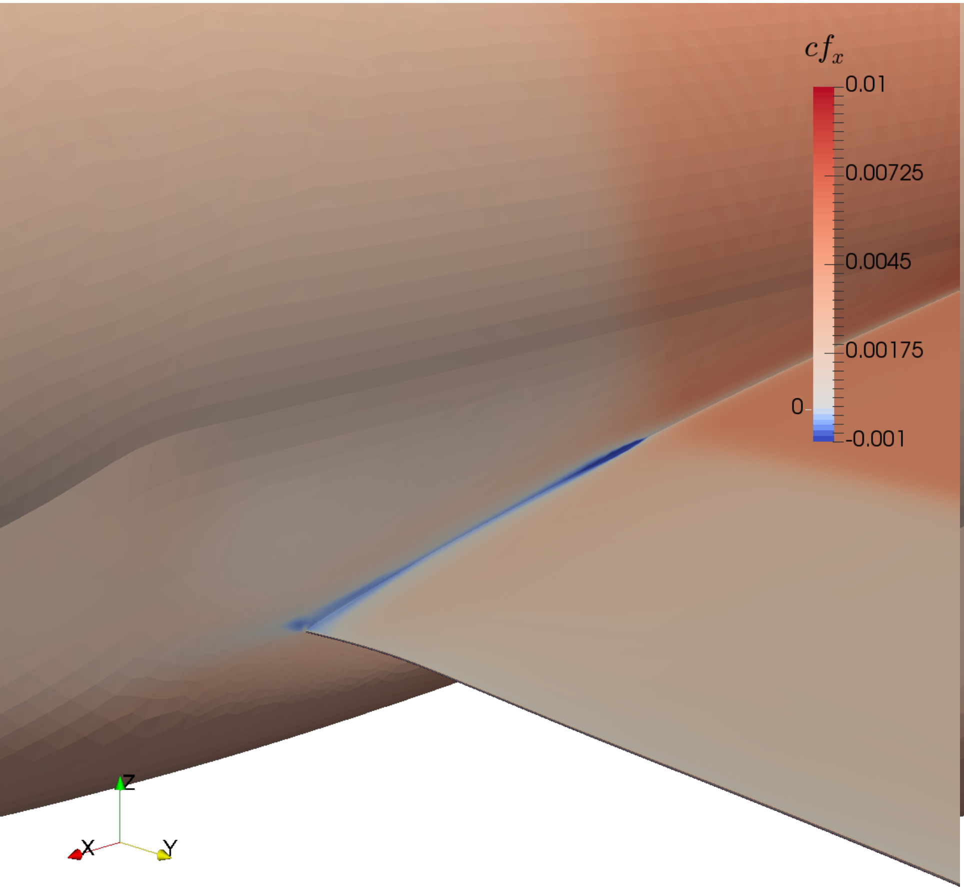


SA - QCR

COFFE Results – Alpha 3.25, Cf_x



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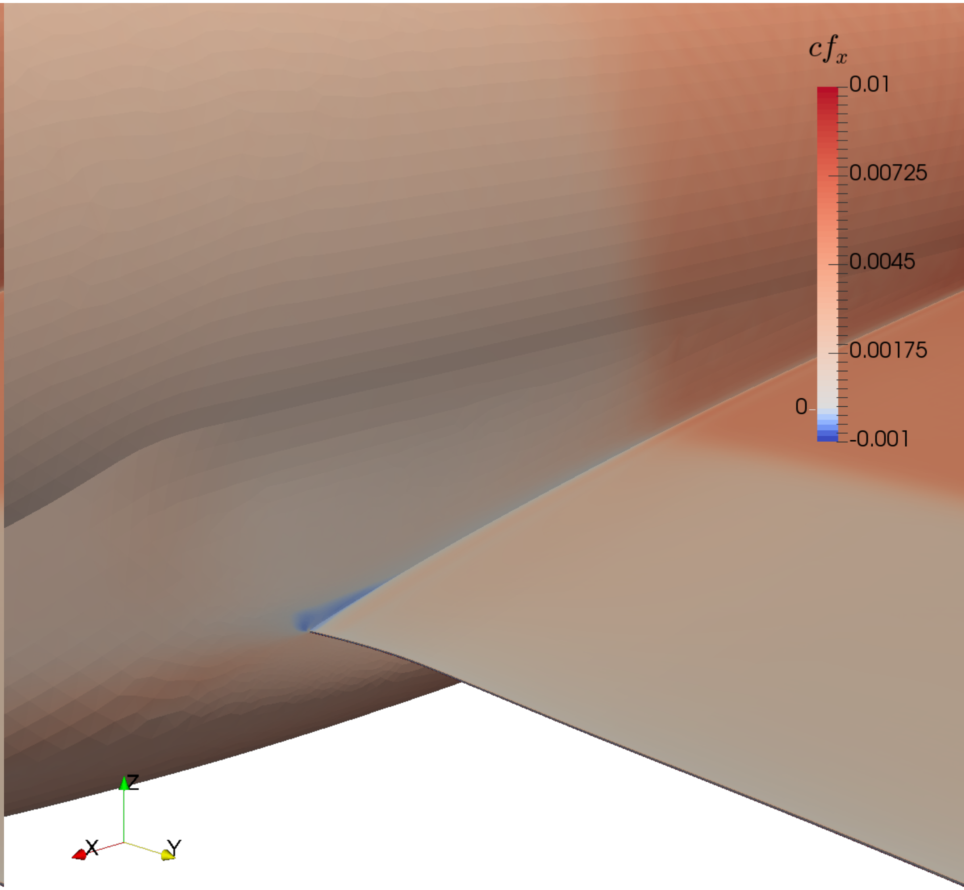
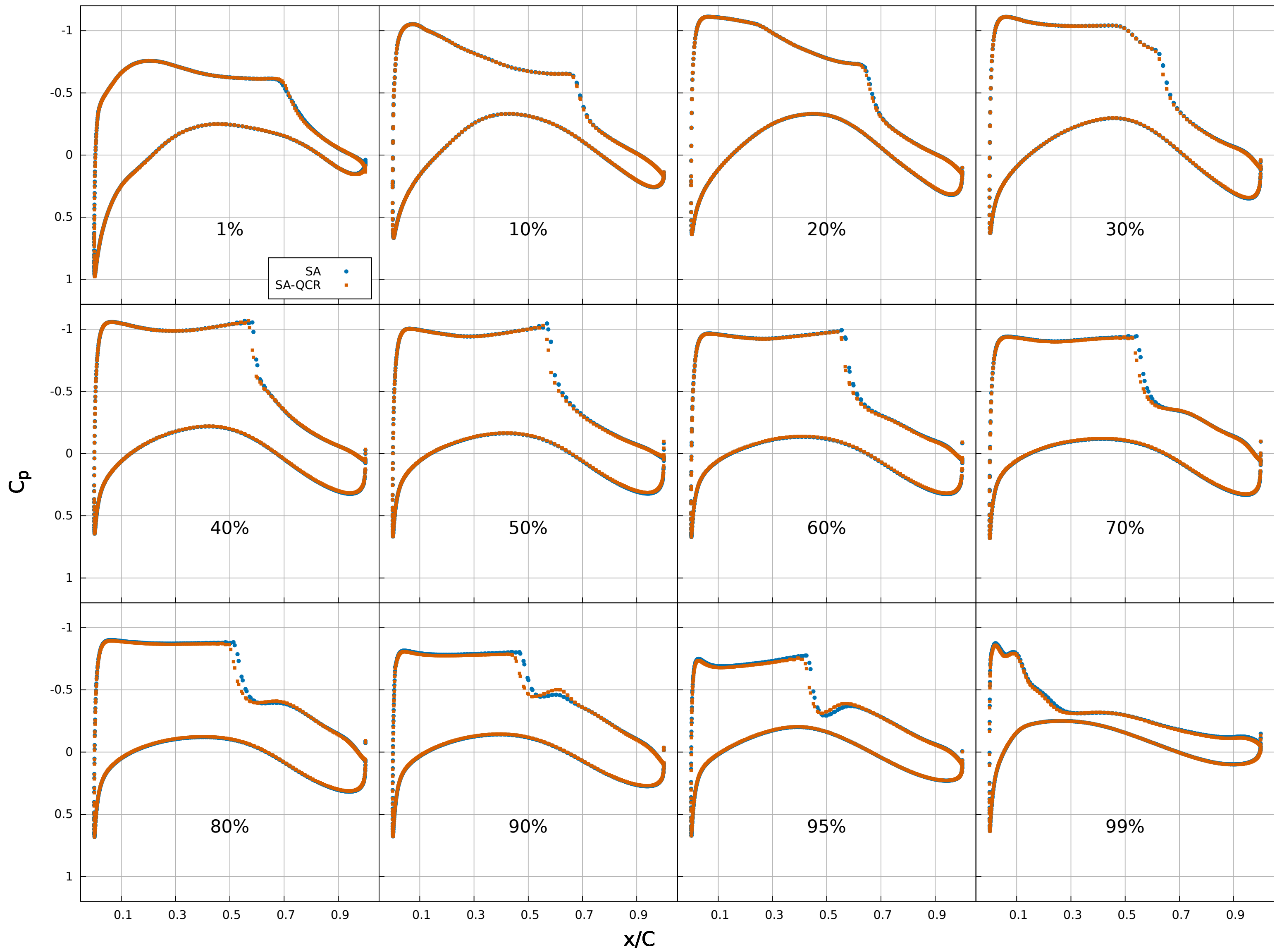
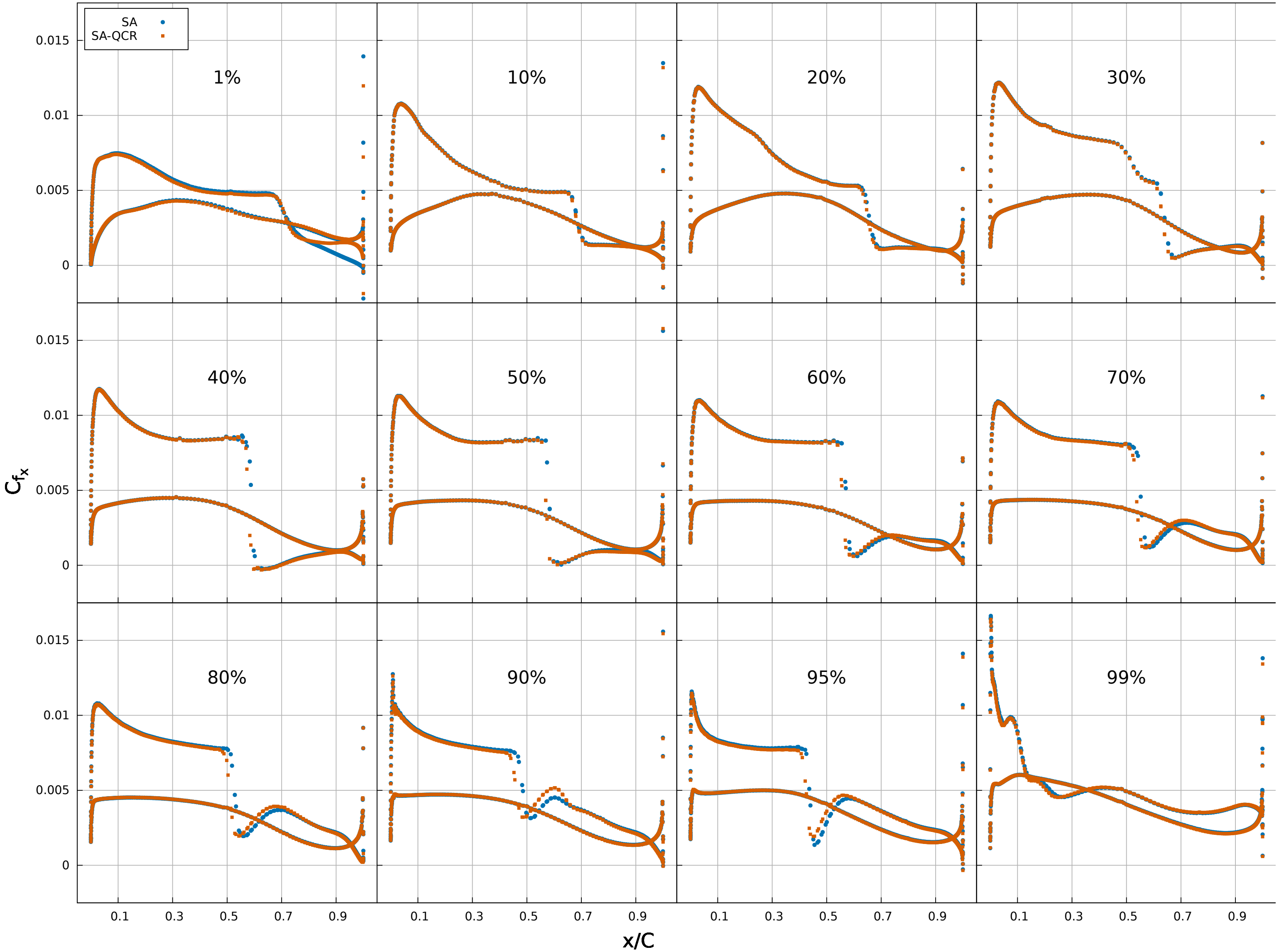


SA - QCR

COFFE Results – Alpha 3.25, Cp

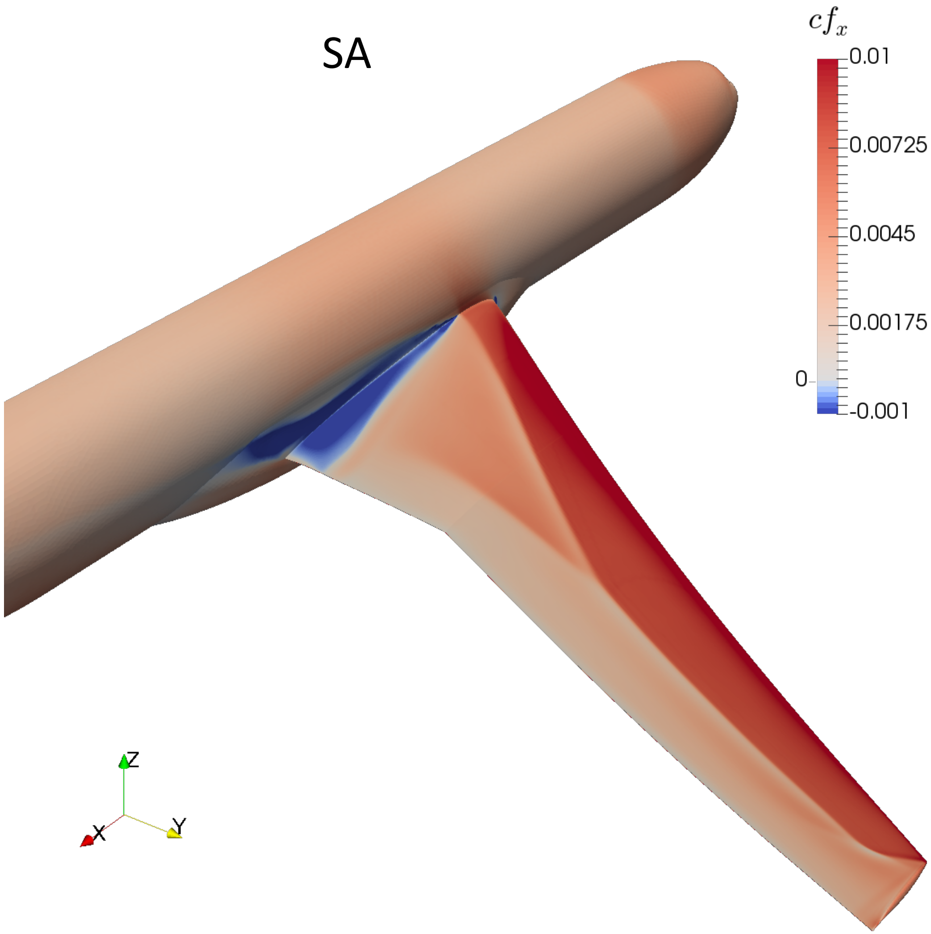


COFFE Results – Alpha 3.25, Cf_x

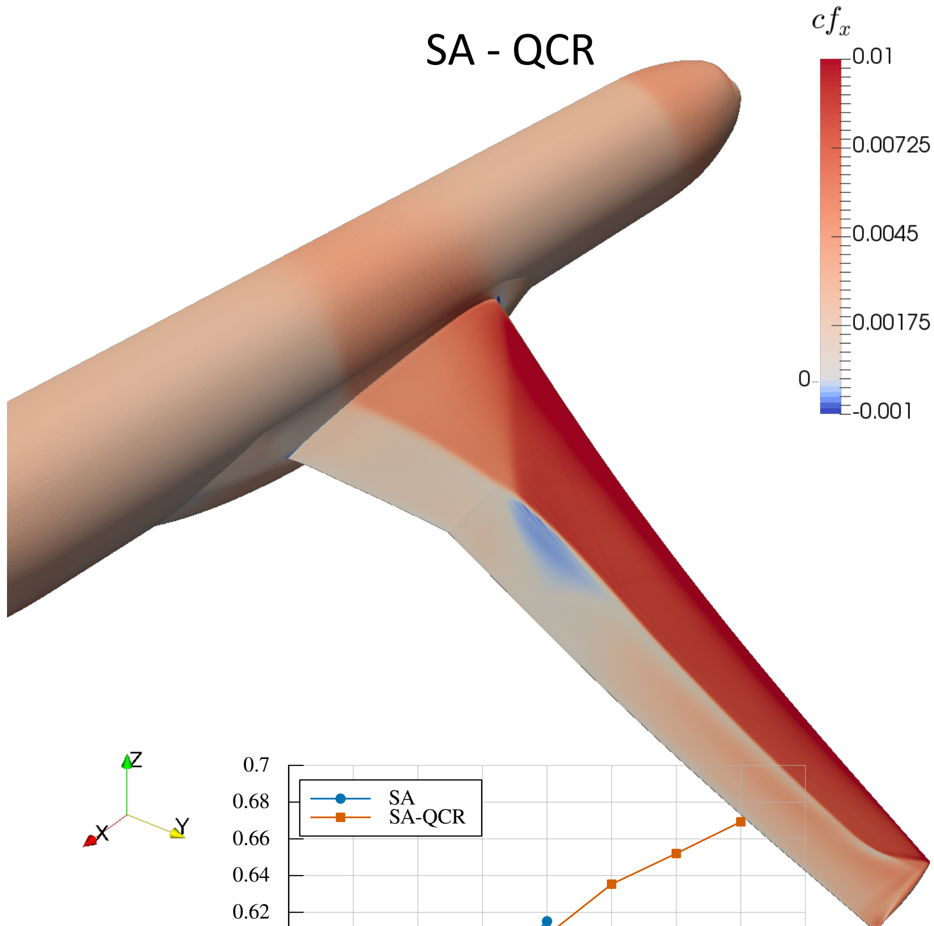


COFFE Results – Alpha 3.5, Cf_x

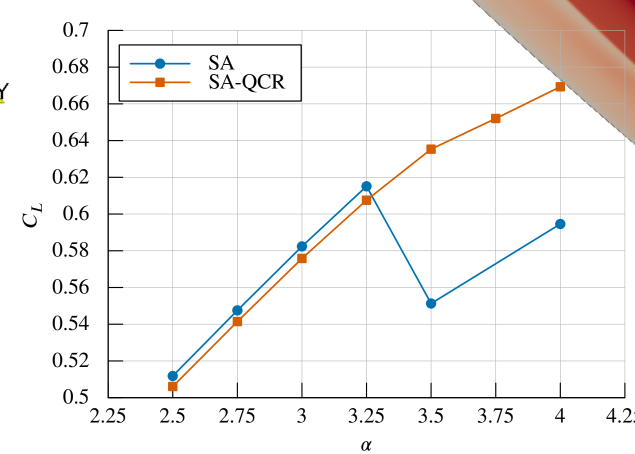
SA



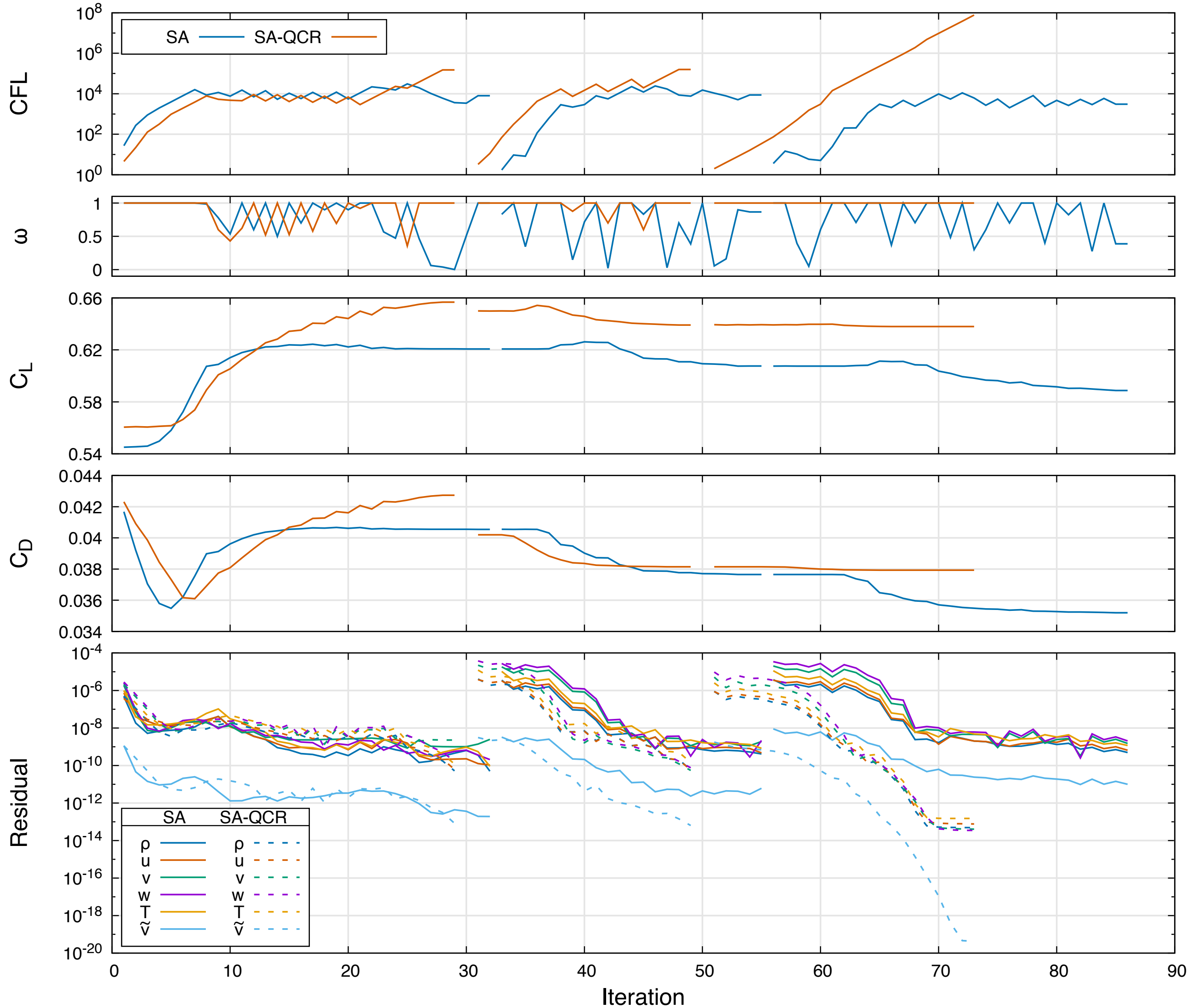
SA - QCR



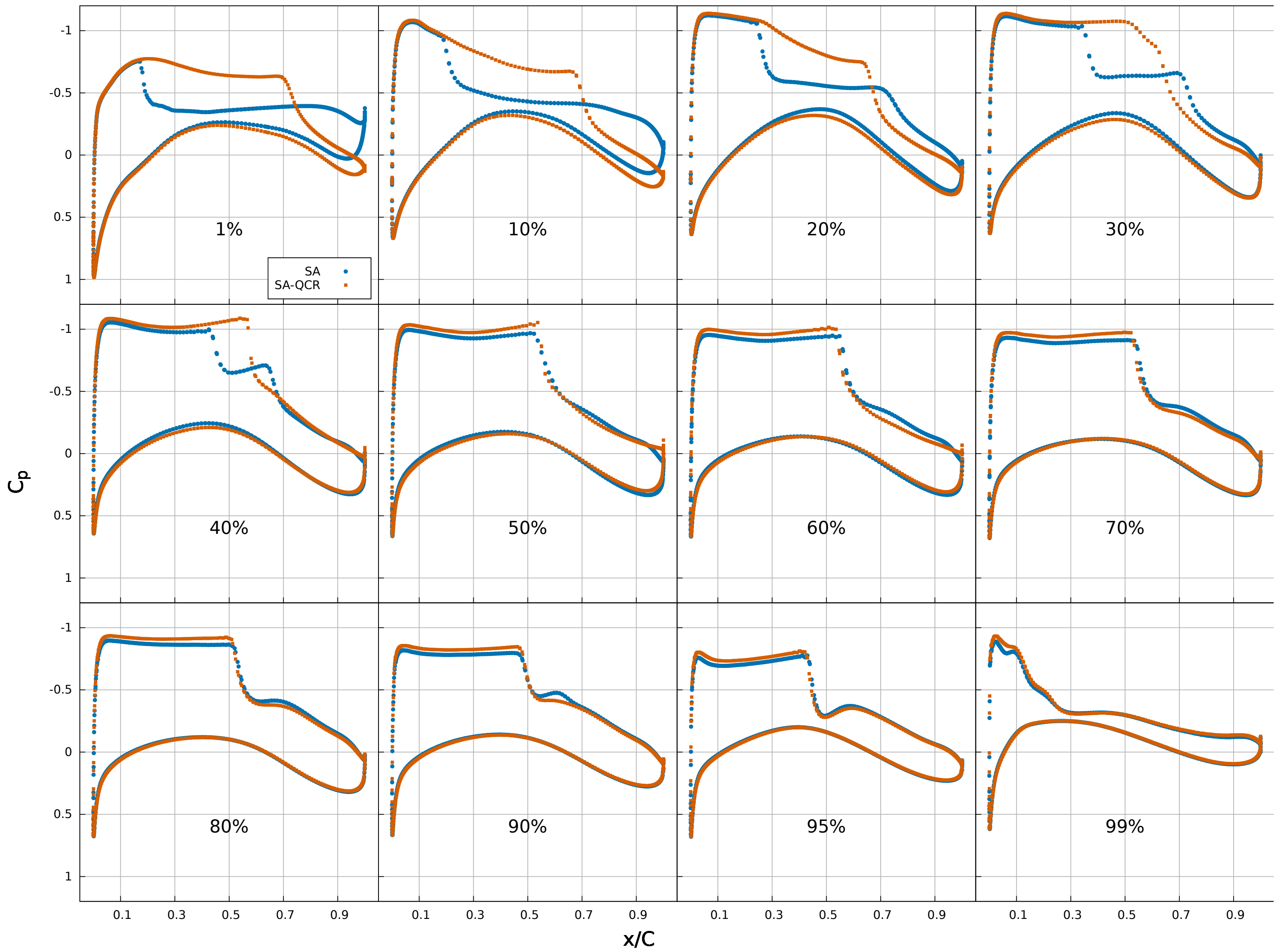
- Shock/Separation Bubble interaction
- Accuracy/Mesh Convergence
- Nonlinear Convergence



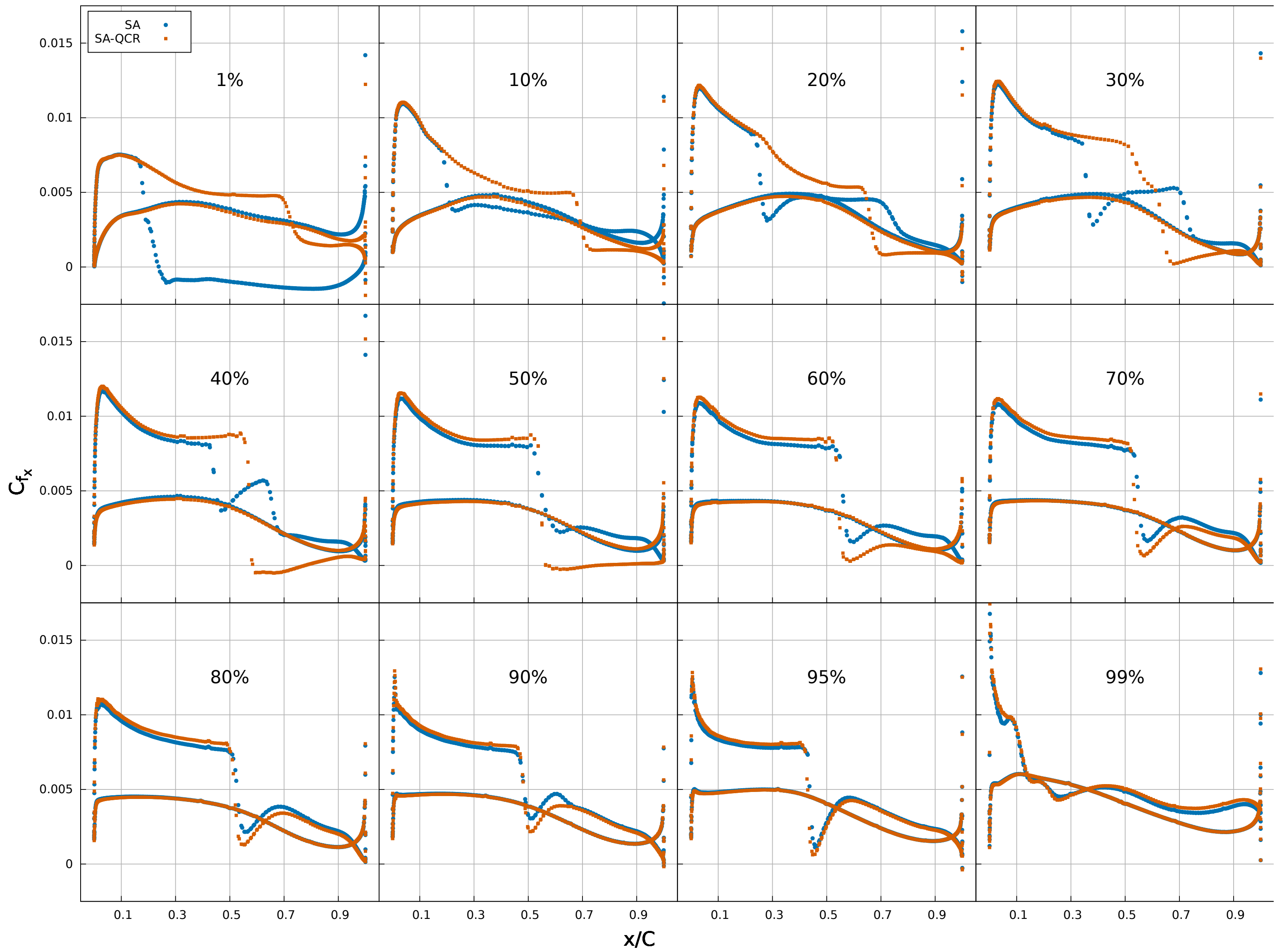
COFFE Results – Alpha 3.5



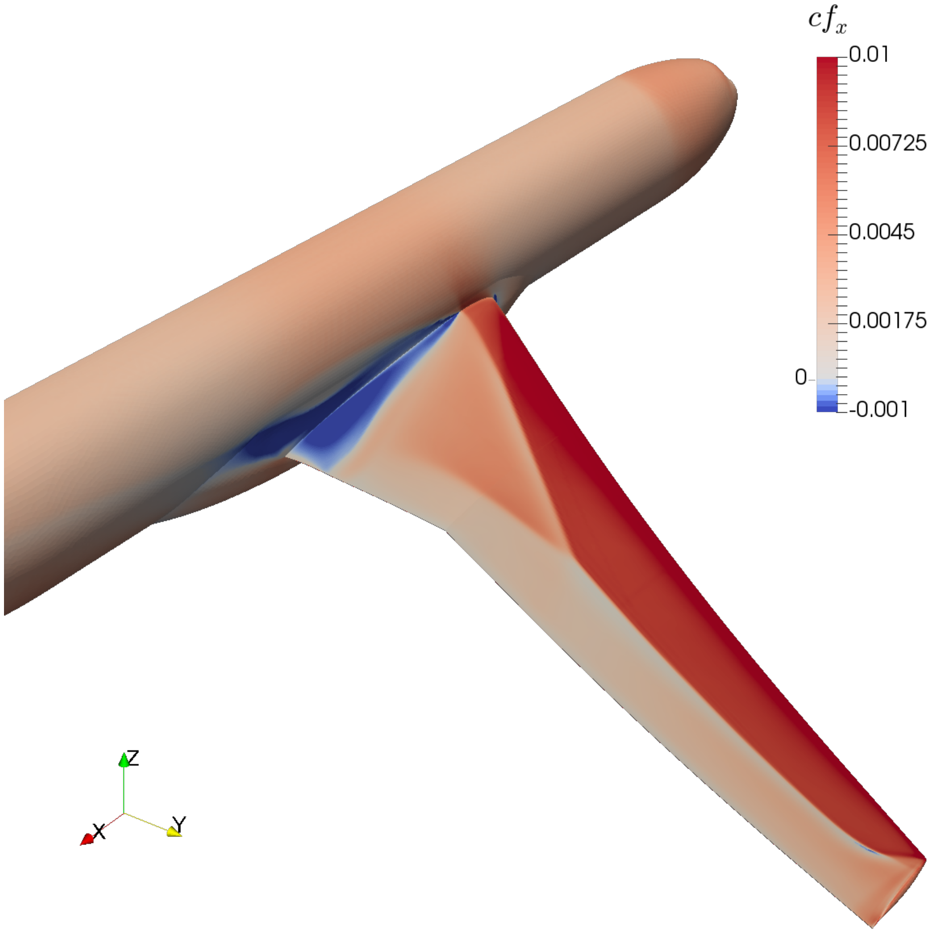
COFFE Results – Alpha 3.5, Cp



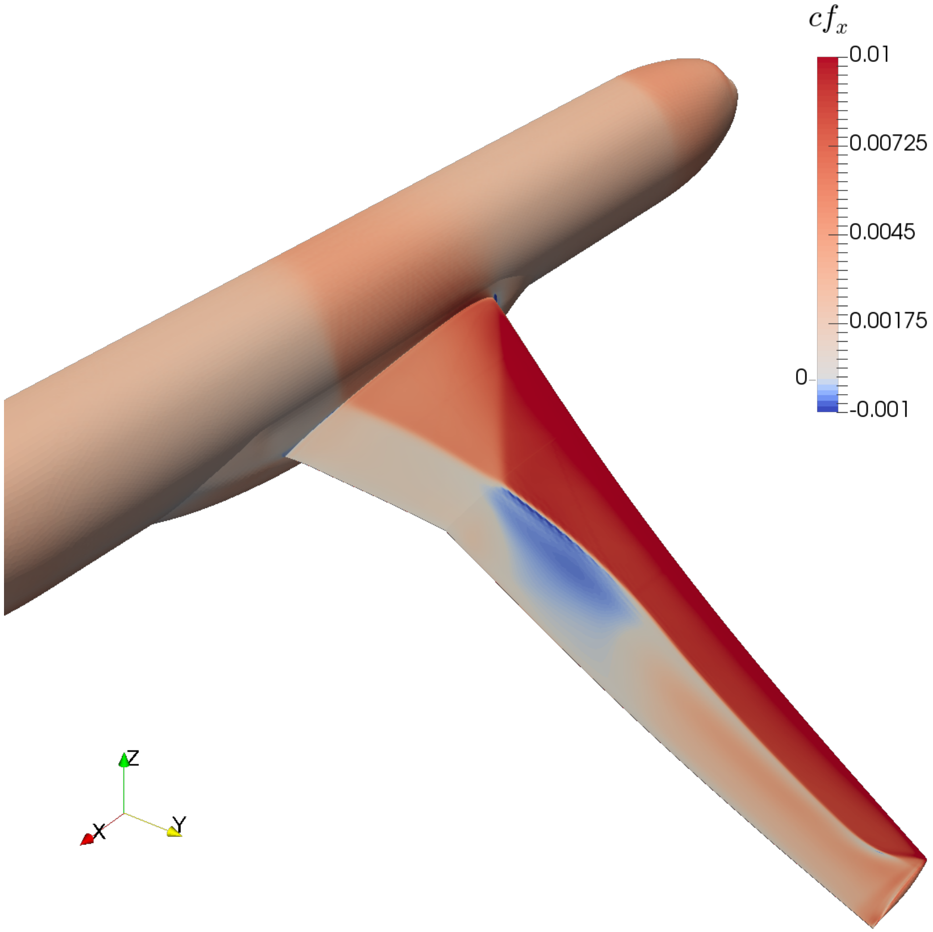
COFFE Results – Alpha 3.5, Cf_x



COFFE Results – Alpha 4.0, Cf_x

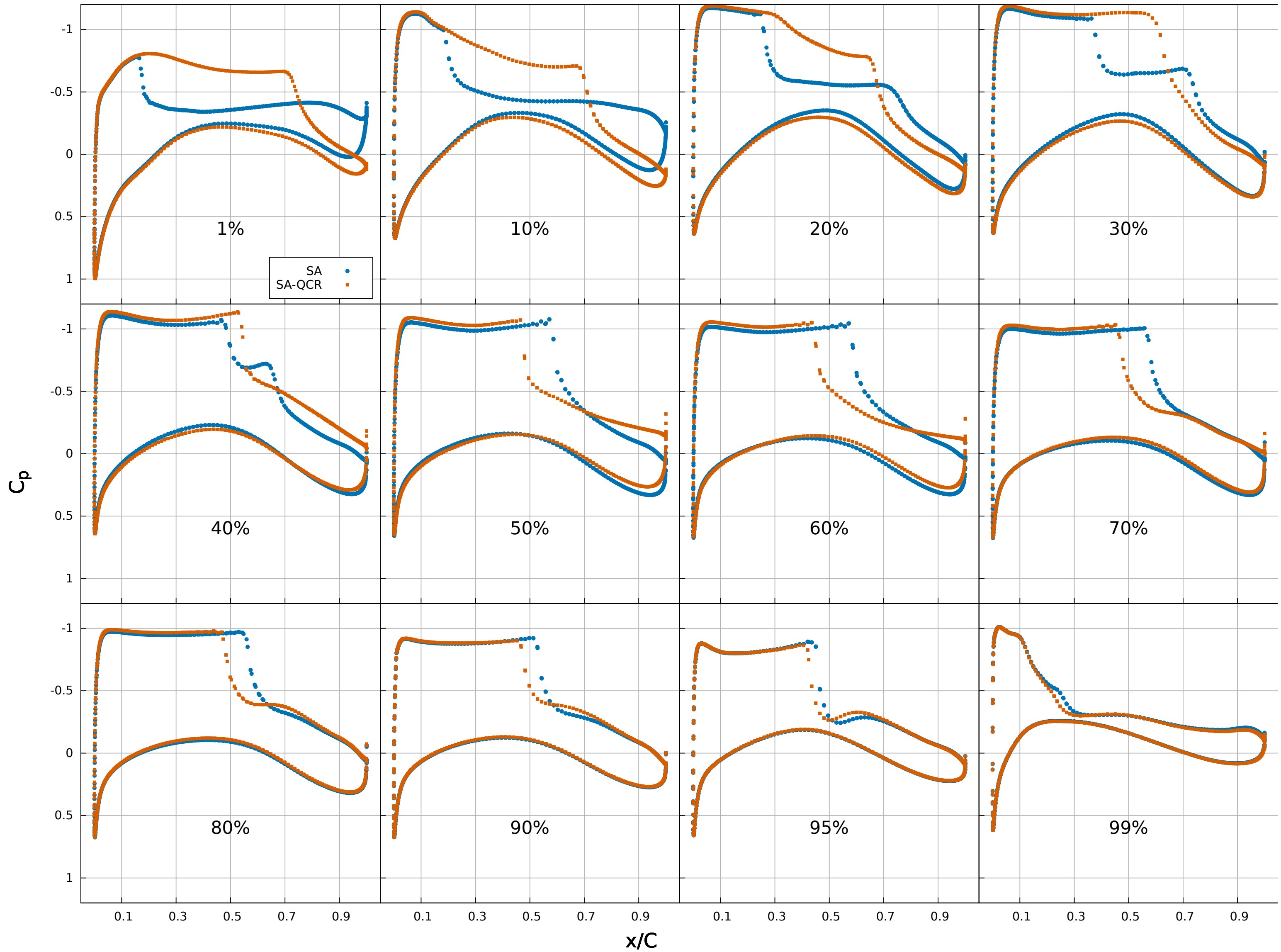


SA

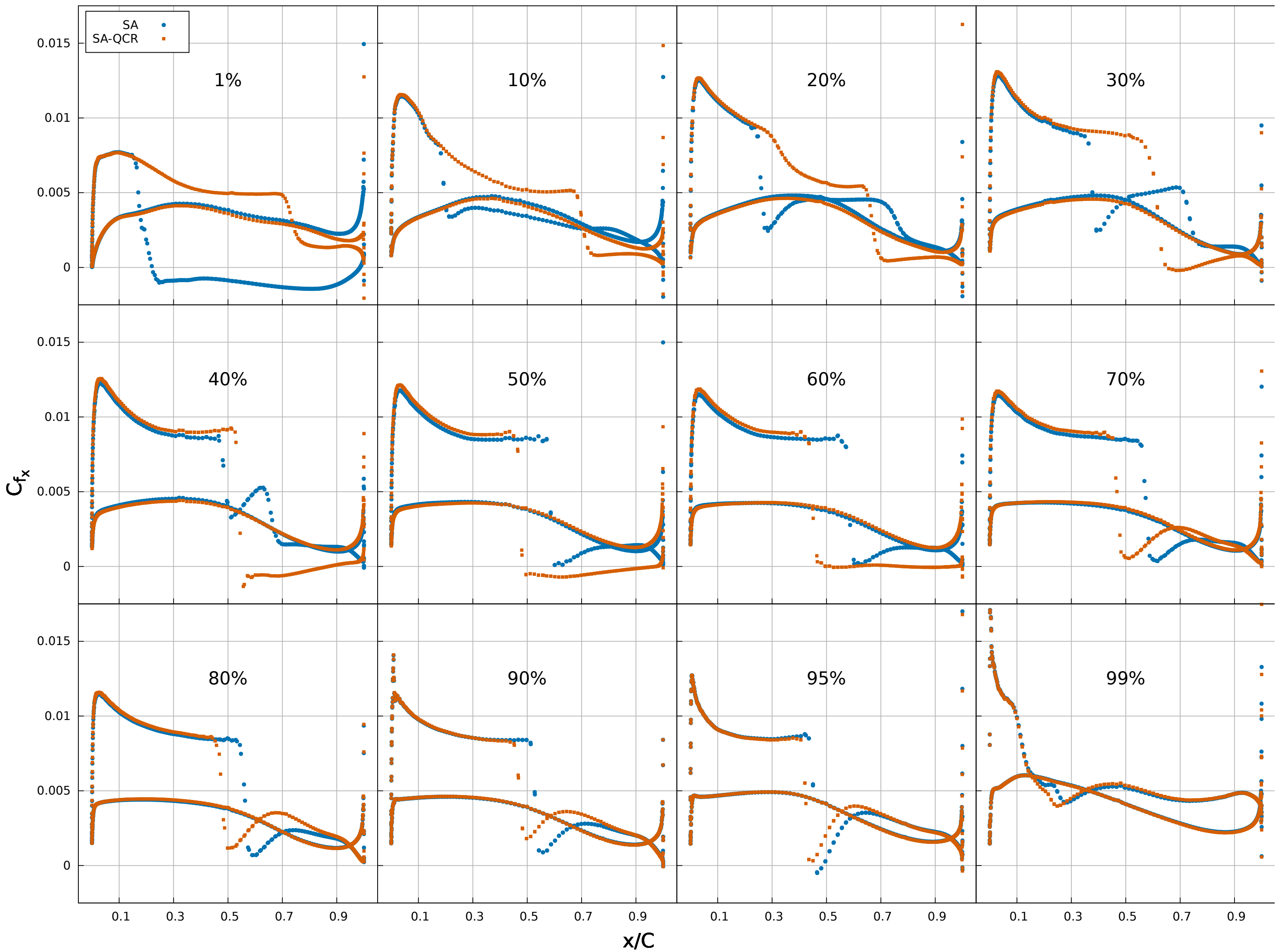


SA - QCR

COFFE Results – Alpha 4.0, Cp

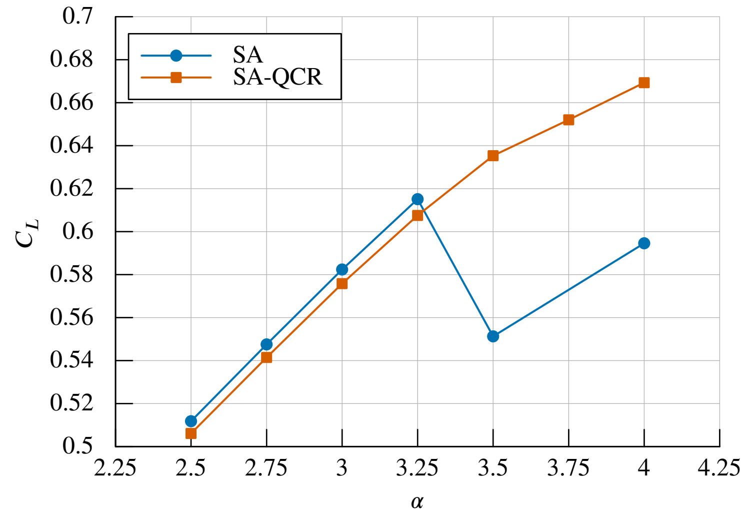


COFFE Results – Alpha 4.0, Cf_x



Conclusions

- **High quality tetrahedral meshes without large angles generated by Steve Karman with Pointwise software**
- **Task 2/3 Cases generally took ~2-3 hours**
- **Subdomain decomposition with ~11,000 nodes per process**
- **Difference in mesh converged for task 2 C_D for P2 WB and WBNP ~ 0.0023**
- **SA-QCR improved the CL/CD vs. alpha polar for task 3**



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