



RANS Test Suite of High-Fidelity CFD Verification Workshop (Hi-Fi CFDVW) 2024:

Summary of Test Case 3 Solutions for Common Research Model High-Lift Wing-Body (CRM-HL-WB) Configuration with SA-neg-QCR2000-R($C_{rot}=1$) Turbulence Model

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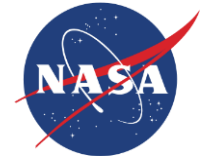
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AIAA High-Fidelity CFD Verification Workshop 2024

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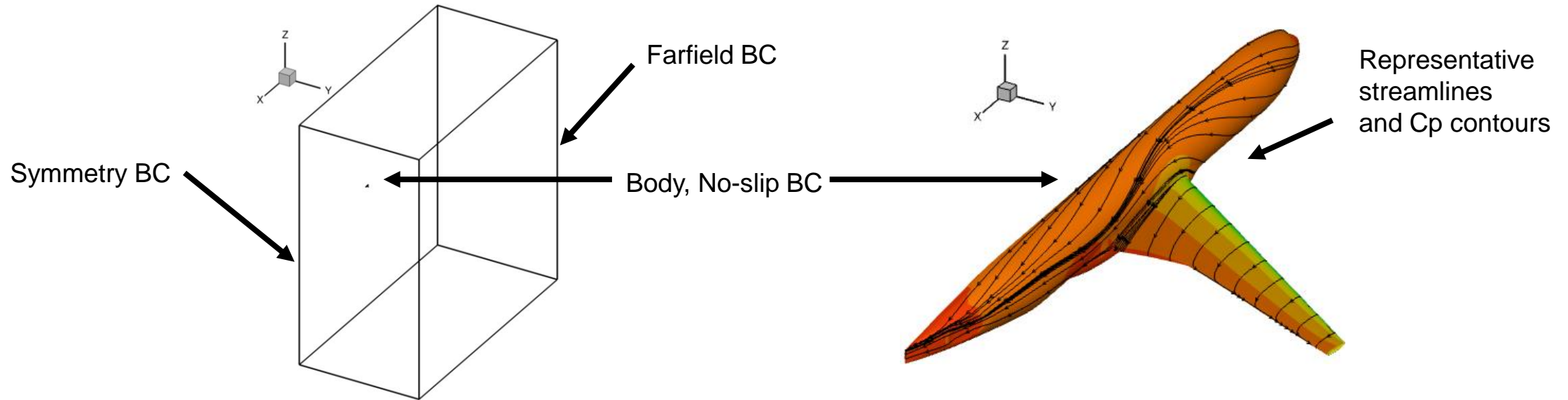


Outline

- Statistics of Submitted Solutions
- Convergence Requirements
- Overview of Solutions
- Separation patterns
- Summary

CRM High-Lift Wing-Body (CRM-HL-WB) Configuration

$$M_{\infty} = 0.2, \alpha = 11^{\circ}, Re_c = 5.6 \times 10^6$$

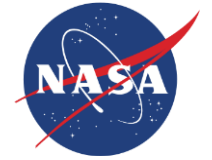


- Hi-Fi CFDVW Test Case 3:

- Common case with Fifth High-Lift Prediction Workshop (HLPW-5)
<https://hiliftpw.larc.nasa.gov/Workshop5/>

- 8 groups submitted solutions with SA-neg-QCR2000-R(Crot=1)

- Government labs, major aerospace companies, academic institutions, commercial software developers, and small businesses
- 12 independent sets of solutions



Discretizations and Grids

- Discretization approaches

- Node-centered, finite-volume, 2nd order (3 groups, 6 sets)
- Cell-centered, finite-volume, 2nd order (3 solvers, 4 sets)
- Node-centered, continuous finite-element, 2nd order (1 solver, 1 set)
- Node-centered, continuous finite-element, high order (1 solver, 1 set)

- Fixed-grid families

- 1.R.01 POINTWISE (PW), mixed-element (3 solvers, 3 sets)
- 1.R.03, 1.R.05, 1.R.07 HELDENMESH (HM), mixed-element (4 solvers, 5 sets)
- 1.L.01(2) ANSA hex dominant (1 solver, 1 set)
- 1.H.04(4) ANSA high-order grids (1 solver, 1 set)
- Solution adapted grids (2 solvers, 2 sets)



Fixed-Grid Statistics

Pointwise 1.R.01 Family

Grid Identifier	Nodes	Cells
1v	956.2K	2.6M
3v	5.3M	12.8M
5v	15.4M	36.1M
7v	34.0M	78.0M
9v	63.4M	143.9M
11v	106.5M	239.8M
13v	165.4M	370.5M
15v	242.6M	541.4M
17v	340.6M	757.9M

ANSA 1.H.04(4) Family

Grid Identifier	DOFs	Cells
A	7.0M	5.0M
B	19.8M	14.2M

HeldenMesh 1.R.03 Family

Grid Identifier	Nodes	Cells
C	1.1M	2.7M
M	7.6M	18.4M
F	58.1M	136.0M

ANSA 1.L.01(2) Family

Grid Identifier	Nodes	Cells
A	5.8M	7.0M
B	14.0M	16.1M
C	37.5M	42.0M
D	73.1M	80.5M
E	187.5	202.4M

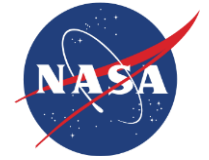
HeldenMesh 1.R.05 Family

Grid Identifier	Nodes	Cells
C	0.9M	2.6M
M	5.8M	17.8M
F	42.9M	131.0M
R	331.2M	1.01B

HeldenMesh 1.R.07 Family

Grid Identifier	Nodes	Cells
Coarse	5.0M	12.0M
Medium	13.4M	31.2M
Fine	38.9M	87.1M
XFine	105.6M	232.4M
UFine	191.0M	415.1M

- 1.R.01 is initial grid family, an improved PW family
1.R.08 has been generated later
- 1.R.03 and 1.R.05 generated by Helden Aerospace,
1.R.07 independently generated at NASA LaRC
- 1.H.04(4) is a high-order (Q2) tetrahedral grids
- 1.L.01(2) is hex-dominated grid generated for
HRLES solutions

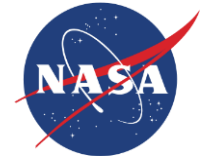


Solution Nomenclature

Code	Discretization method	Hi-Fi ID	HLPW-5 ID	Grids
FUN3D, NASA LaRC	FV NC 2 nd order	01.1	R-001.3	1.R.01 (1v – 13v)
		01.2	R-001.2	1.R.03 (C, M, F)
GGNS-T1/EPIC, Boeing	FEM NC 2 nd order	02	A-003	Adapted
USM3D-ME, NASA LaRC	FV CC 2 nd order	03.1	R-003.4	1.R.05 (C, M, F, R)
		03.2	R-003.2	1.R.07 (Coarse – UFine)
Dragon, Bombardier	FV CC 2 nd order	04	R-008.5	1.R.01 (5v – 11v)
FUN3D, Textron	FV NC 2 nd order	05.1	R-013.1	1.R.01 (1v – 17v)
		05.2	R-013.2	1.R.05 (C, M, F)
CFD++, MetaComp	FV CC 2 nd order	06	N/A	1.L.01(2) (A, B, C, D, E)
Wolf, INRIA	FV NC 2 nd order	07.1	N/A	1.R.05 (C, M, F)
		07.2	N/A	Adapted
COFFE, CREATE-AV	FEM NC High Order P2Q2	08	N/A	1.H.04(4) (A, B)

- FV – finite volume
- FEM – finite element

- CC – cell centered
- NC – node centered

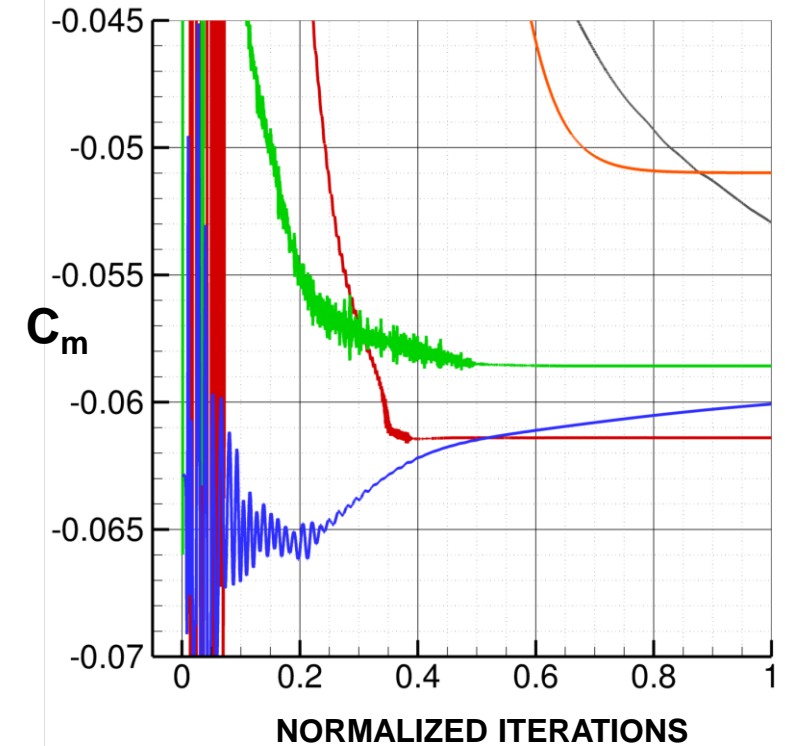
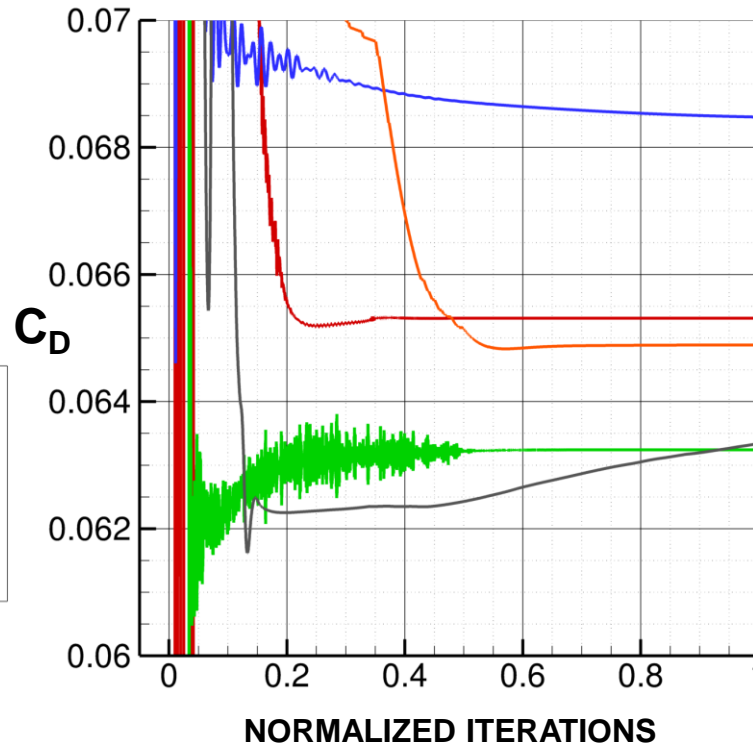
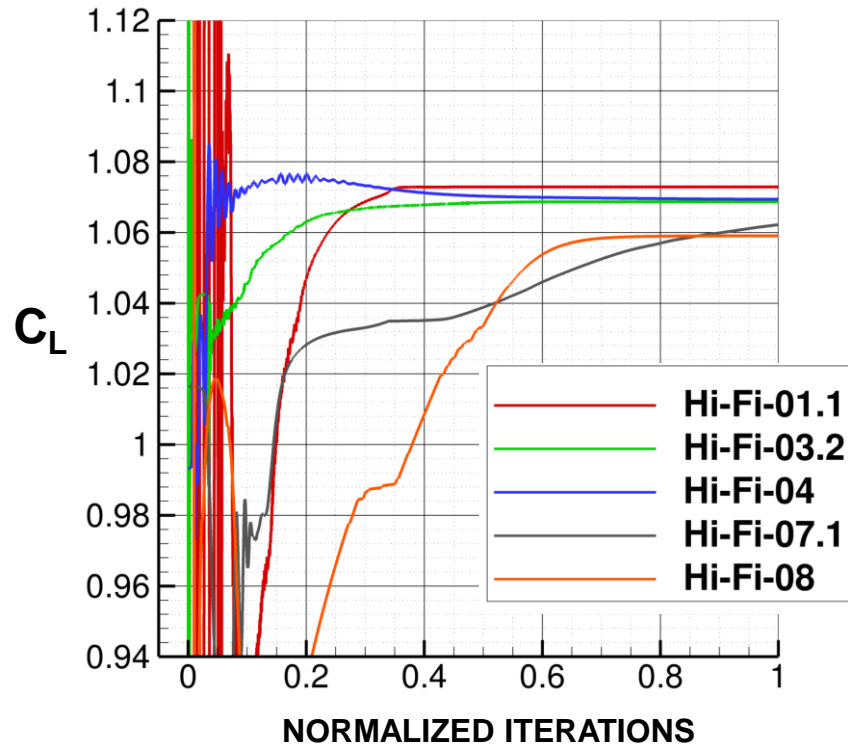


Convergence Requirements

- Iterative convergence criteria
 - Residual reduction below 1E-8 (combined meanflow and turbulence model residual)
 - Residual reduction 7 orders from maximum level (combined meanflow and turbulence model residual)
 - CD, CL, and CM do not change in fourth decimal place in last 1000 iterations
- Grid converged solutions
 - Computed on fine enough grids
 - Satisfied at least one iterative convergence criterion
 - Aerodynamic coefficients are plotted versus characteristic mesh size $N^{(-1/3)}$
 - ✓ N is grid degrees of freedom (e.g., nodes for node-centered solutions, cells for cell-centered solutions)

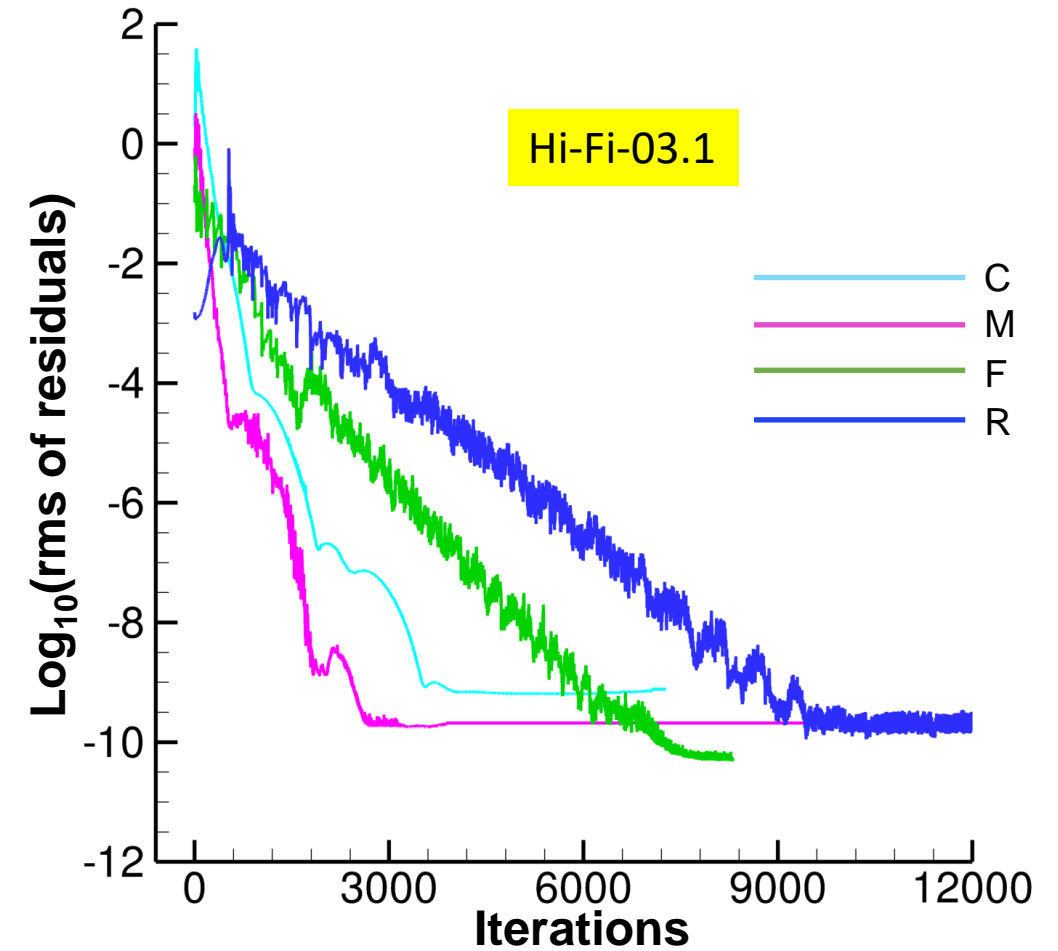
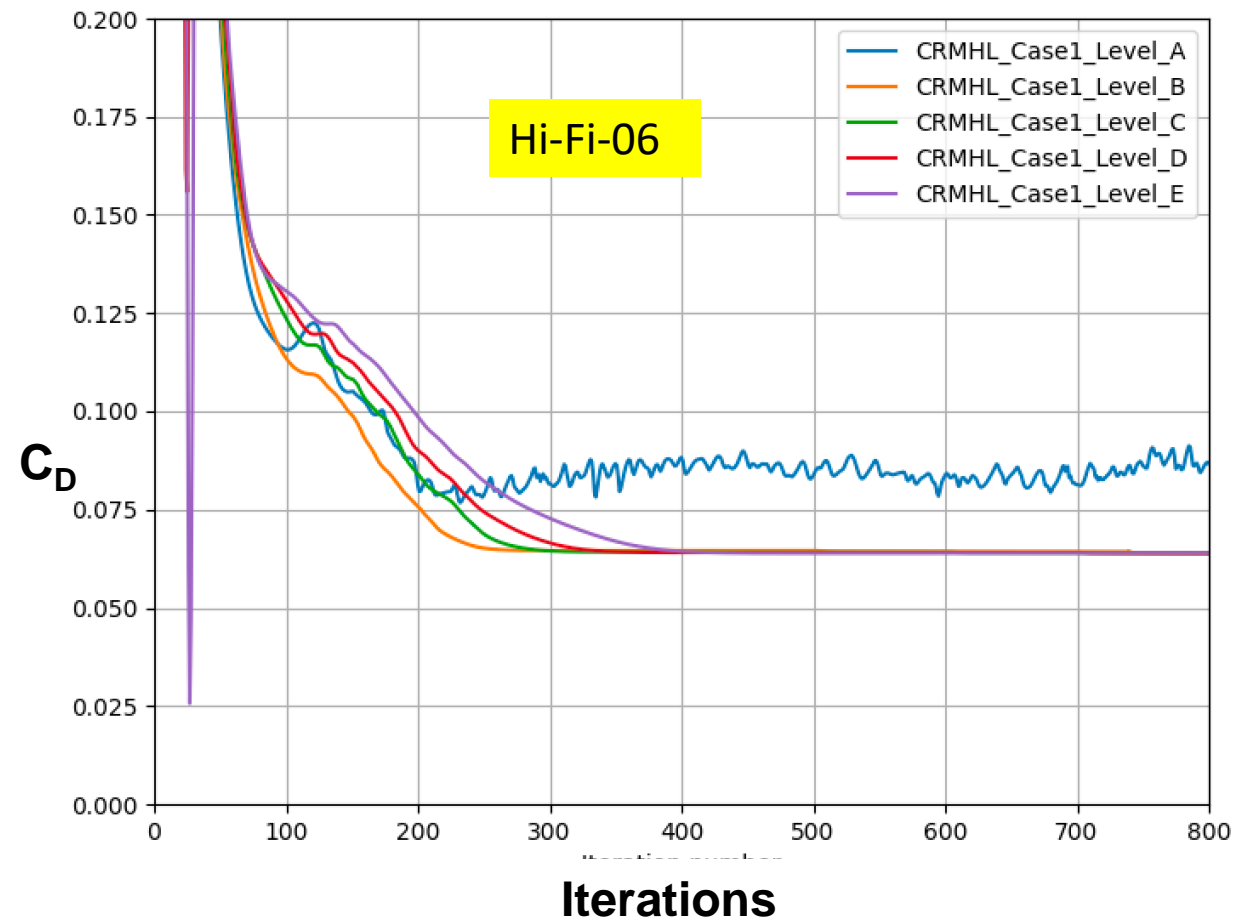


Overview of Solutions

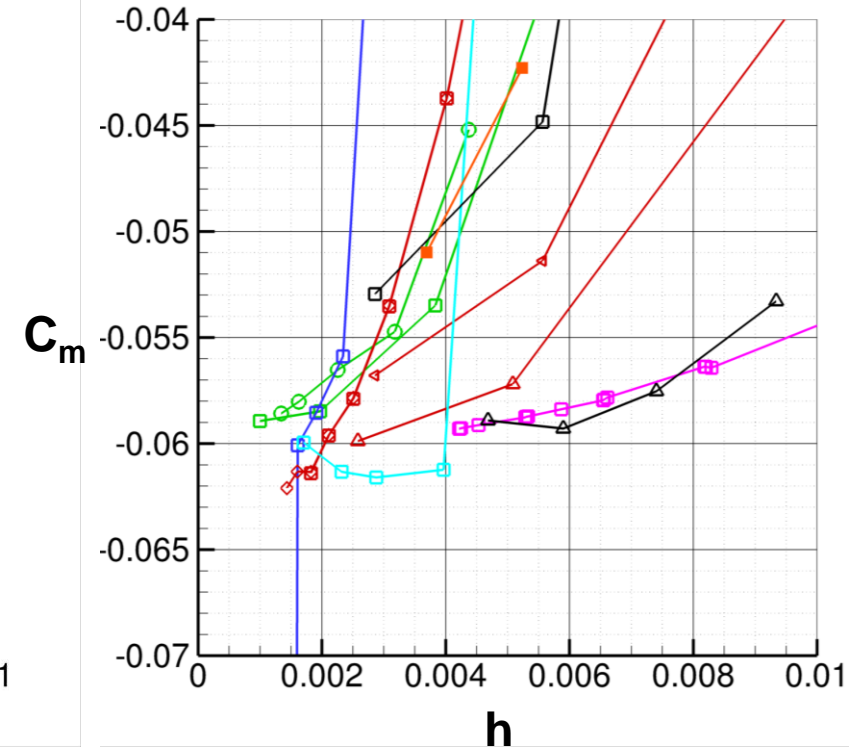
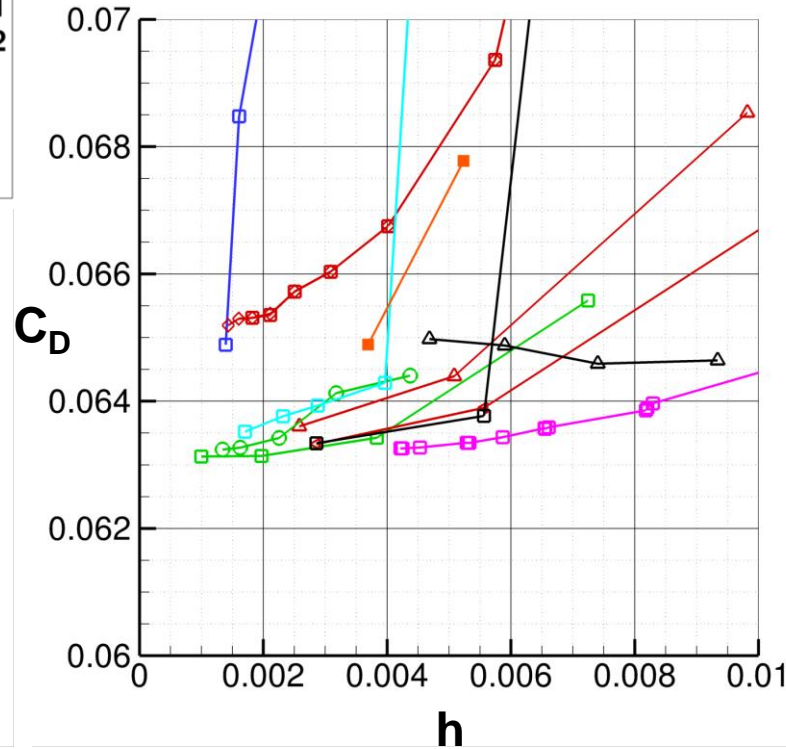
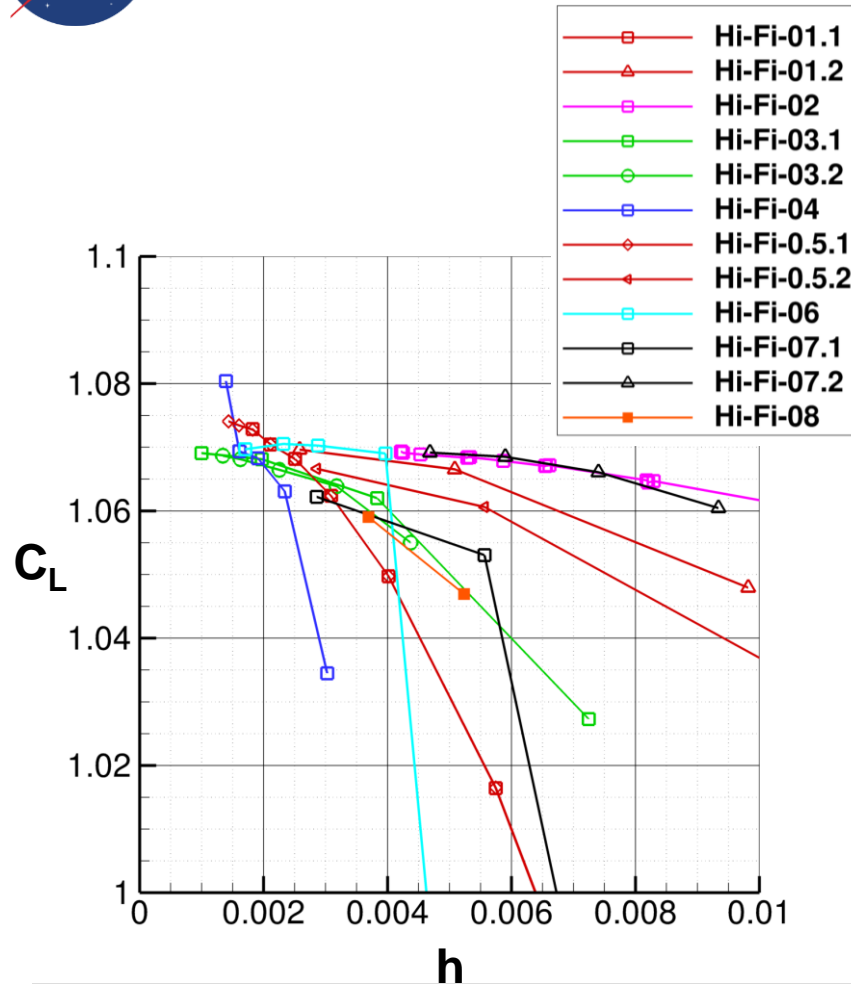


- Only five submissions provided quantitative iterative convergence data
- Visual assessment of plot flatness
- Focus on variation over last 20% of iterations on finest submitted grid
 - Hi-Fi-01.1, Hi-Fi-03.2, and Hi-Fi-08 plots appear as sufficiently flat
 - Hi-Fi-04 and Hi-Fi-07.1 solutions would benefit from additional iterations

Examples: Iterative Convergence

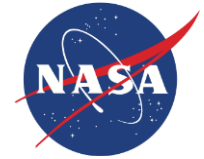


All Solutions: Grid Convergence of CL and CD

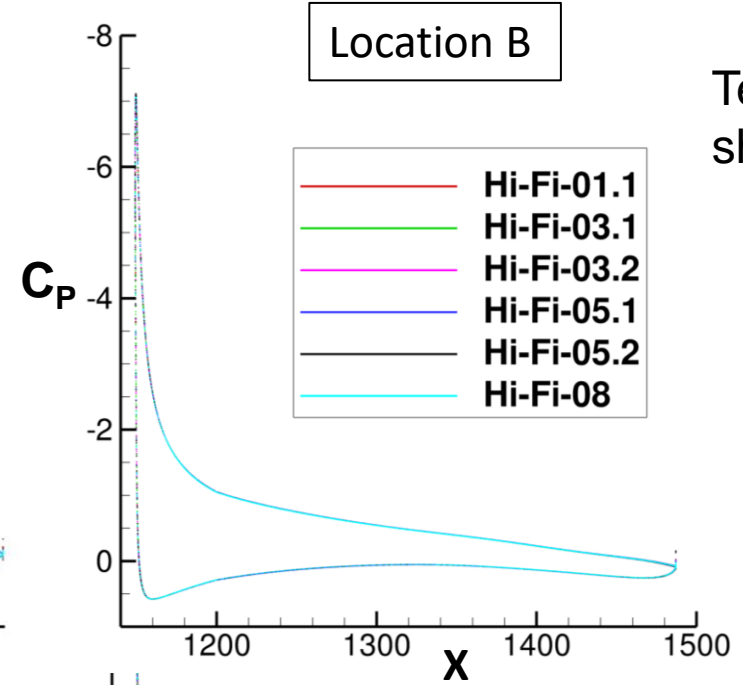
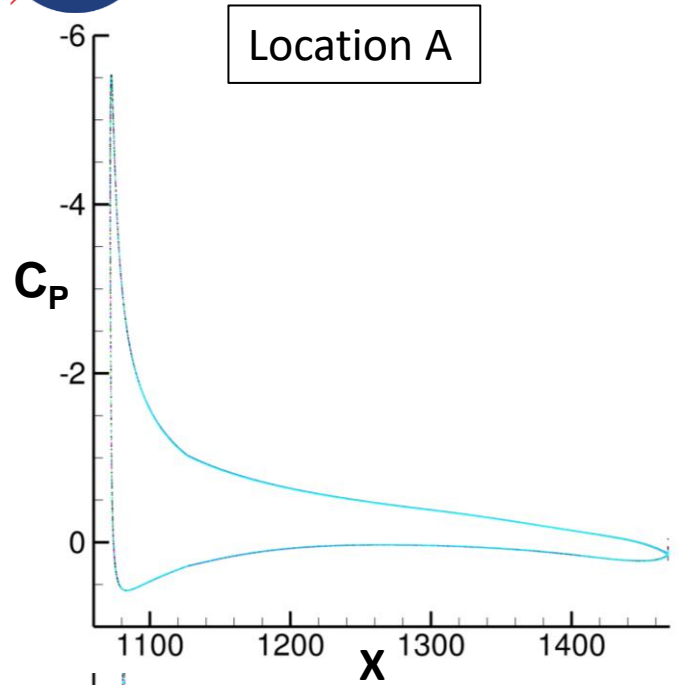


- C_L variation is within 2% range [1.062, 1.081]
- C_D variation is within 20 counts, 3% range [0.063, 0.065]
- C_m variation is within 24% range [-0.063, -0.051]

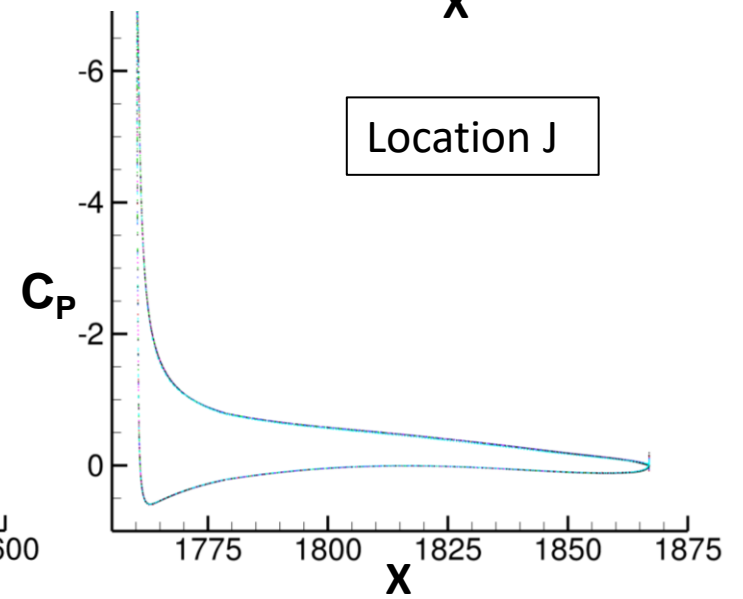
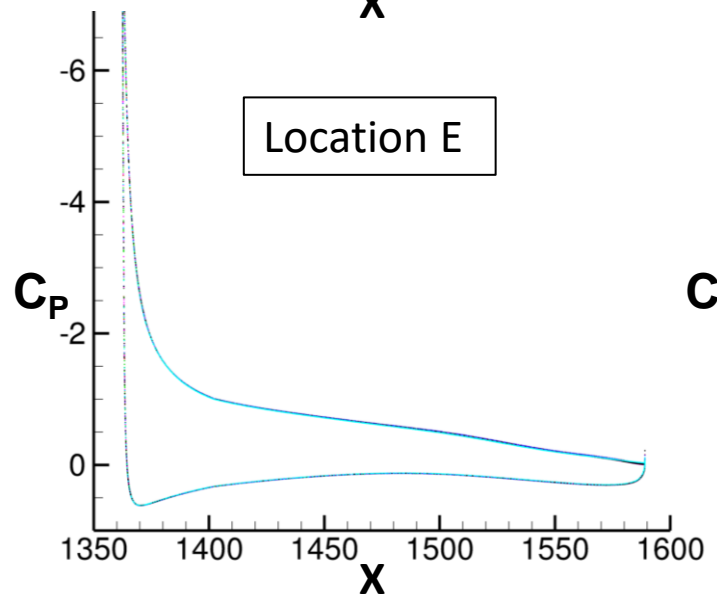
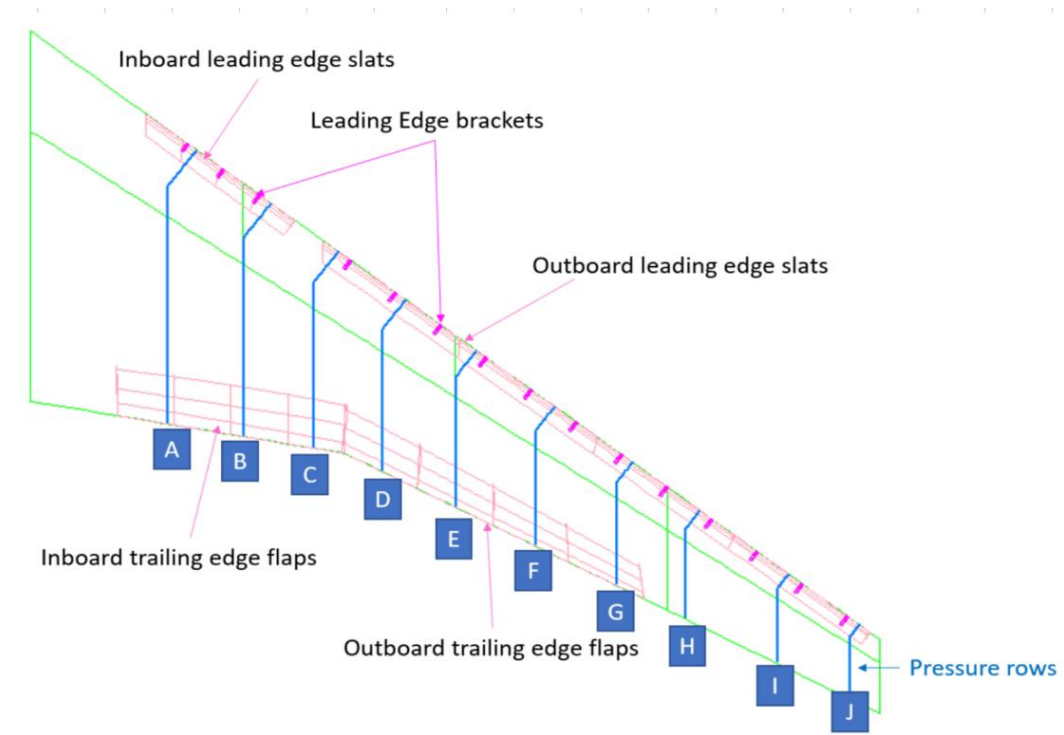
Grid convergence is not observed



All Solutions: Surface Pressure Cuts

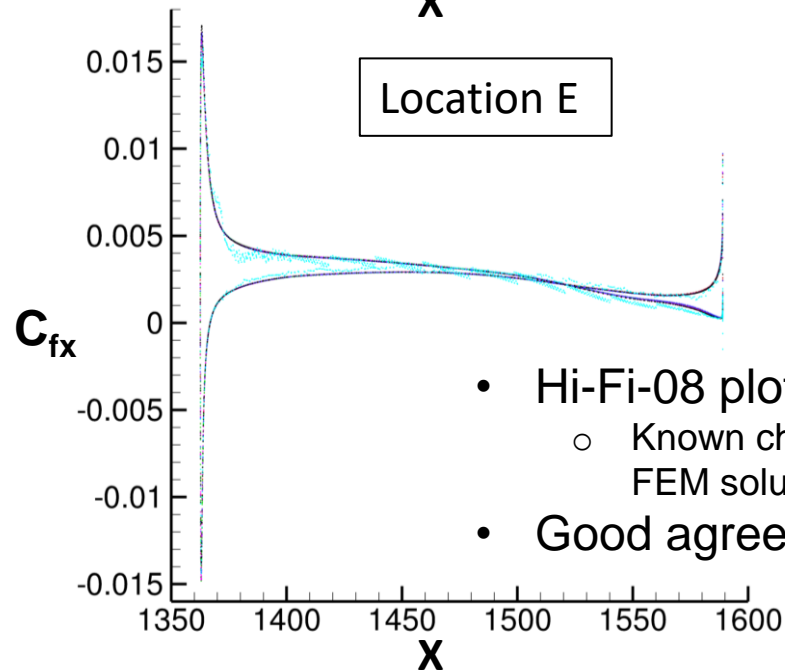
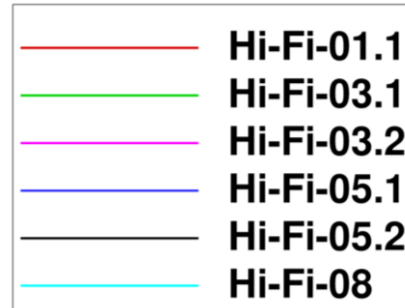
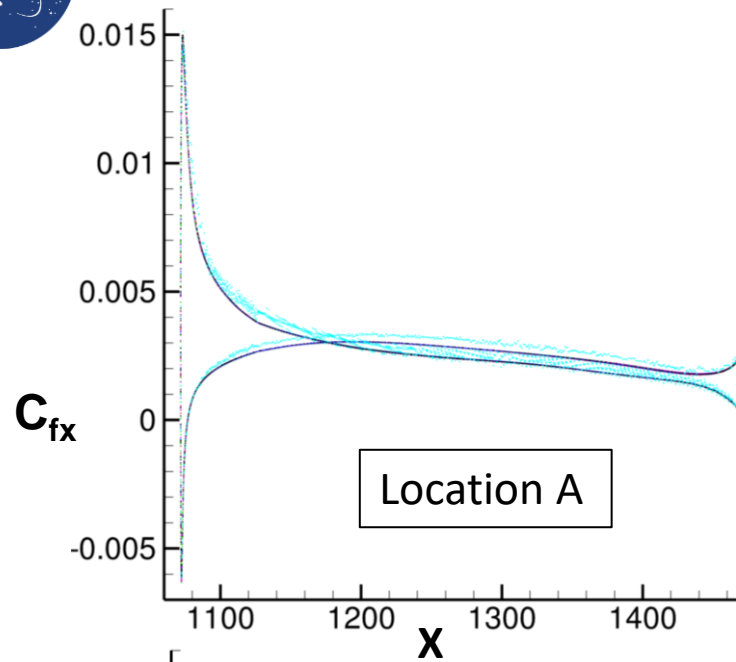


Test Case geometry does not have high-lift devices, shown only for reference

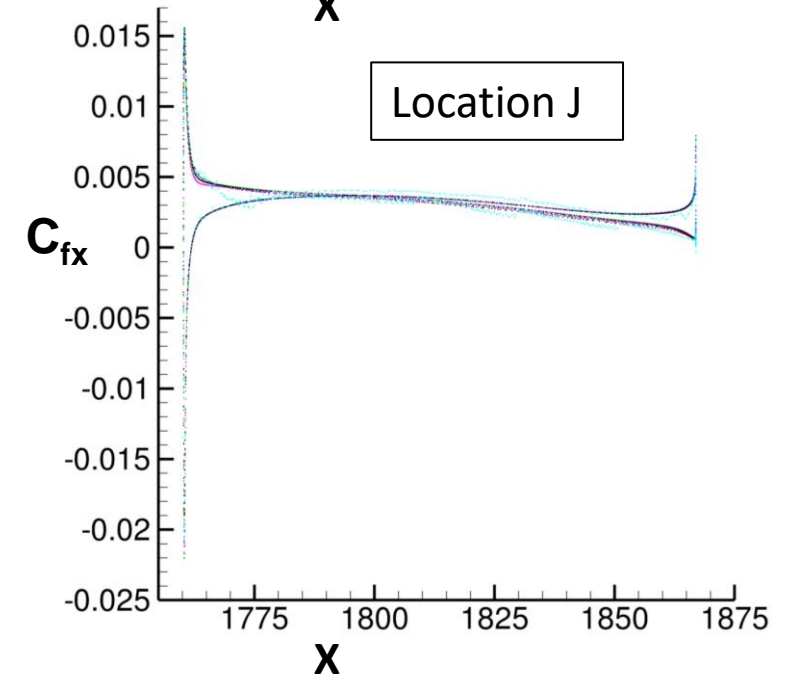
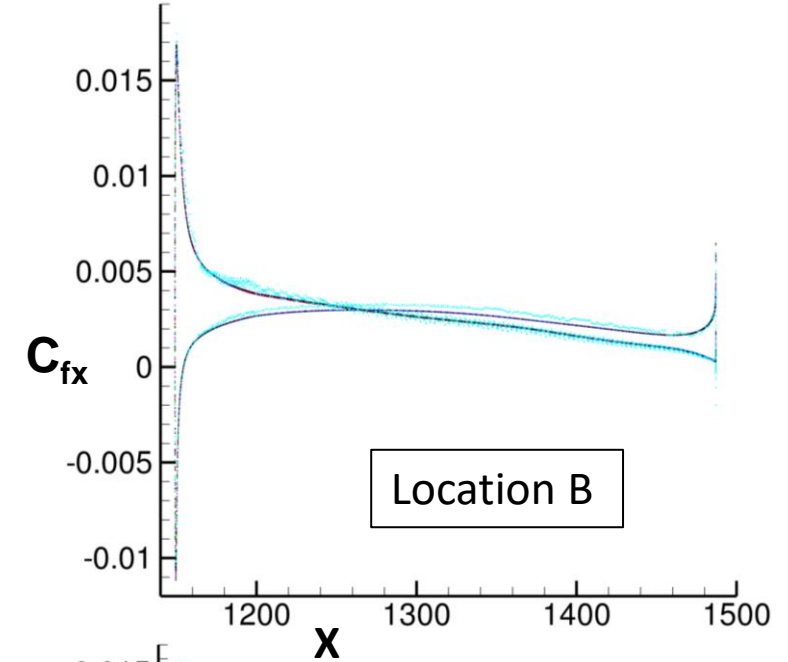


Good agreement between solutions

All Solutions: Skin Friction Cuts



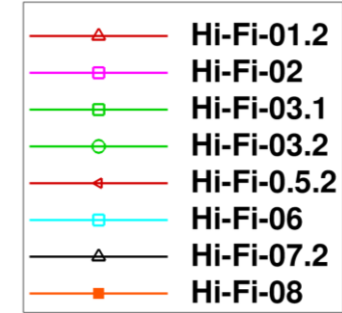
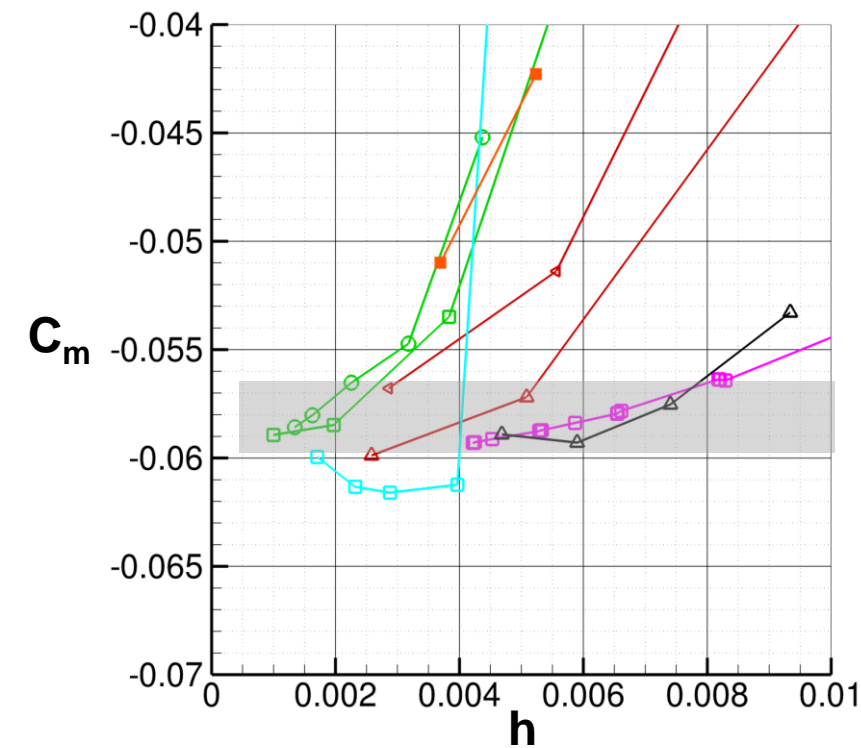
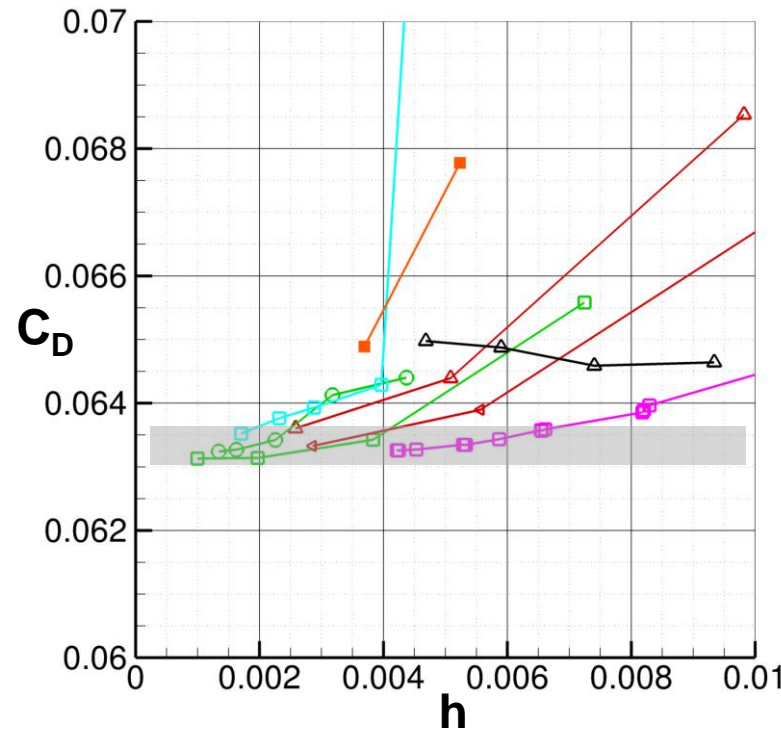
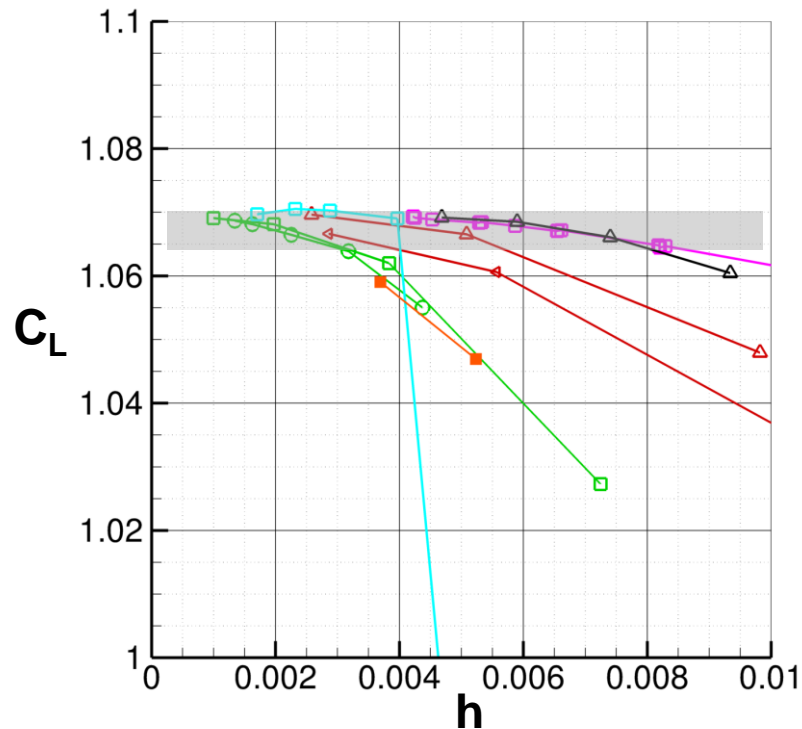
- Hi-Fi-08 plots deviate from other solutions
 - Known challenges for representing skin friction of FEM solutions on under-resolved surface mesh
- Good agreement between FV solutions



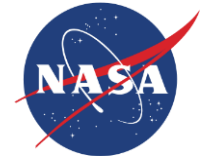
Grid Convergence: Selected Solutions

- Selecting solutions without known deficiencies:
 - Some grid families provide insufficient leading-edge resolution (1.R.01)
 - High-order solutions (Hi-Fi-08) moving in the right direction; too coarse grids
 - Some adapted-grid solutions (Hi-Fi-07.2) insufficiently converged

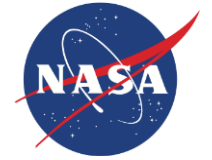
Grid convergence is observed



- C_L variation is within 0.5% range [1.065, 1.070] (shaded)
- C_D variation is within 5 counts, 0.8% range [0.0631, 0.0636] (shaded)
- C_m variation is within 5% range [-0.060, -0.057] (shaded)



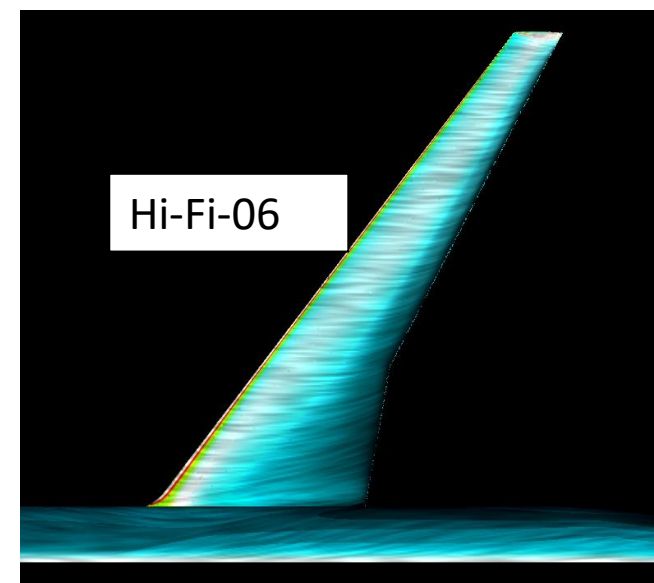
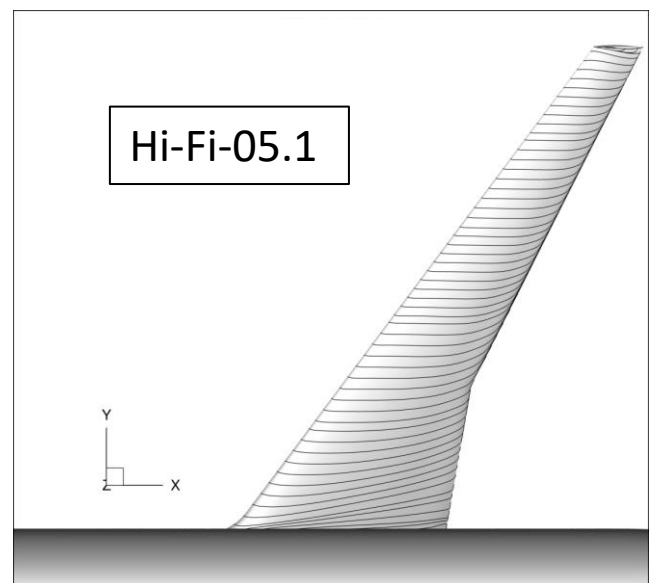
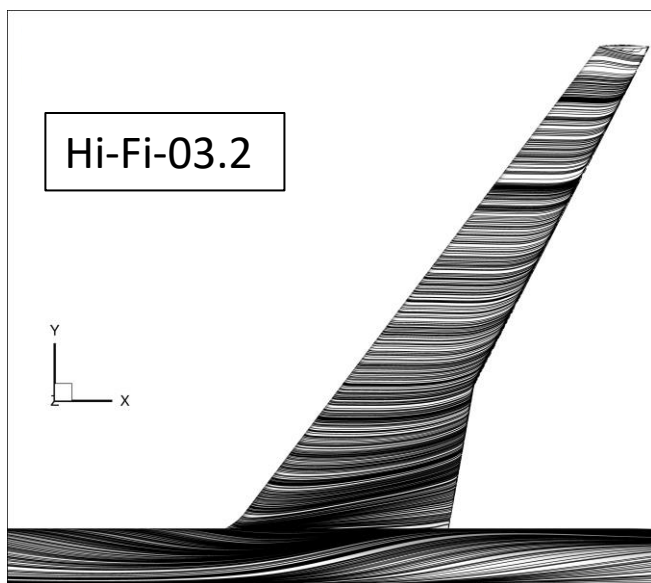
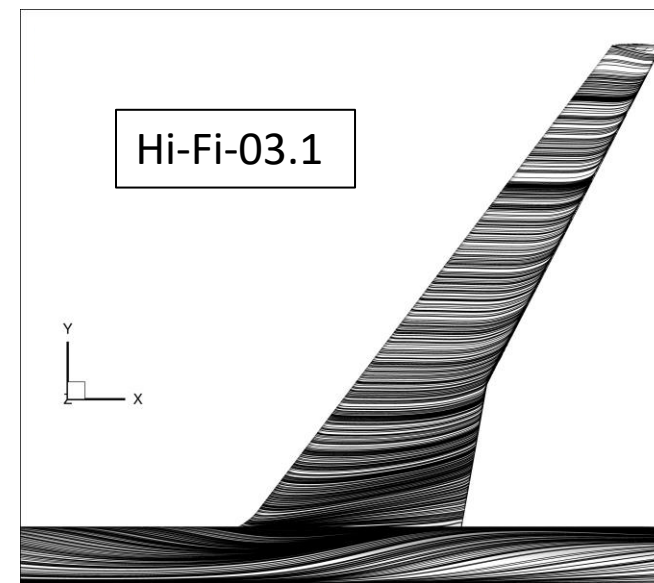
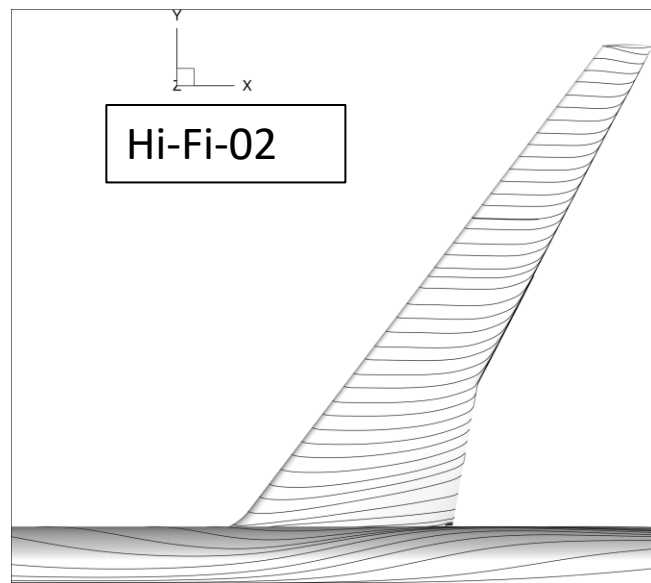
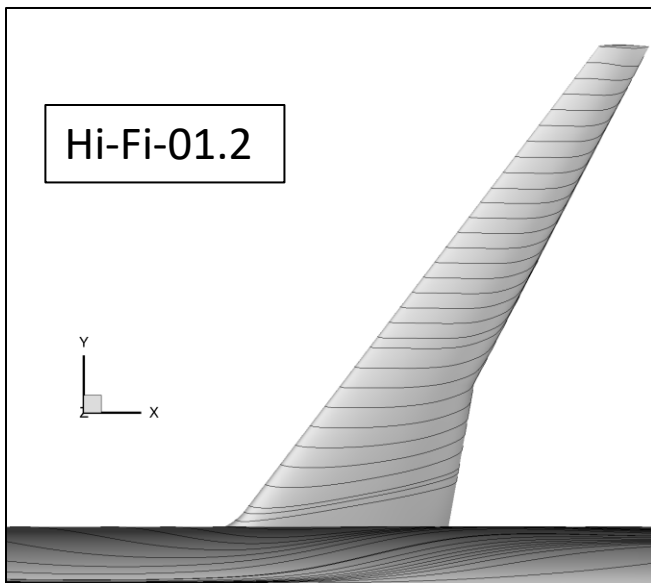
Separation Patterns



Main Trends

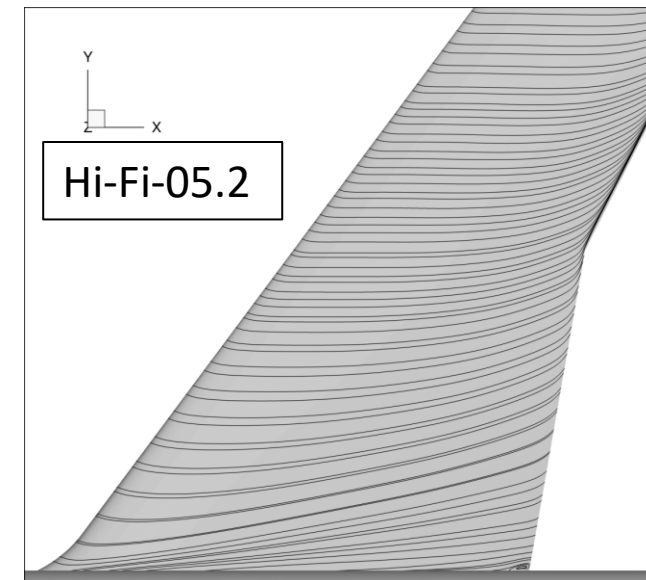
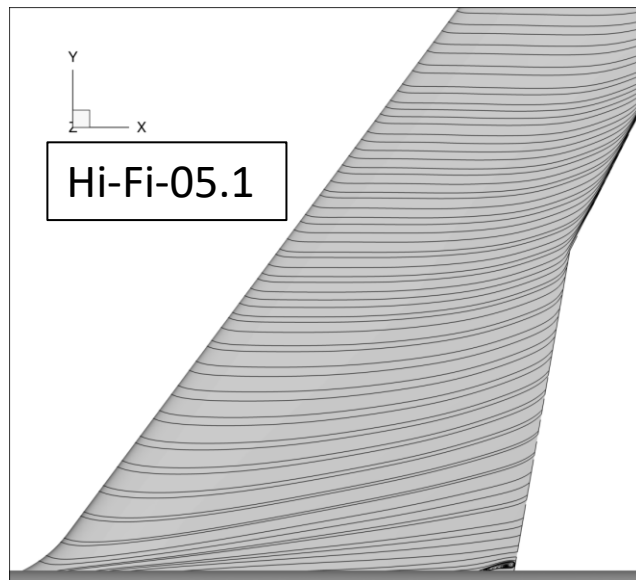
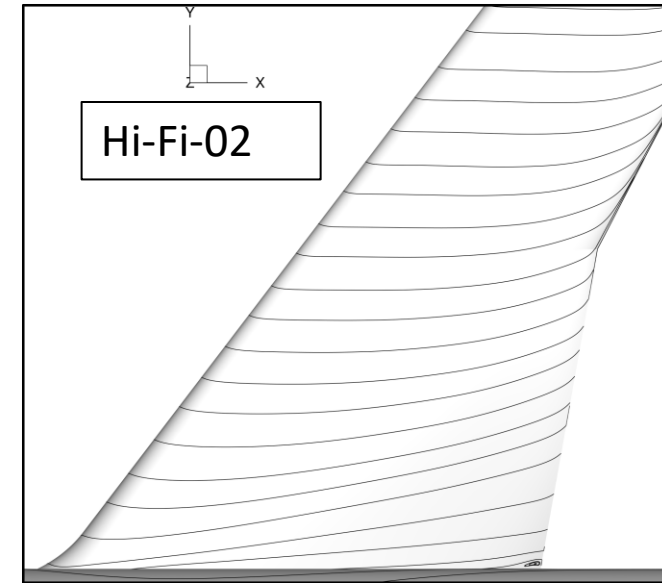
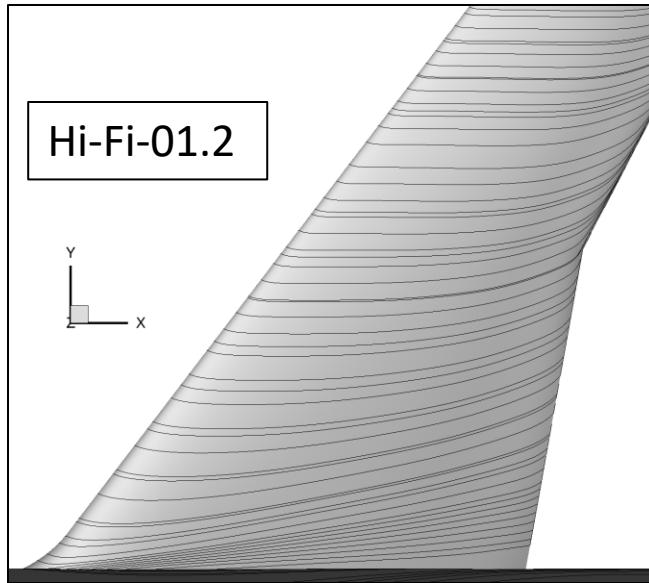
- Many (not all) solutions reported massive separation on coarse grids
 - May be affected by grid inadequate resolution and insufficient iterative convergence
 - There are fully-converged, massively-separated solutions on some coarse grids
- Some solutions observed mild leading-edge separation
- Well-converged fine-grid solutions show small separation
- Four views of streamlines for separation focus
 - CFD View 1 – Global view on upper-surface wing flow
 - CFD View 2 – View of fuselage-wing juncture separation at trailing edge
 - CFD View 4 – View of wing-tip separation
 - CFD View SP1.1 – View of midspan trailing-edge separation

CFD View 1
Global view of flow over upper wing surface



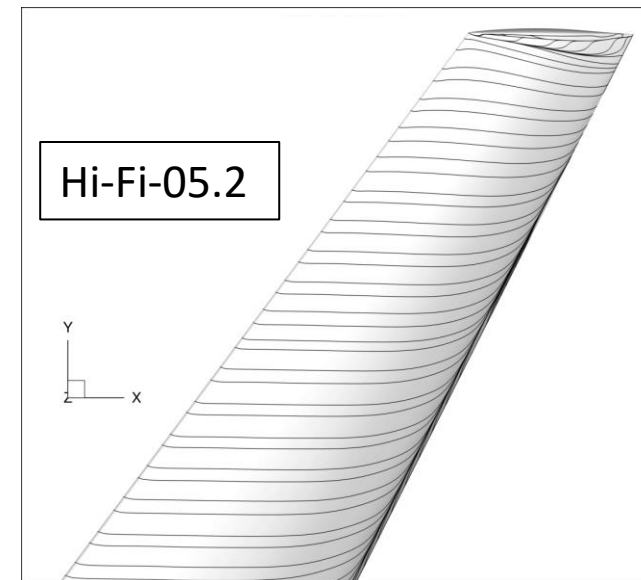
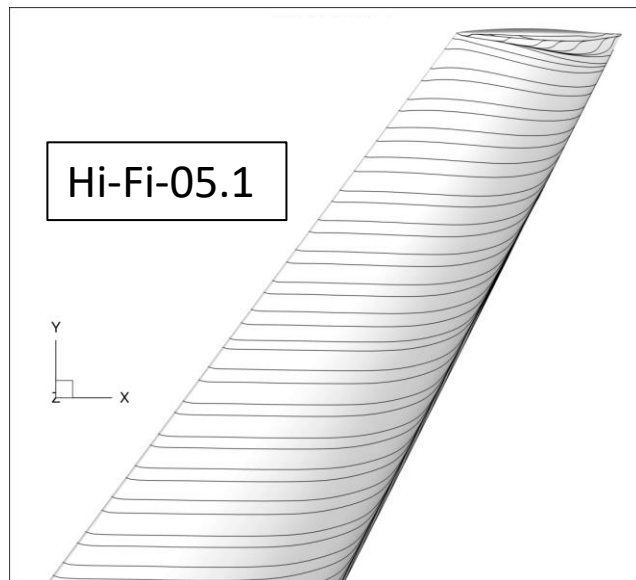
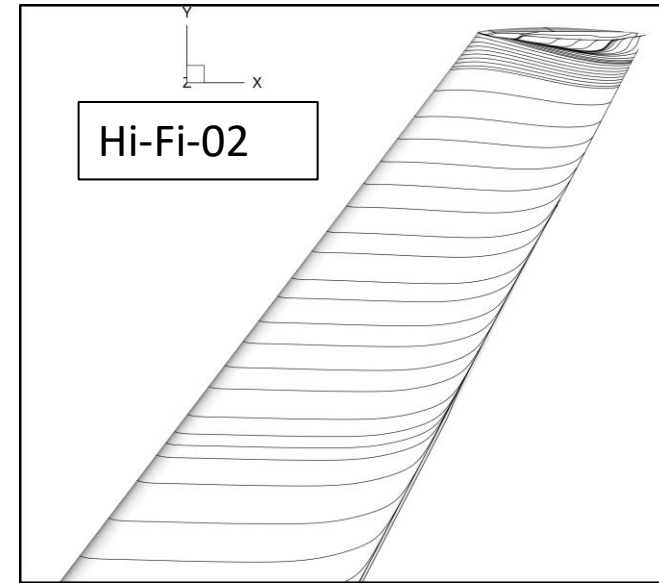
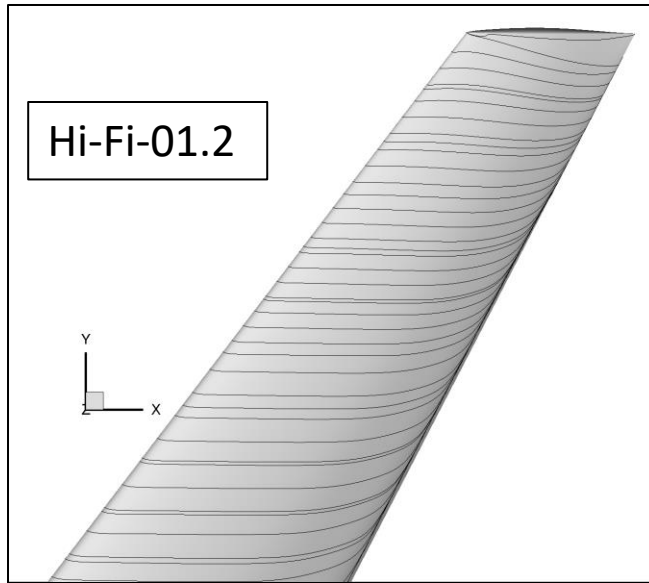
CFD View 2

Focus on juncture separation bubble

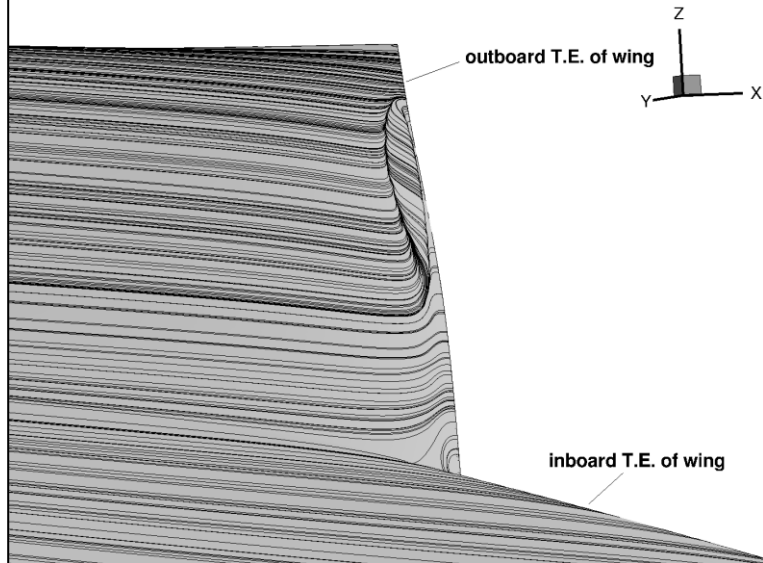


CFD View 4

Focus on wing-tip separation



Hi-Fi-01.1 (165M points)



CFD View Sp1.1.
Trailing-edge separation
Dependence on grid resolution

Node-centered
finite-element

1.R.01

Adapted

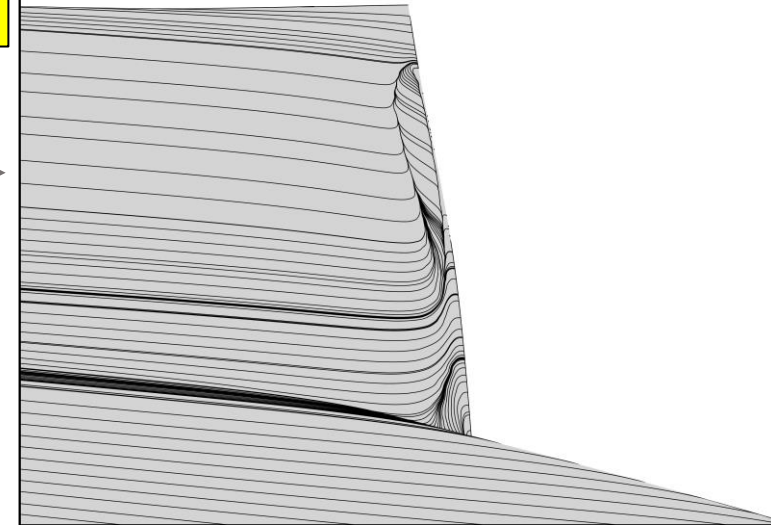
Node-centered
finite-volume

Cell-centered
finite-volume

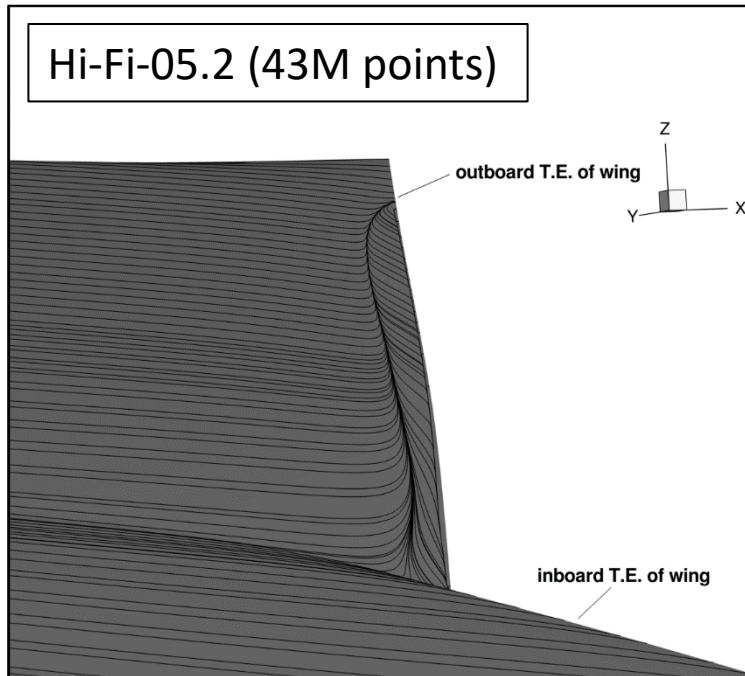
1.R.05

Trailing-edge separation pattern is different
on grids with under-resolved surface mesh

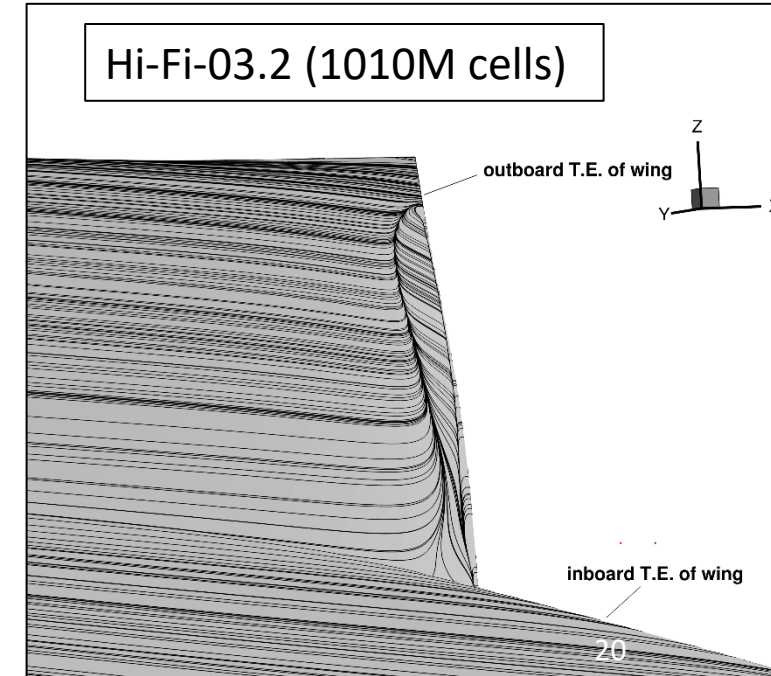
Hi-Fi-02 (13.3M points)

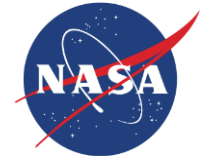


Hi-Fi-05.2 (43M points)



Hi-Fi-03.2 (1010M cells)





Summary

- Relatively close agreement between all solutions
- No grid convergence evident from totality of submissions
- Grid convergence observed for solutions on selected grid families
 - Different grid families (HM, Adapted, HRLES)
 - Generated by different groups
 - Different discretizations (FV-NC, FV-CC, FEM)
- Similar separation patterns on grids with sufficient resolution