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DRAG PREDICTION WORKSHOP 8
WORKING GROUP #3: BUFFET

Transonic Buffet Prediction with Unsteady CFD

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Overview

- Test Case 1a/1b
  - Steady State vs Time Accurate with FUN3D
  - Beyond RANS: wall resolved implicit large eddy simulation with PyFR
- Test Case 2
  - Common Research Model Groundwork: steady state mesh and geometry sensitivity studies.
  - Steady State vs Time Accurate with FUN3D

References

1. L. Jacquin, P. Molton, S. Deck, B. Maury, and D. Soulevant, “Experimental Study of Shock Oscillation over a Transonic Supercritical Profile,” AIAA Journal, Vol. 47, No 9, 2009, Pages 1985-1994
2. Shunsuke Koike, Makoto Ueno, Kazuyuki Nakakita and Atsushi Hashimoto, “Unsteady Pressure Measurement of Transonic Buffet on NASA Common Research Model,” Japan Aerospace Exploration Agency, 2016
3. Brion Vincent, Julien Dandois, Marie Couliou, Daniel Florentin. “Towards the improvement of the ONERA transonic S3Ch wind tunnel. STO-AVT-338 - Specialists’ Meeting on ‘Advanced Wind Tunnel Boundary Simulation’,” May 2021, Berlin, Germany.
4. L. Jacquin, V. Brion, P. Molton, D. Sipp, J. Dandois, S. Deck, F. Sartor, E. Coustols, and D. Caruana, “Testing in Aerodynamics Research at ONERA: the Example of the Transonic Buffet,” AerospaceLab, Issue 12, December 2016
5. Ngoc-Cuong Nguyen , Sebastien Terrana, and Jaime Peraire, “Wall-resolved implicit large eddy simulation of transonic buffet over the OAT15A airfoil using a discontinuous Galerkin method,” Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, January 2020
6. T. Dzanica, F. D. Witherden, “Positivity-Preserving Entropy-Based Adaptive Filtering for Discontinuous Spectral Element Methods,” Department of Ocean Engineering, Texas A&M University, November 2022

DPW-8 Buffet Working Group:
ONERA OAT15a

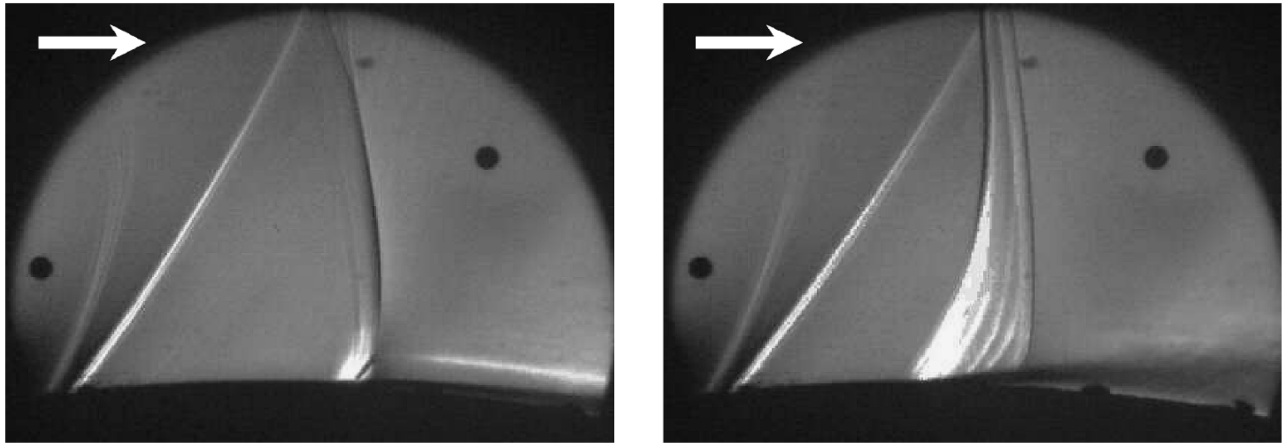
Test Cases

Test Case 1a/1b

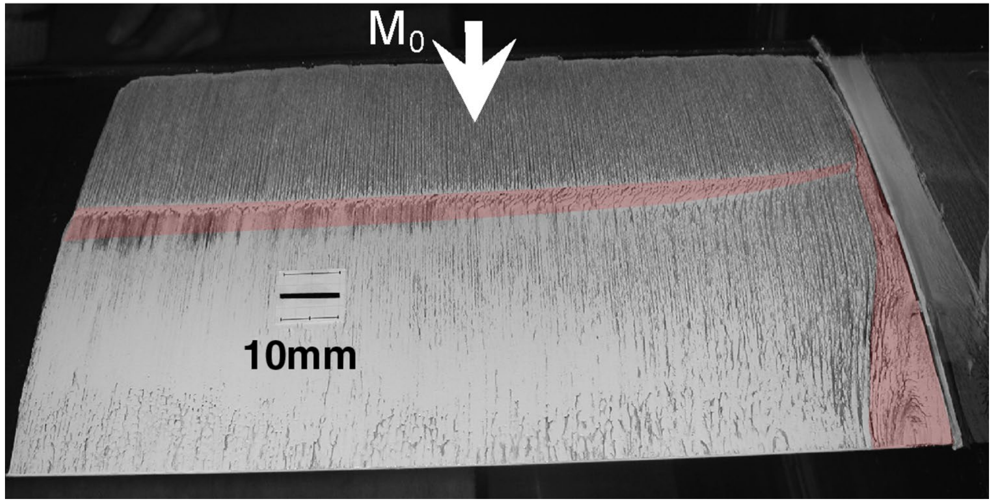
- ONERA OAT15A Supercritical Transonic Airfoil Section (230mm)
- Mach = 0.73
- Re = 3.0e6
- Alpha = [1.36, 1.50, 2.50, 3.00, 3.10, 3.25, 3.40, 3.50, 3.60, 3.90]
- 1a) Steady State CFD
- 1b) Unsteady CFD

Reference Experimental Data

- Wind tunnel data [1, 4] indicates onset of transonic buffet via shock position oscillation around 3.1 degrees alpha.
- Mid-span flow considered predominantly two dimensional, some lateral wall effects observed on outer 20% of span



Reproduced from [1]

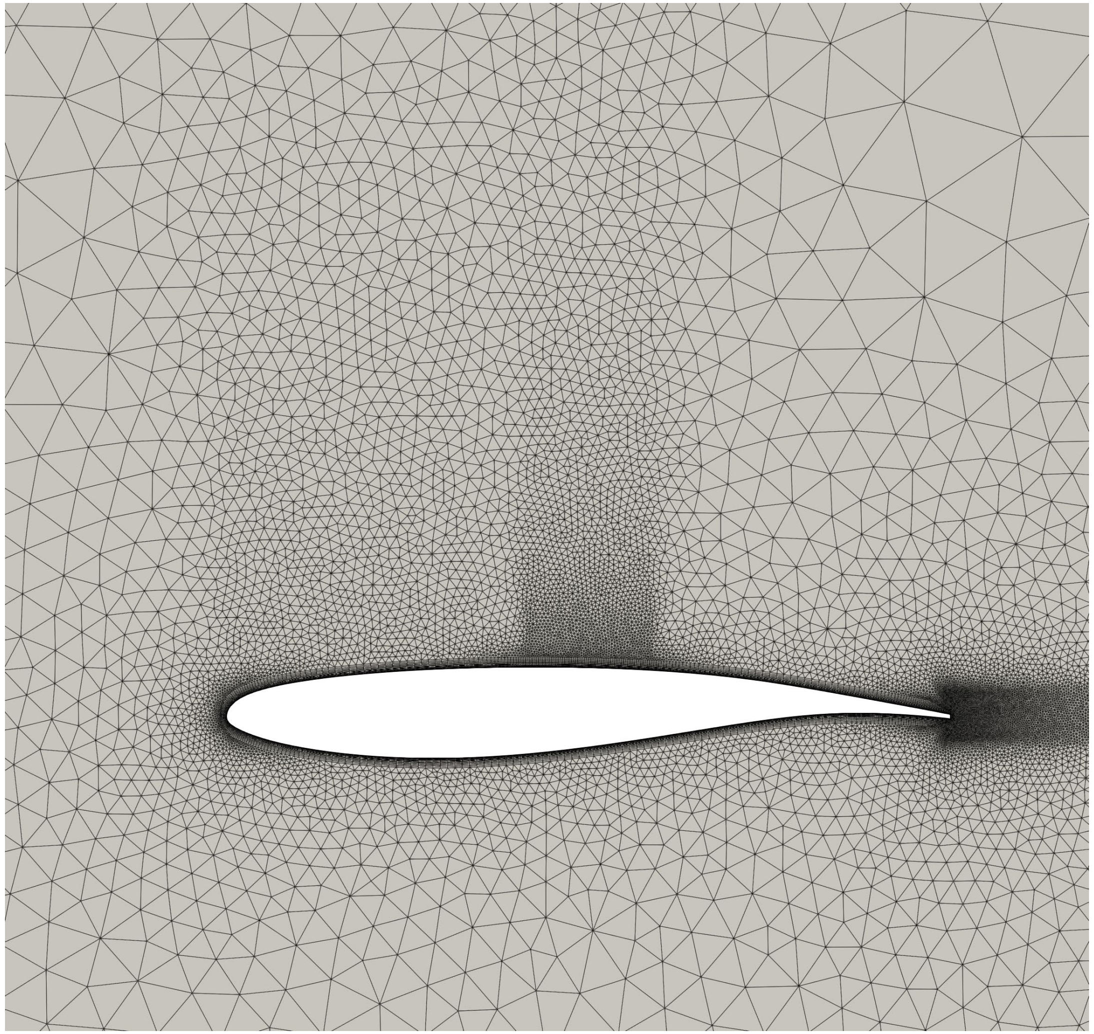


Reproduced from [1] with flow features highlighted

Mesh: Level 1

ONERA-OAT15A_230mmChord_780mmSpan_upZ_2024_09_05_Unstructured_Level-1.pw

Level	Chordwise Refinement Factor	Cells	Nodes	Δs_c x/c=0.45 (inches)	Δs_w x/c=0.45 (inches)
1	1	47,187	63,480	0.0276	0.000062
2	1.5	89,616	122,630	0.0184	0.000041
3	2	150,333	209,778	0.0138	0.000031
4	2.5	235,491	337,510	0.0110	0.000025
5	3	353,725	522,458	0.0092	0.000021
6	3.5	517,448	790,852	0.0079	0.000018

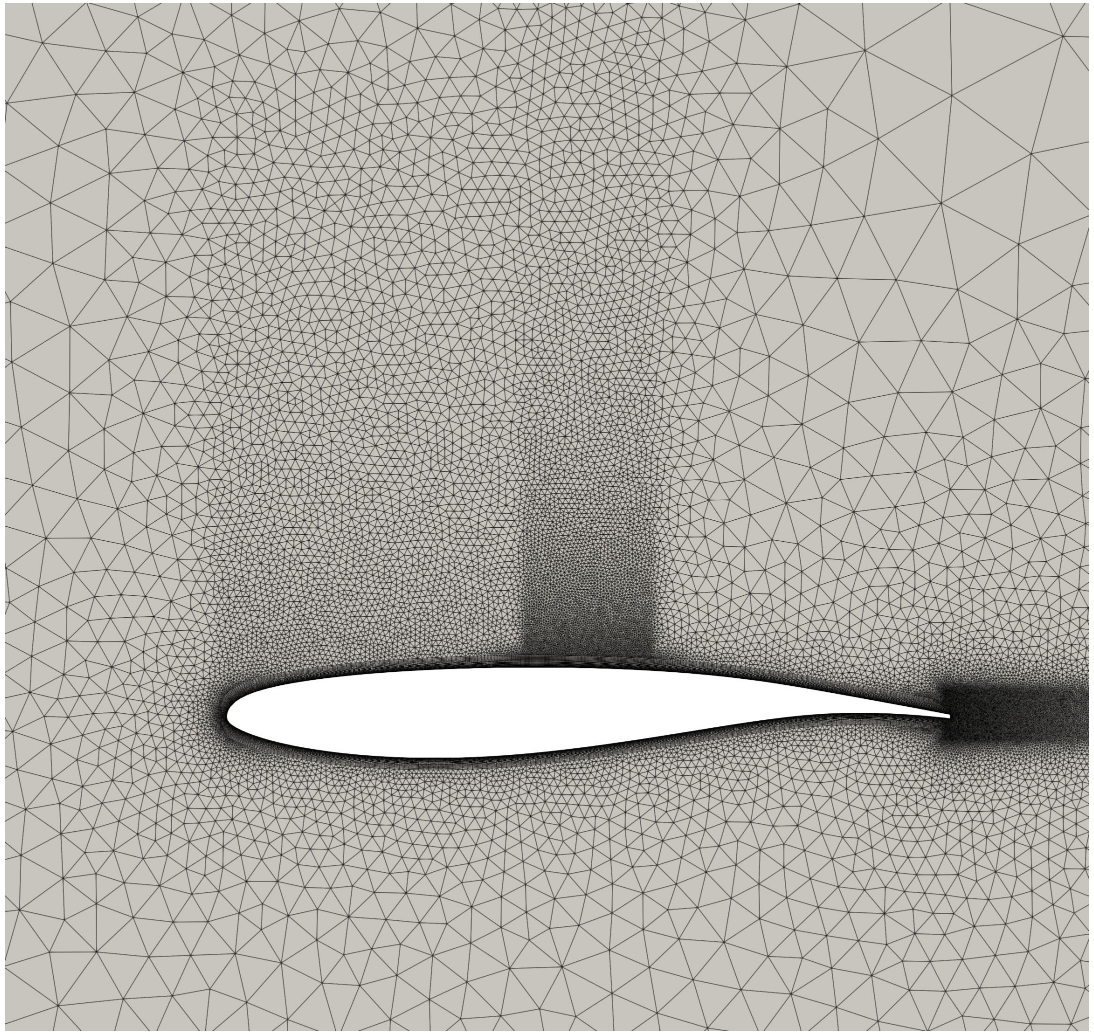


Δs_c = chordwise spacing
Δs_w = wall normal spacing

Mesh: Level 2

ONERA-OAT15A_230mmChord_780mmSpan_upZ_2024_09_05_Unstructured_Level-2.pw

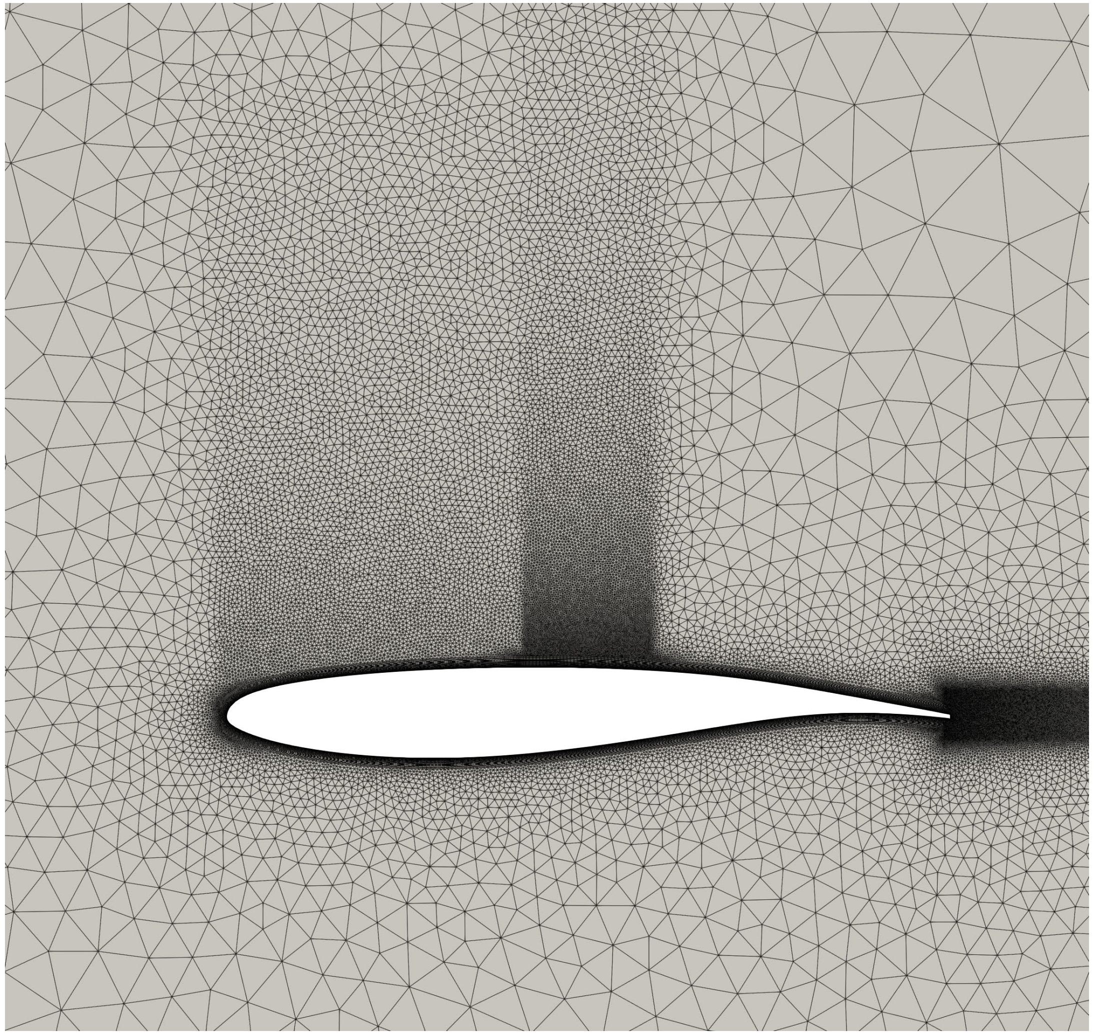
Level	Chordwise Refinement Factor	Cells	Nodes	Δs_c x/c=0.45 (inches)	Δs_w x/c=0.45 (inches)
1	1	47,187	63,480	0.0276	0.000062
2	1.5	89,616	122,630	0.0184	0.000041
3	2	150,333	209,778	0.0138	0.000031
4	2.5	235,491	337,510	0.0110	0.000025
5	3	353,725	522,458	0.0092	0.000021
6	3.5	517,448	790,852	0.0079	0.000018



Mesh: Level 3

ONERA-OAT15A_230mmChord_780mmSpan_upZ_2024_09_05_Unstructured_Level-3.pw

Level	Chordwise Refinement Factor	Cells	Nodes	Δs_c x/c=0.45 (inches)	Δs_w x/c=0.45 (inches)
1	1	47,187	63,480	0.0276	0.000062
2	1.5	89,616	122,630	0.0184	0.000041
3	2	150,333	209,778	0.0138	0.000031
4	2.5	235,491	337,510	0.0110	0.000025
5	3	353,725	522,458	0.0092	0.000021
6	3.5	517,448	790,852	0.0079	0.000018



Mesh: Level 4

ONERA-OAT15A_230mmChord_780mmSpan_upZ_2024_09_05_Unstructured_Level-4.pw

Level	Chordwise Refinement Factor	Cells	Nodes	Δs_c x/c=0.45 (inches)	Δs_w x/c=0.45 (inches)
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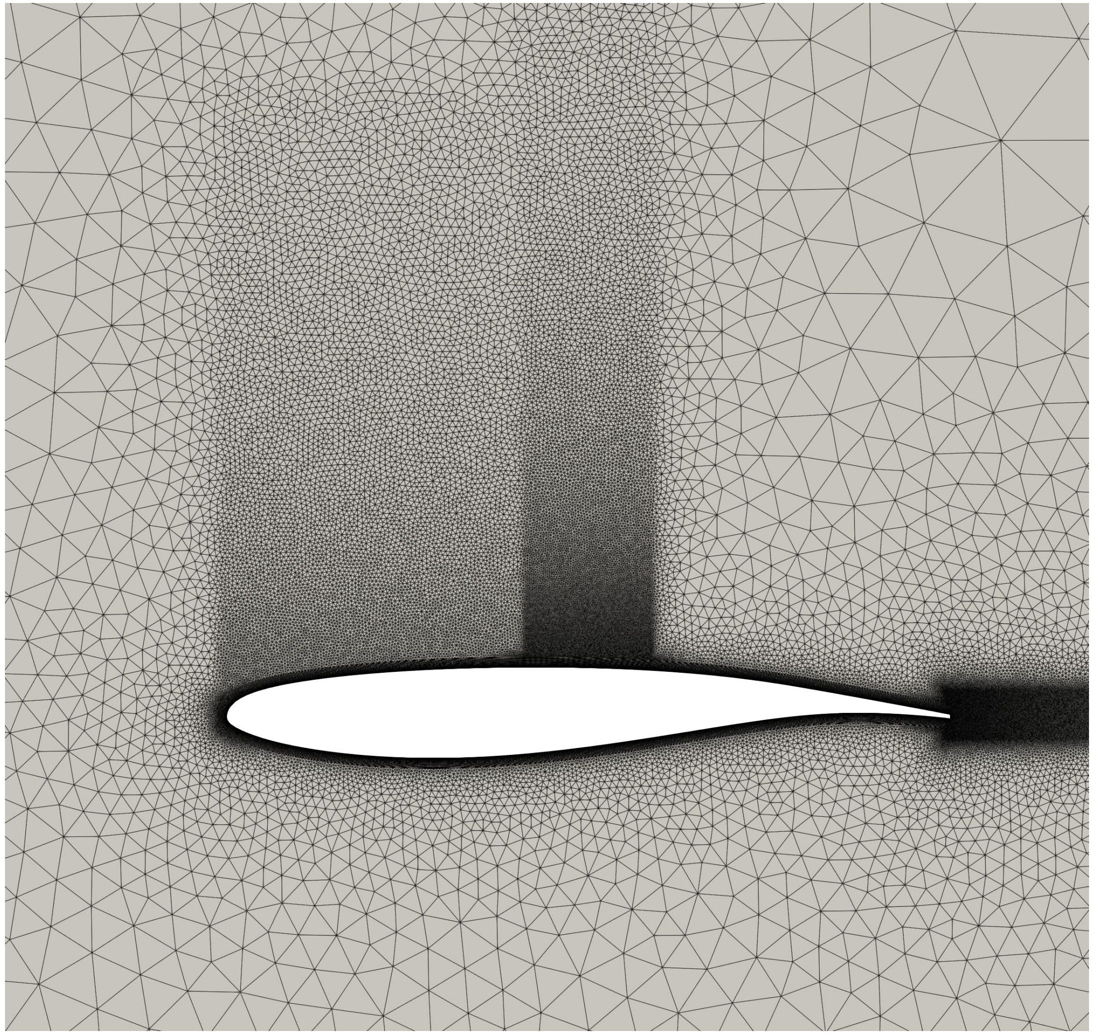
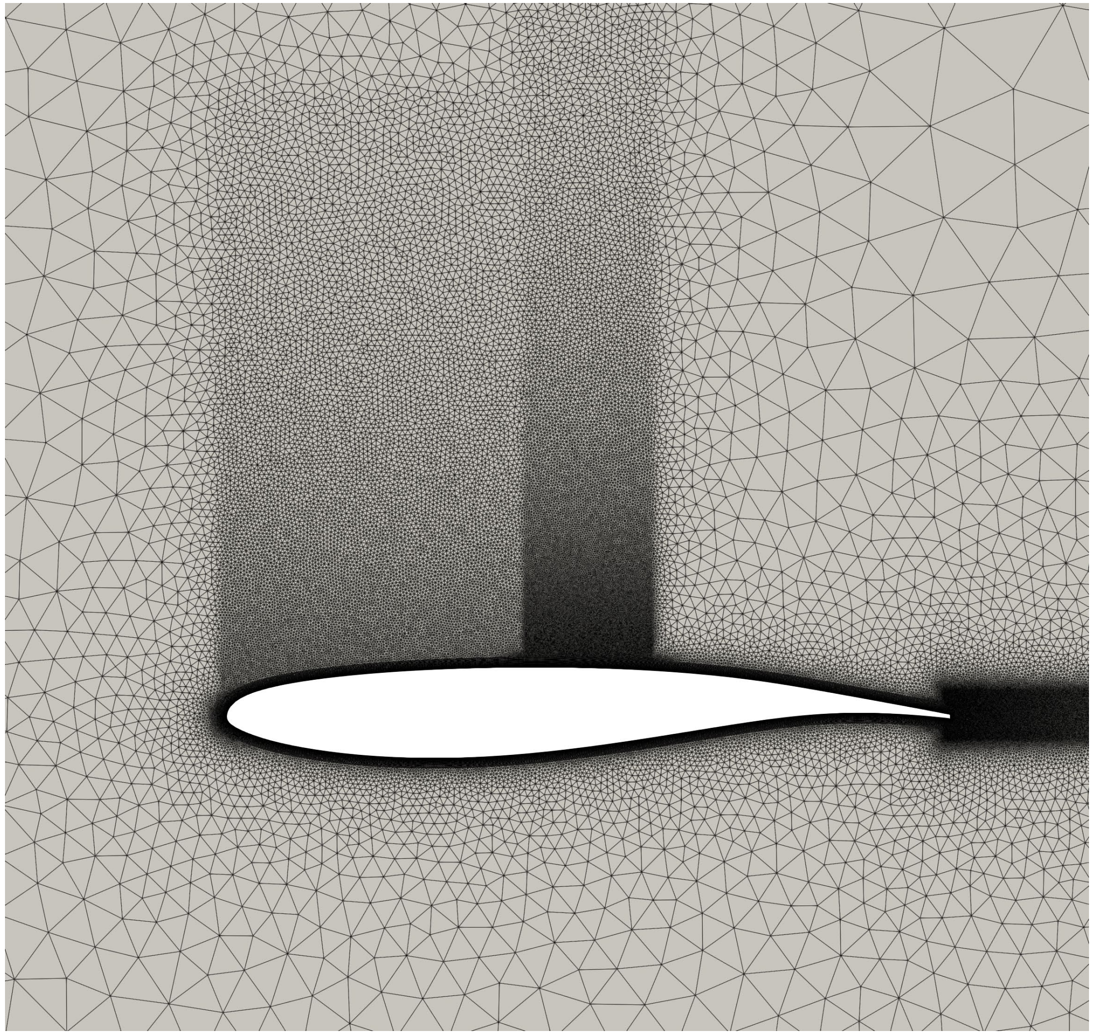
2	1.5	89,616	122,630	0.0184	0.000041
3	2	150,333	209,778	0.0138	0.000031
4	2.5	235,491	337,510	0.0110	0.000025
5	3	353,725	522,458	0.0092	0.000021
6	3.5	517,448	790,852	0.0079	0.000018



Mesh: Level 5

ONERA-OAT15A_230mmChord_780mmSpan_upZ_2024_09_05_Unstructured_Level-5.pw

Level	Chordwise Refinement Factor	Cells	Nodes	Δs_c x/c=0.45 (inches)	Δs_w x/c=0.45 (inches)
1	1	47,187	63,480	0.0276	0.000062
2	1.5	89,616	122,630	0.0184	0.000041
3	2	150,333	209,778	0.0138	0.000031
4	2.5	235,491	337,510	0.0110	0.000025
5	3	353,725	522,458	0.0092	0.000021
6	3.5	517,448	790,852	0.0079	0.000018



Mesh: Level 6

ONERA-OAT15A_230mmChord_780mmSpan_upZ_2024_09_05_Unstructured_Level-6.pw

Level	Chordwise Refinement Factor	Cells	Nodes	Δs_c x/c=0.45 (inches)	Δs_w x/c=0.45 (inches)
1	1	47,187	63,480	0.0276	0.000062
2	1.5	89,616	122,630	0.0184	0.000041
3	2	150,333	209,778	0.0138	0.000031
4	2.5	235,491	337,510	0.0110	0.000025
5	3	353,725	522,458	0.0092	0.000021
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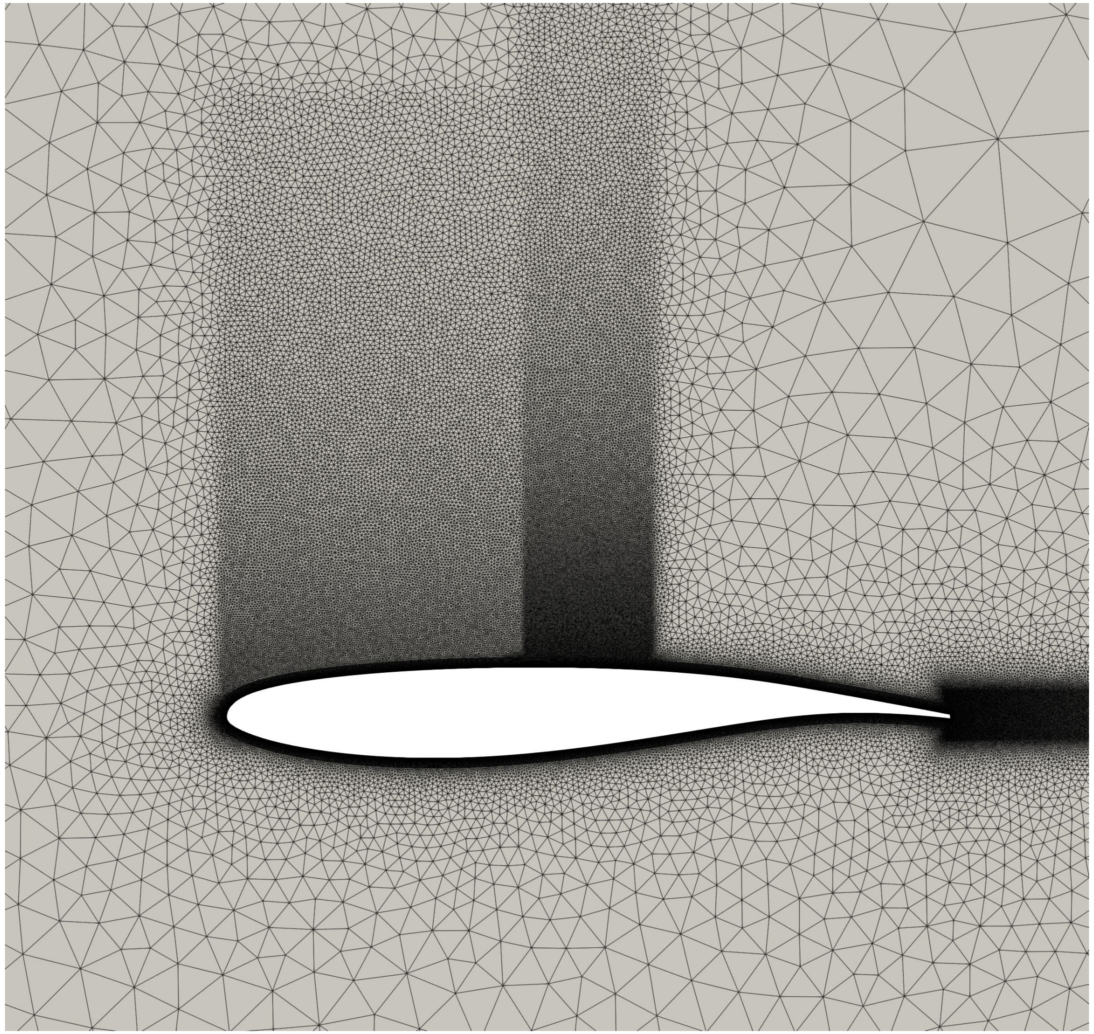
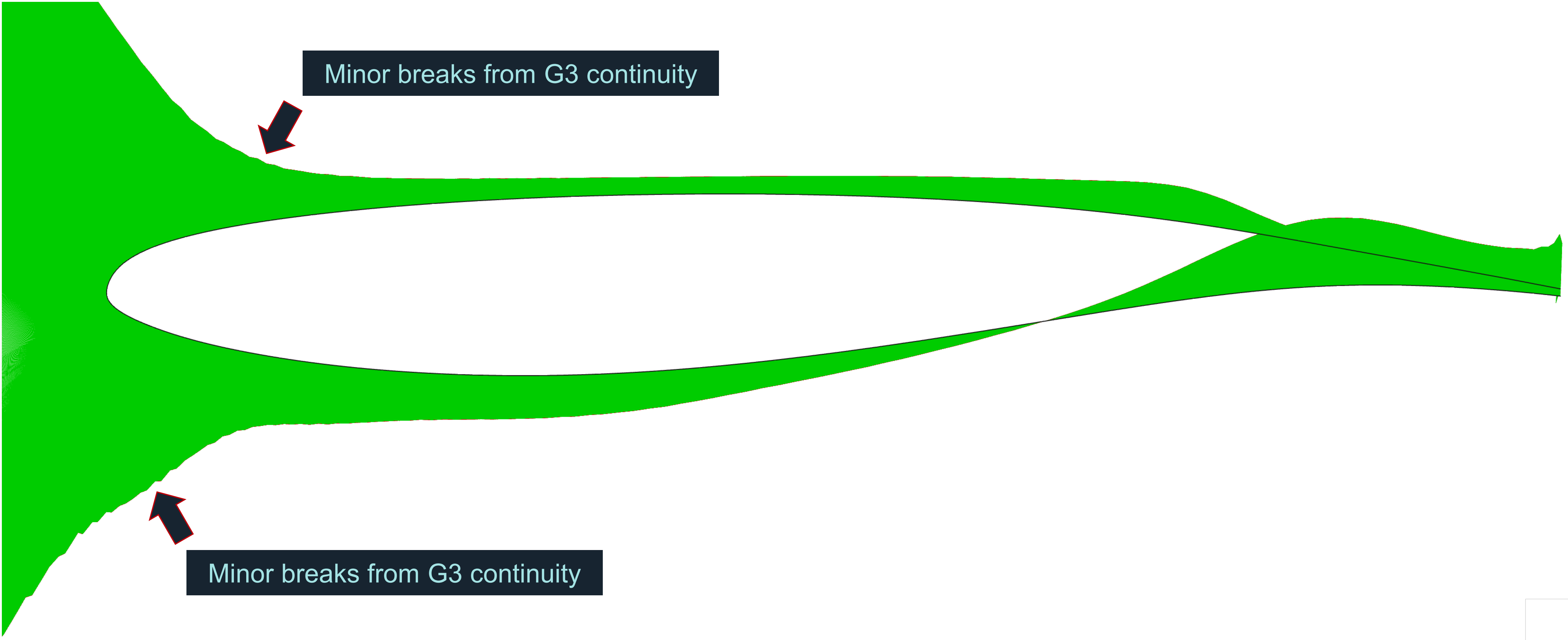


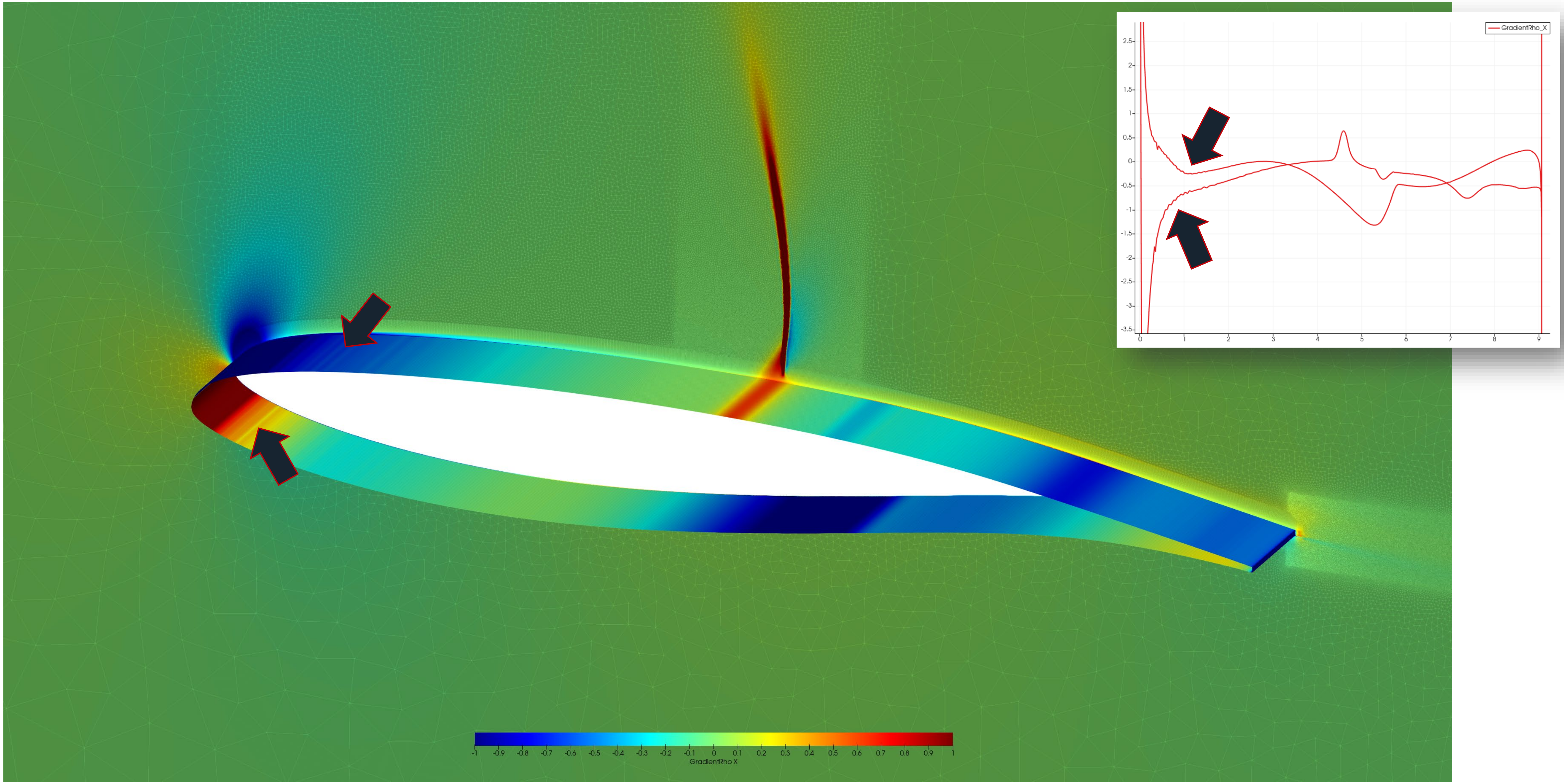
Geometry: High Resolution Curvature Comb Analysis

ONERA-OAT15A_230mmChord_780mmSpan_upZ_2024_09_05.igs sha1sum: d0ccaf63f0302cac6ad23264fbfc8239dcefd205



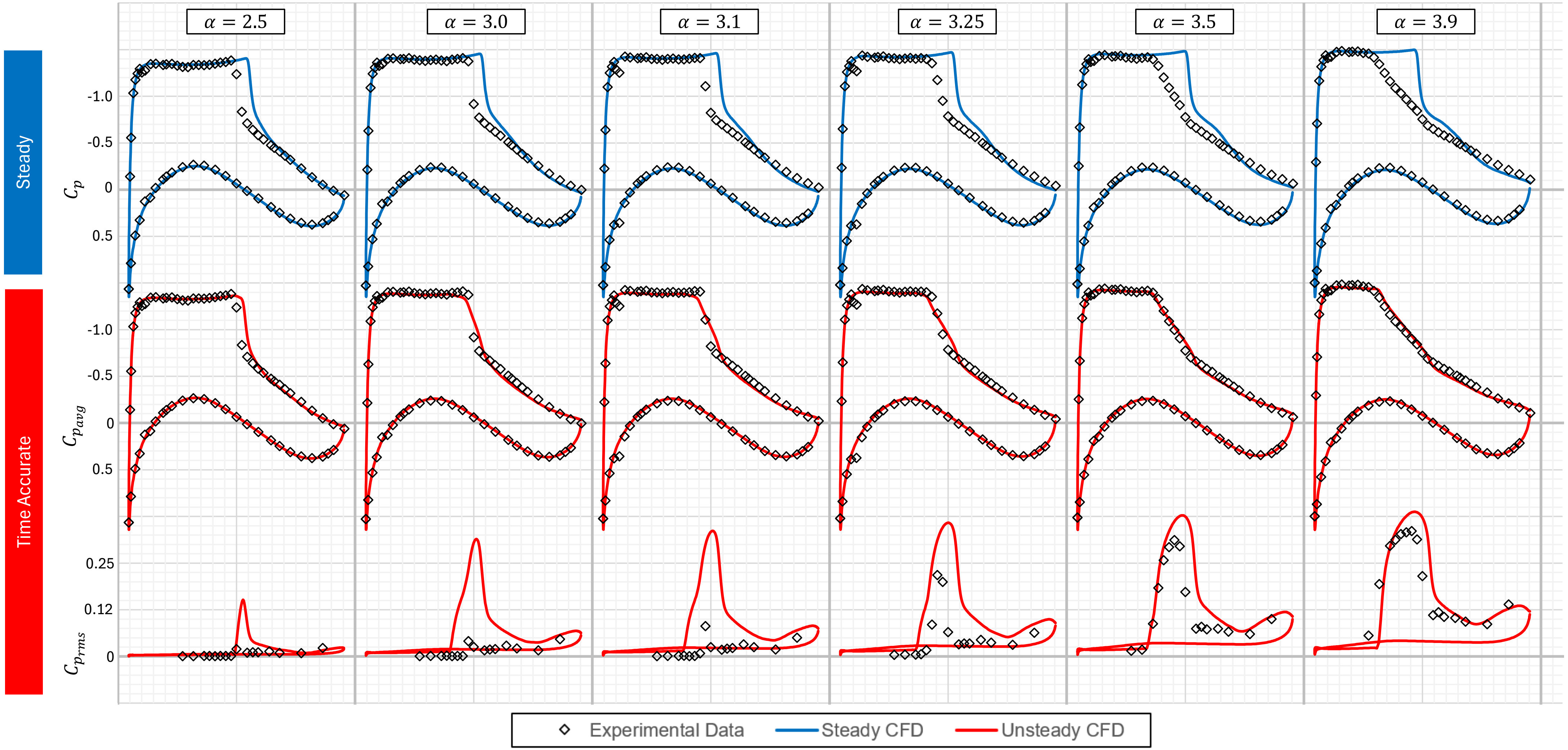
Geometry: CFD Solution Influence

X-component of Density Gradient, ONERA-OAT15A_230mmChord_780mmSpan_upZ_2024_09_05_Unstructured_Level-6.pw, Alpha=1.36, Steady State



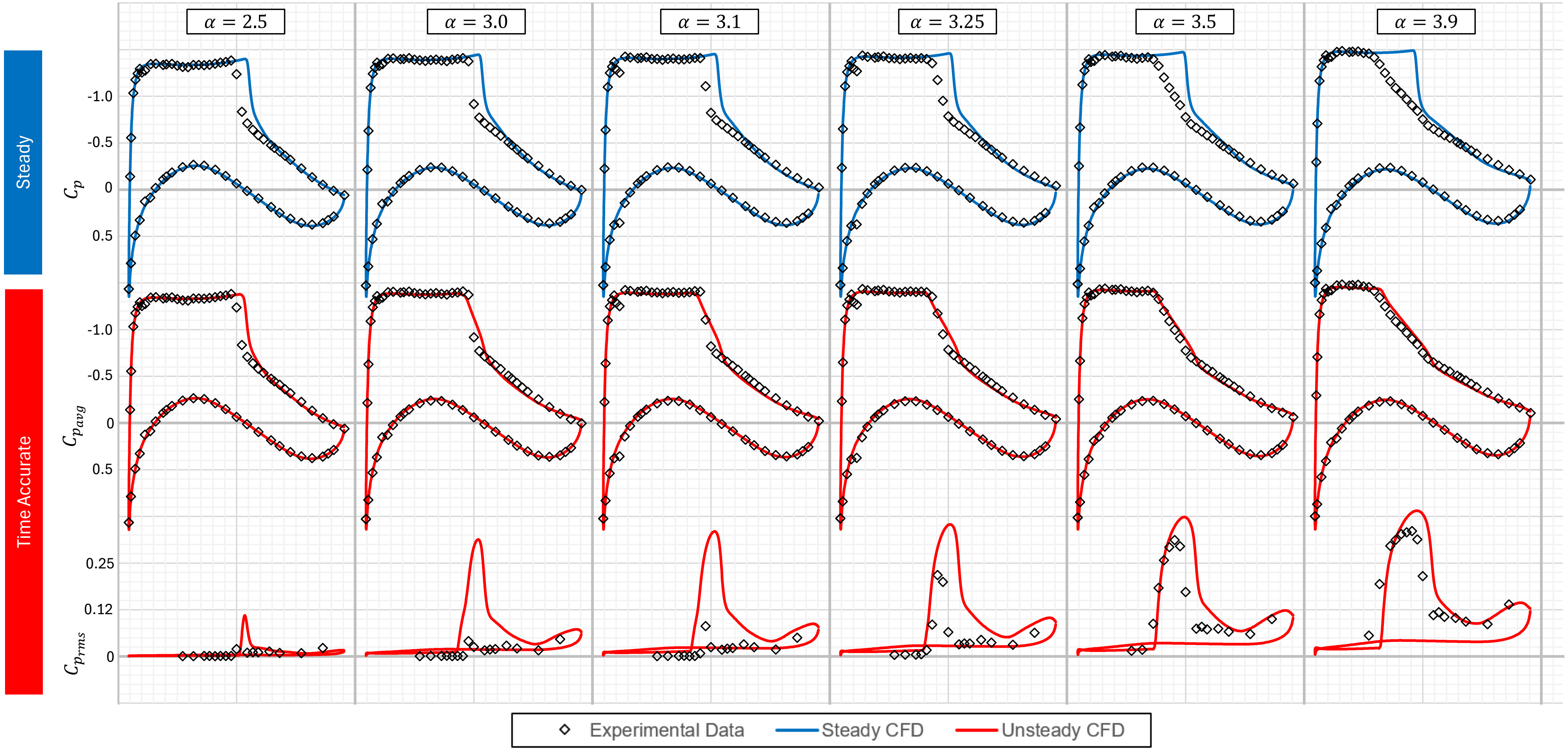
DPW-8 Case 1a/1b M=0.73 Re_c=3M

Mesh: ONERA-OAT15A_230mmChord_780mmSpan_upZ_2024_09_05_Unstructured_Level-1



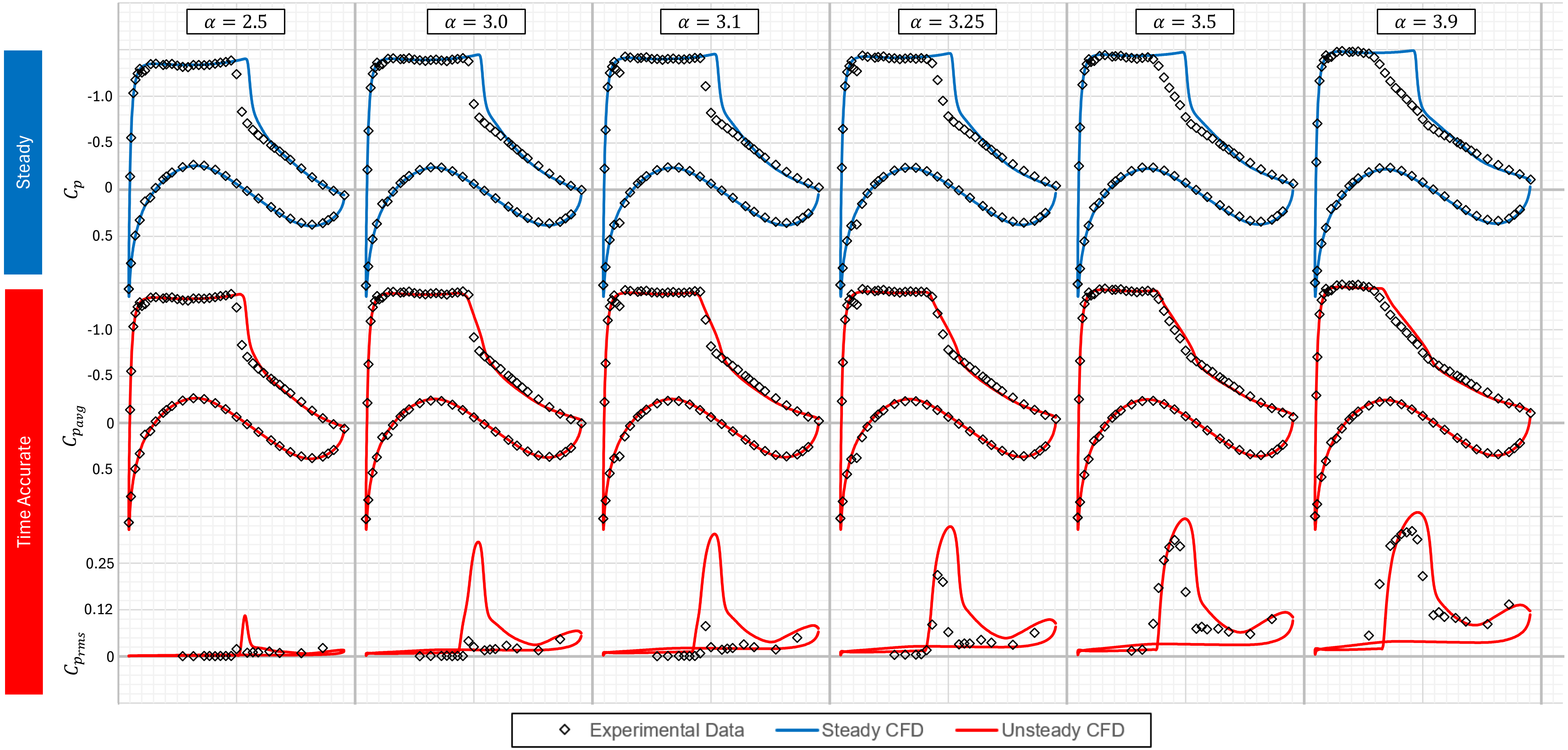
DPW-8 Case 1a/1b M=0.73 Re_c=3M

Mesh: ONERA-OAT15A_230mmChord_780mmSpan_upZ_2024_09_05_Unstructured_Level-2



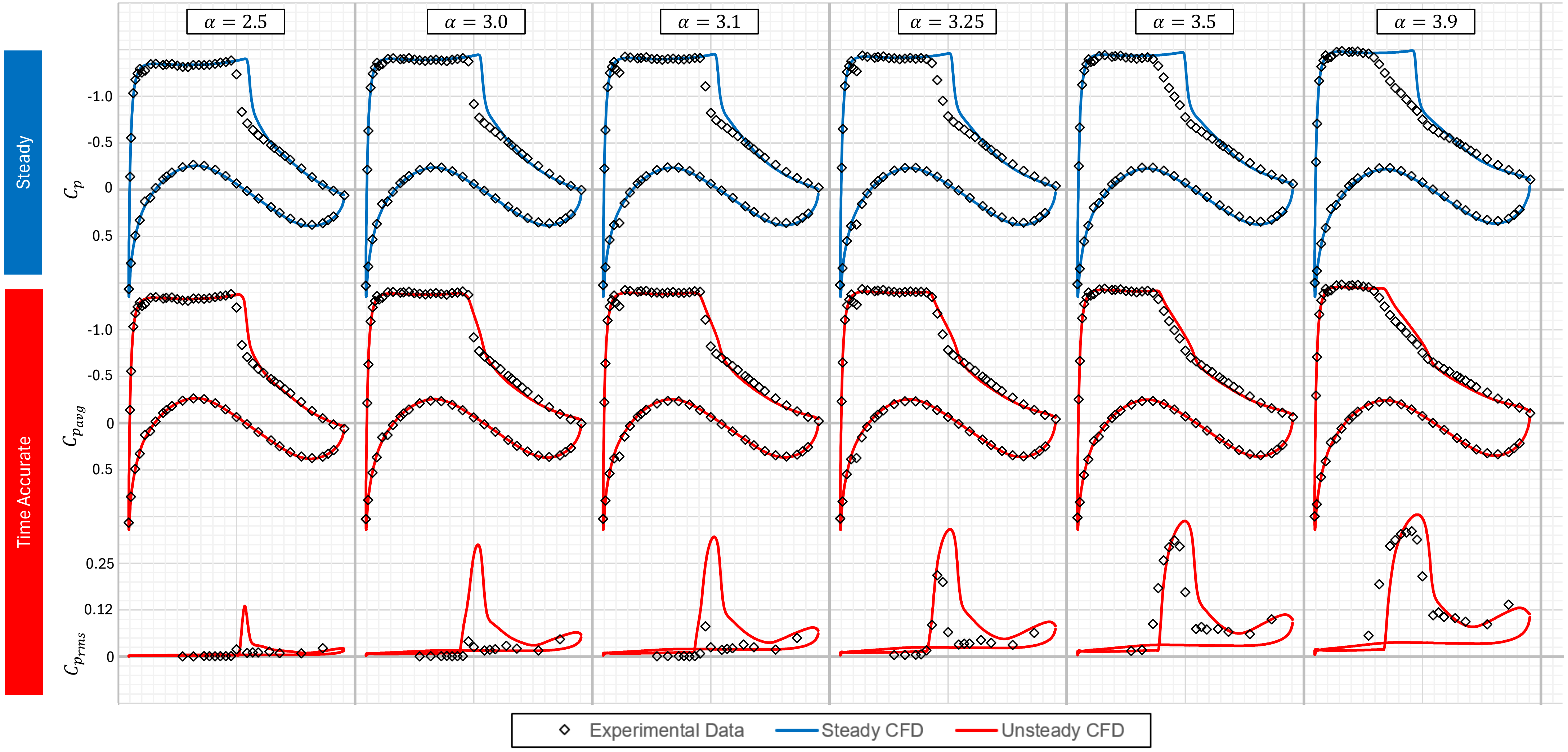
DPW-8 Case 1a/1b M=0.73 Re_c=3M

Mesh: ONERA-OAT15A_230mmChord_780mmSpan_upZ_2024_09_05_Unstructured_Level-3



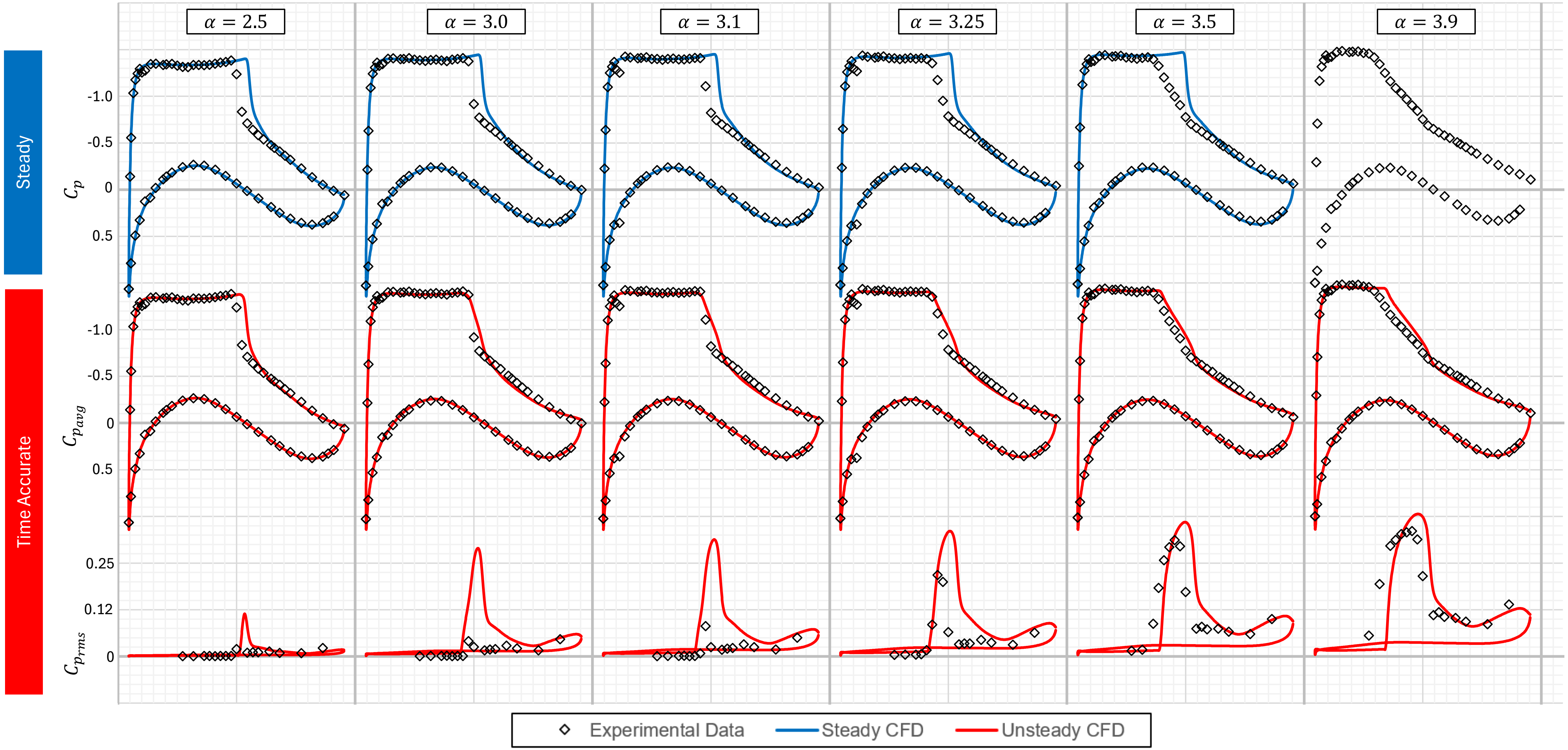
DPW-8 Case 1a/1b M=0.73 Re_c=3M

Mesh: ONERA-OAT15A_230mmChord_780mmSpan_upZ_2024_09_05_Unstructured_Level-4



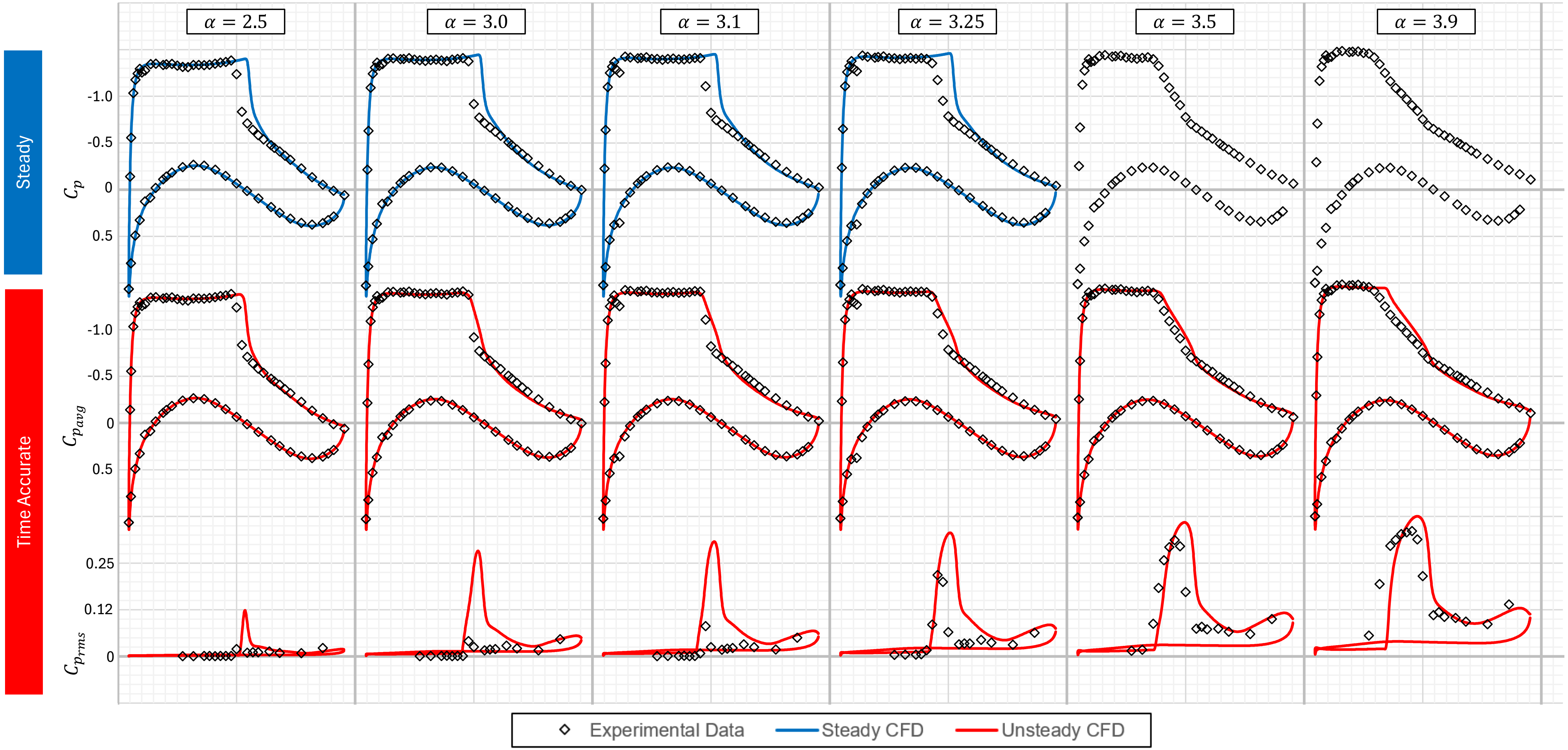
DPW-8 Case 1a/1b M=0.73 Re_c=3M

Mesh: ONERA-OAT15A_230mmChord_780mmSpan_upZ_2024_09_05_Unstructured_Level-5



DPW-8 Case 1a/1b M=0.73 Re_c=3M

Mesh: ONERA-OAT15A_230mmChord_780mmSpan_upZ_2024_09_05_Unstructured_Level-6



Pressure Frequency Spectrums

Ref [1] x/c=0.45

Ref [3] x/c=0.80

Ref [3] x/c=0.90

3 different sample points
3 different y-axis units

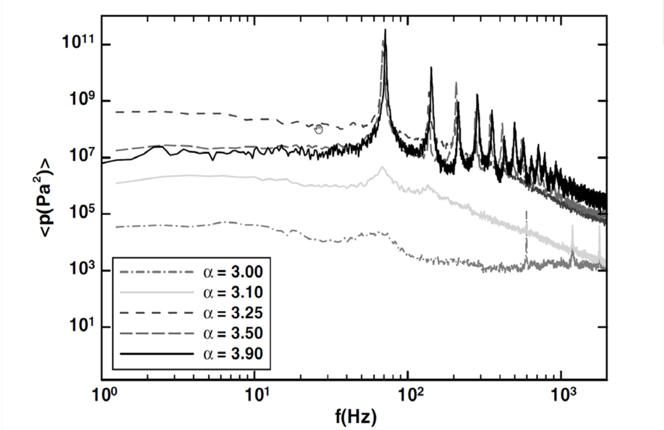
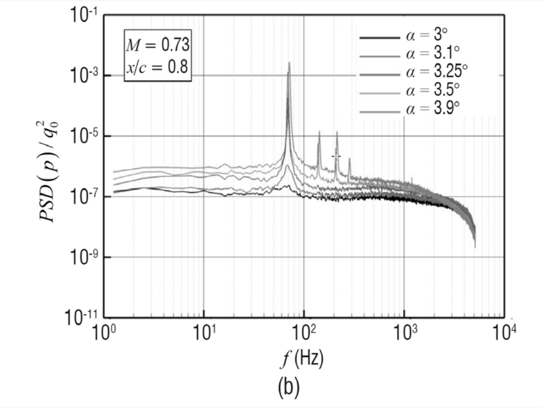
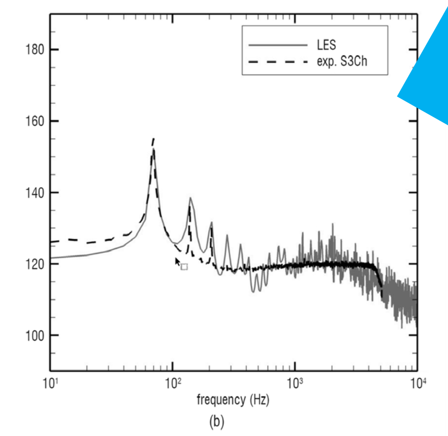


Fig. 10 Influence of incidence on the pressure power spectrum at $X/c = 0.45$ (Kulite no. 7). Upstream Mach number $M_0 = 0.73$.





l airfoil OAT15A) – (a) An iso-value of the Q criteria colored by the longitudinal
) PSD of pressure fluctuations (SPL in dB) at x/c=0.9 [19].

Time Accurate AoA=3.5 CFD
Results Overlay in Red

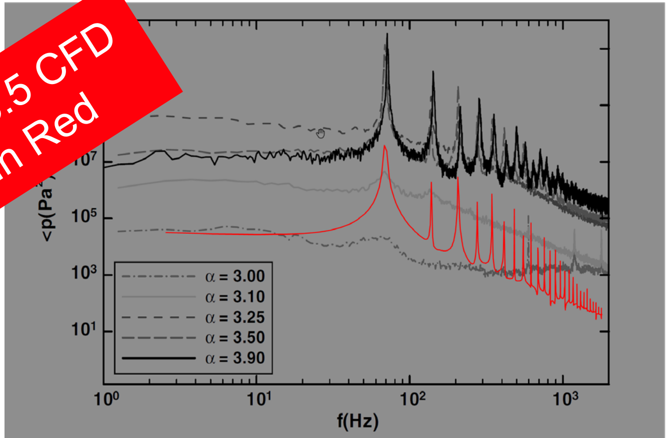
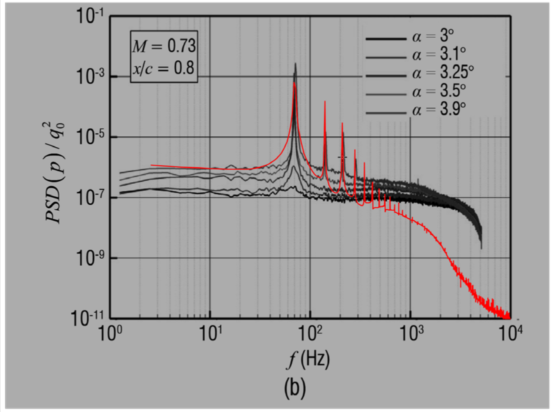
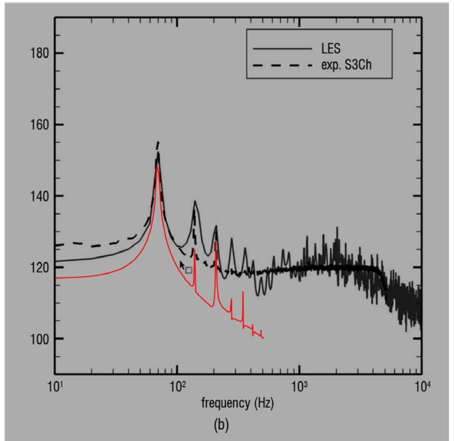


Fig. 10 Influence of incidence on the pressure power spectrum at $X/c = 0.45$ (Kulite no. 7). Upstream Mach number $M_0 = 0.73$.





l airfoil OAT15A) – (a) An iso-value of the Q criteria colored by the longitudinal
) PSD of pressure fluctuations (SPL in dB) at x/c=0.9 [19].

Conclusions

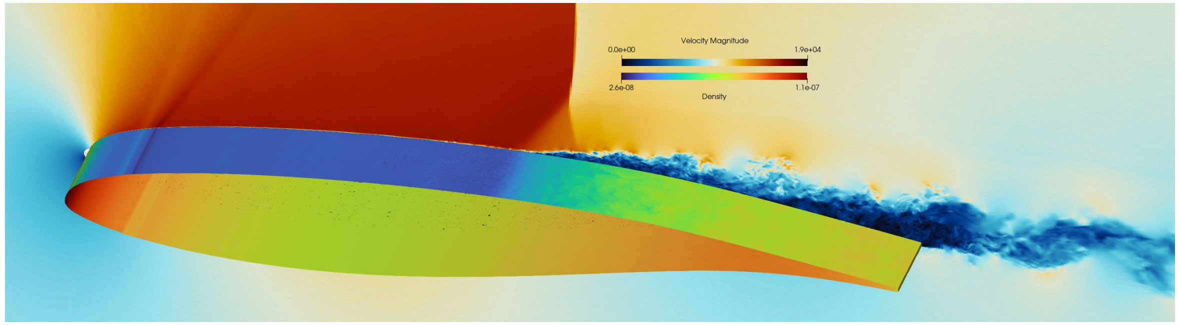
- Time accurate CFD shows improved prediction of average pressure distribution when shock position oscillations are present.
- Primary shock oscillation frequency seems to have been captured well

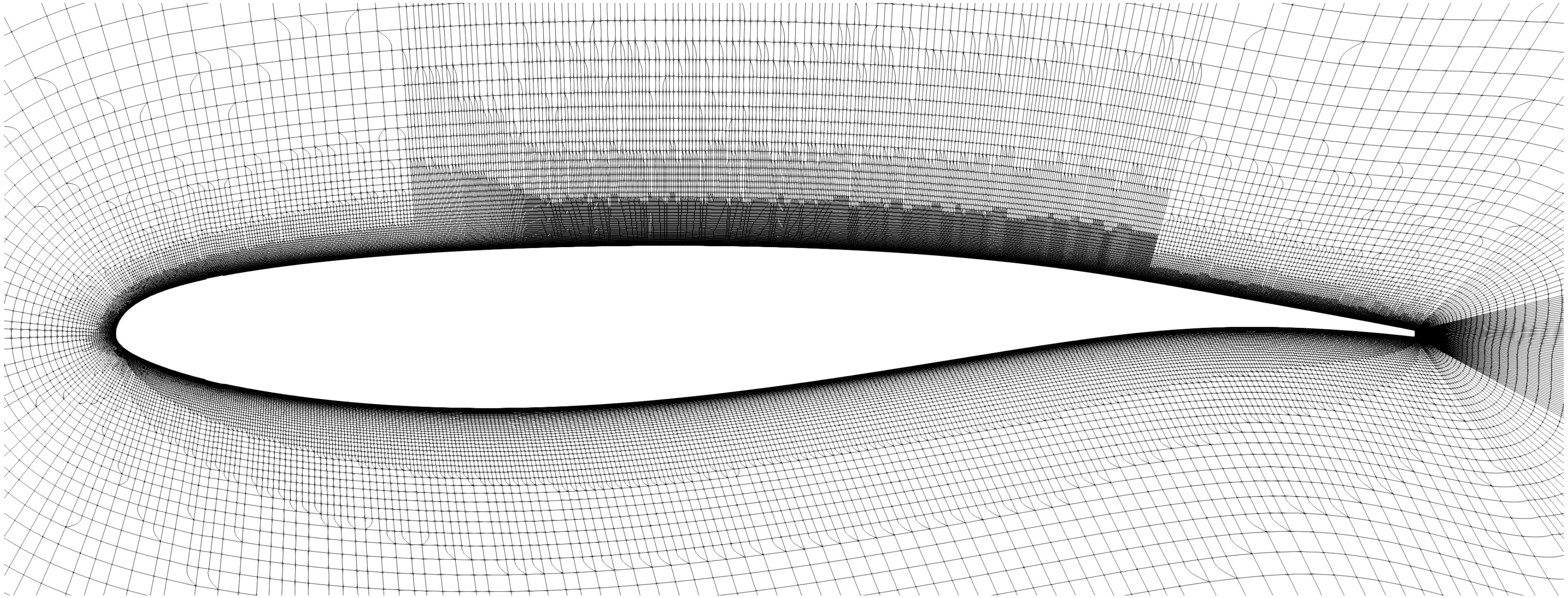
ONERA OAT15a: Beyond RANS

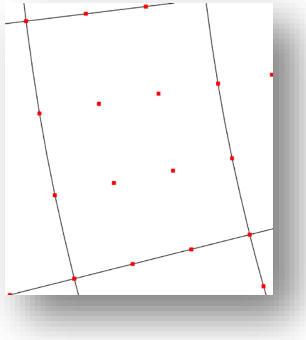
Implicit LES with PyFR

Solver and Mesh

- Solver: PyFR
  - – Implicit LES
  - – Entropy filter shock capturing [ref 6]
- Custom p=3 pseudo structured 2.5D mesh
  - Surface b-spline extracted from committee provided iges file
  - 0.1mm x 3mm trip strips added as described in [ref 5]
  - $\Delta x+ \approx 20$
  - $\Delta y+ \approx 1$
  - $\Delta z+ \approx 20$
  - Node Count: 97.8M
- 3^{rd} order solution basis



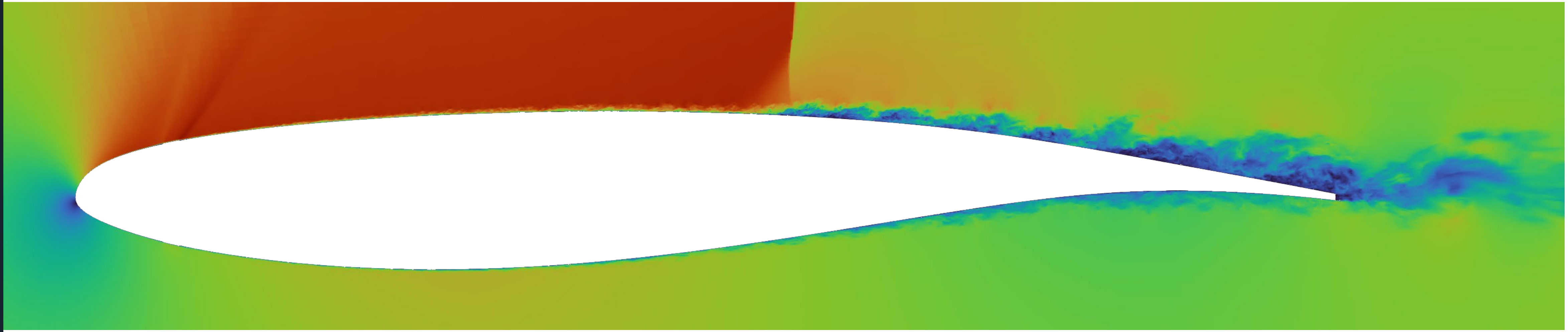




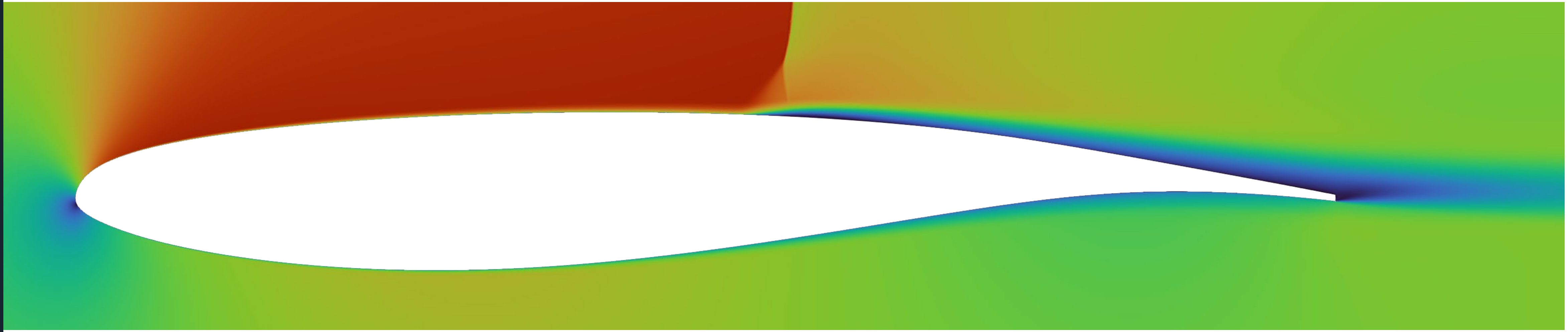
Comparison

(single timestep snapshots with similar shock locations)

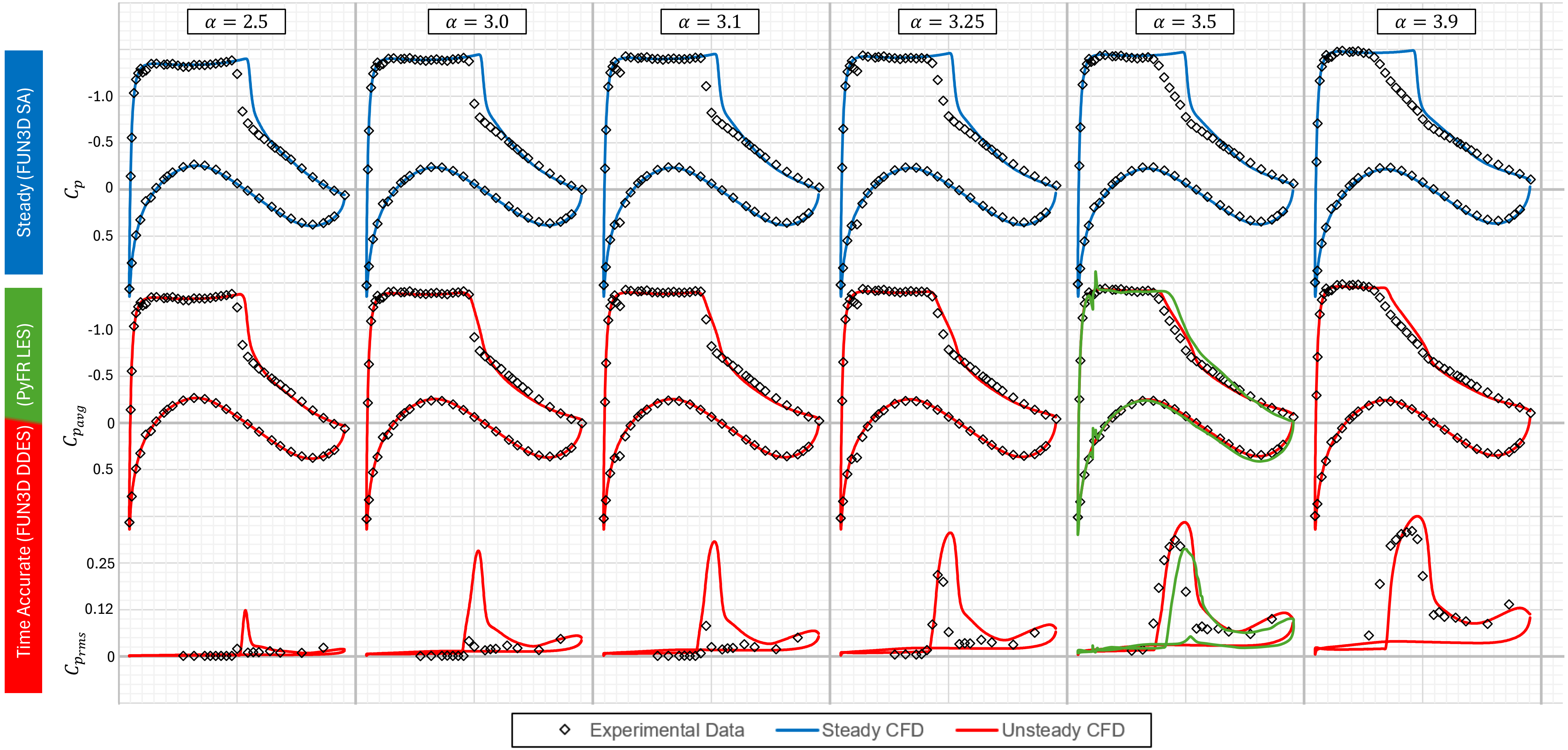
PyFR: ILES



FUN3D: DDES



Results



Steady (FUN3D SA)
(PyFR LES)
Time Accurate (FUN3D DDES)
$\alpha = 2.5$
$\alpha = 3.0$
$\alpha = 3.1$
$\alpha = 3.25$
$\alpha = 3.5$
$\alpha = 3.9$
C_p
$C_{p_{avg}}$
$C_{p_{rms}}$
-1.0
-0.5
0
0.5
0.25
0.12
Experimental Data
Steady CFD
Unsteady CFD

Conclusions

- Challenge: Compute Requirements
  - "2.5D" cases such as this one are costly but accessible to us.
  - Full aircraft simulations at these resolutions would be a serious computational challenge for us.
- Challenge: Accessibility of knowledge base for "best practices"
  - Less common simulation type compared to traditional RANS
  - Scientific journal articles
  - Community discussion boards
  - Source code
- Challenge: High-order mesh generation and post-processing
  - Custom mesh generator developed for this test case
  - Post-processing results is resource intensive
- Good test of HPC resources
- Reasonable agreement to experimental data
  - Increased physical time simulated is likely to yield better results
  - Available computational time for this study was a limiting factor

DPW-8 Buffet Working Group: Case 2

Test Cases

“Classic” DPW Test Case

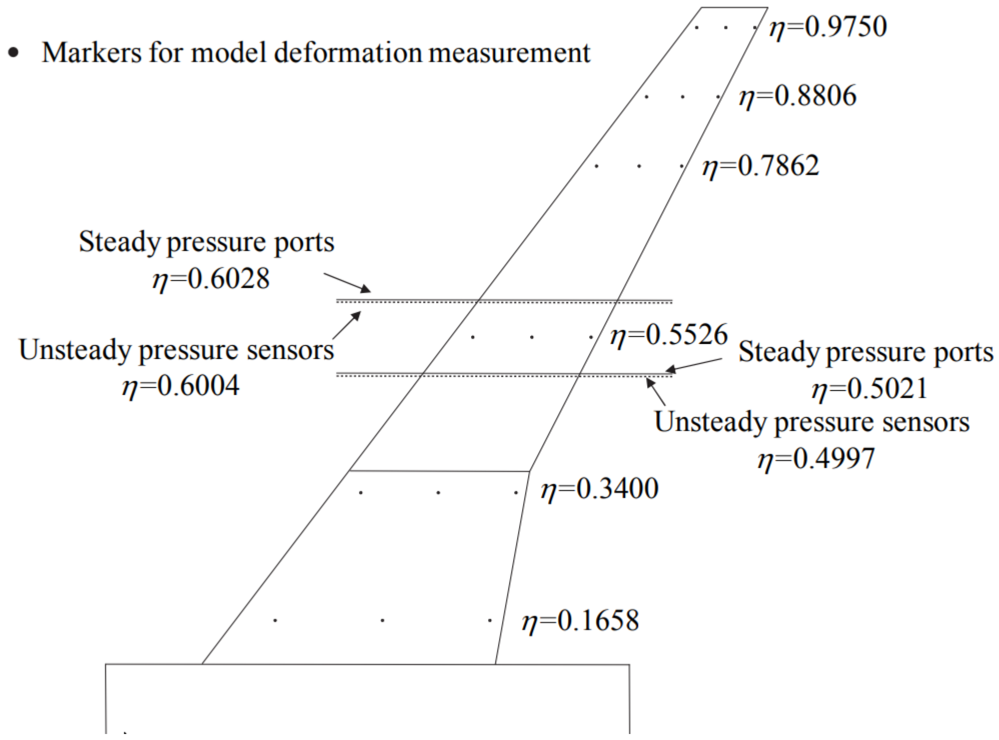
- Wing/Body Common Research Model (various wing deformation definitions)
- Full scale mesh, wind tunnel Reynolds number.
- Mach = 0.85
- Re = 5.0e6
- C_L=0.5

DPW8 Buffet WG Test Case 2

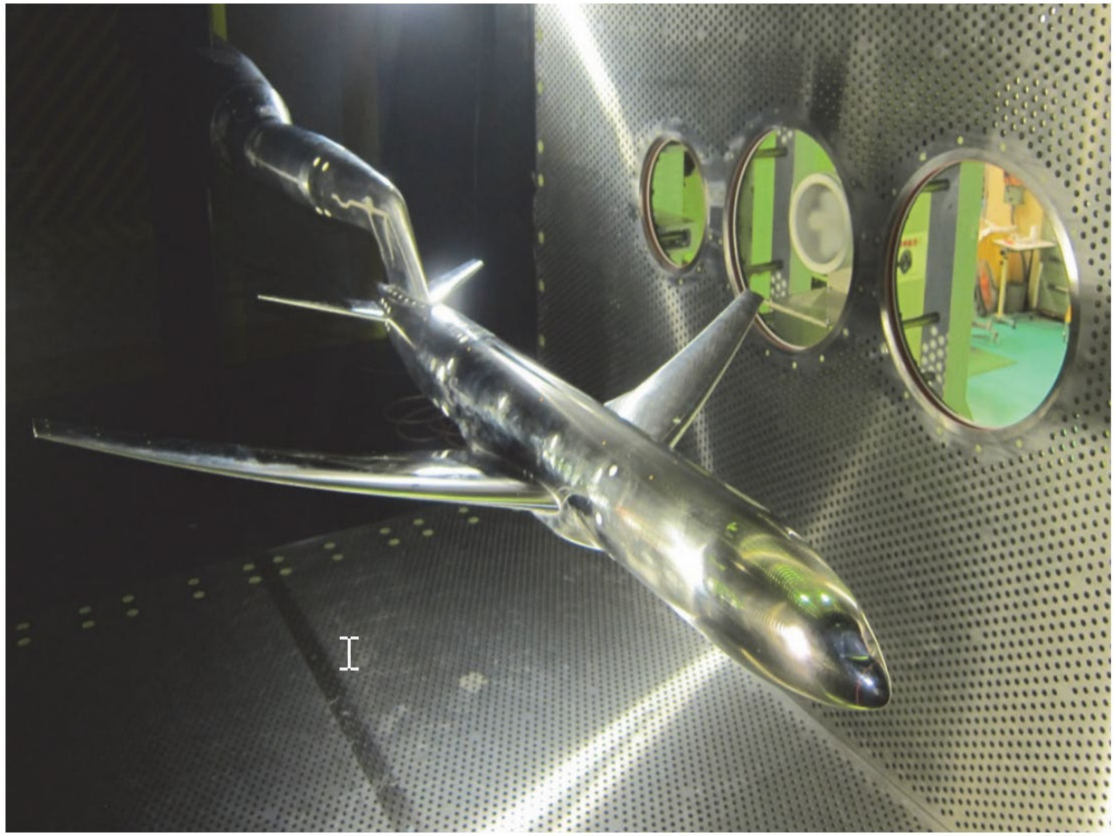
- Common Research Model wing/body/tail0 configuration from reference [2] wind tunnel model
- 80% scale compared to typical CRM wind tunnel scale, 2.16% of full scale
- Mach = 0.85
- Re = 1.515e6
- Alpha = [1.22, 2.29, 4.84, 5.89]

Reference Experimental Data: Buffet Test Case

- Wind tunnel data [2] indicates onset of transonic buffet around 4 degrees alpha.



Reproduced from [2]

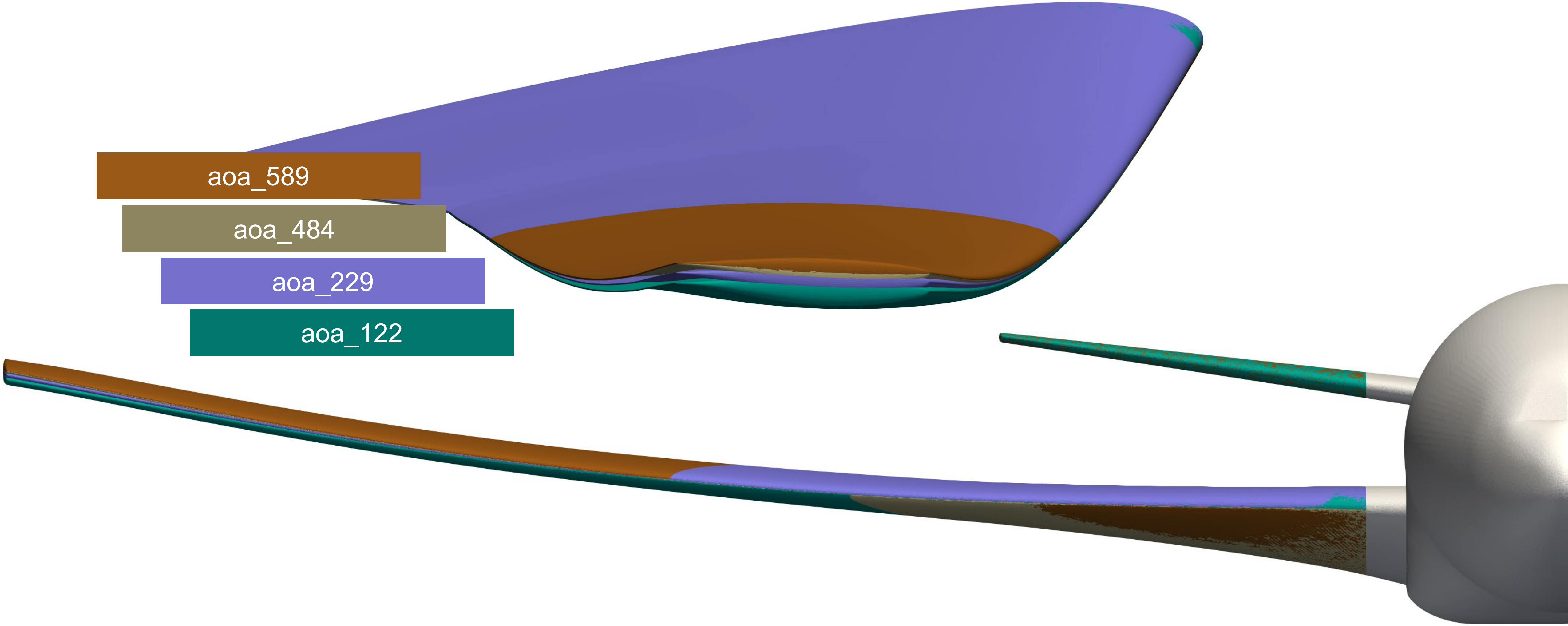


Reproduced from [2]

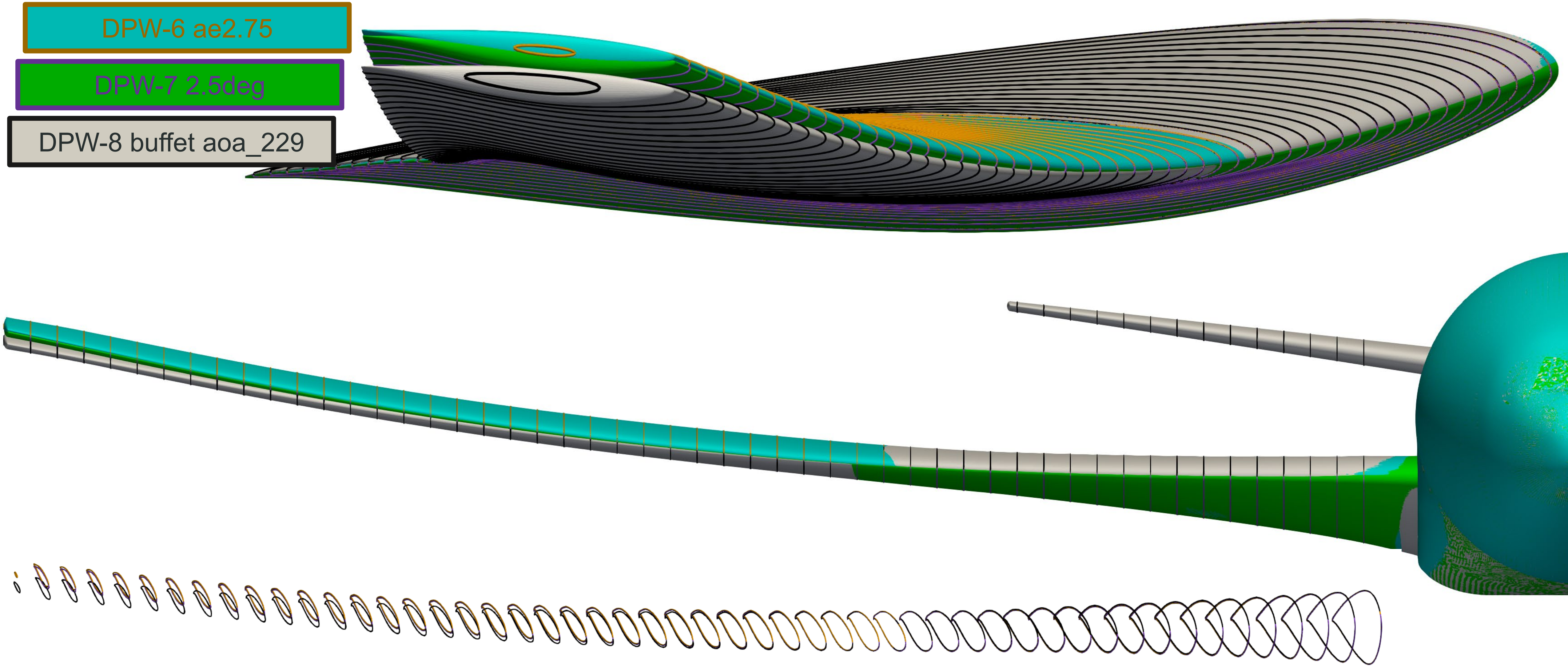
Reference Experimental Data: Classic DPW Test Case

- Langley National Transonic Facility Test 197 Run 44
- Langley National Transonic Facility Test 197 Run 51
- Langley National Transonic Facility Test 197 Run 53
- AMES 11ft Transonic Wind Tunnel Test 216 run 126
- AMES 11ft Transonic Wind Tunnel Test 216 run 130
- AMES 11ft Transonic Wind Tunnel Test 216 run 133

Geometry Comparison: DPW-8 Buffet Geometries



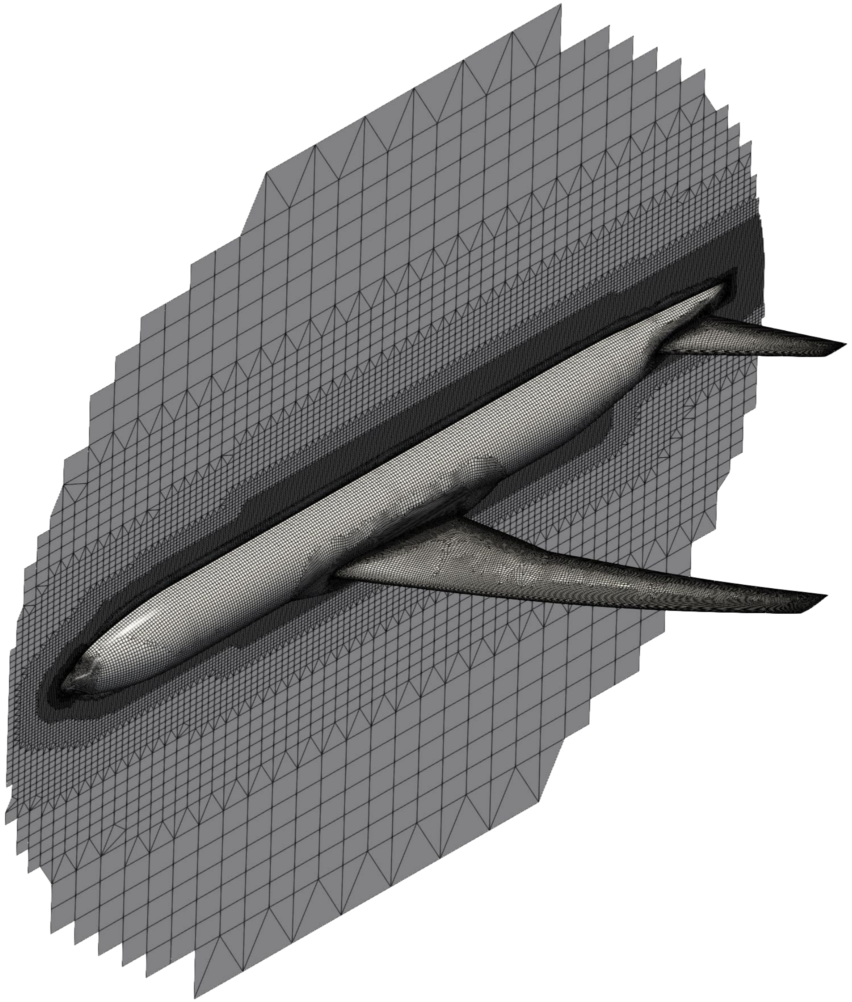
Geometry Comparison: Other CRM Geometries



Mesh: Level 1

wbh_aoa229_buffet_deformed_Level-1.b8.ugrid

Level	Tetrahedrons	Pyramids	Prisms	Hexahedrons	Total Cells	Nodes
1	12,389,064	1,808,169	271,557	14,292,475	28,761,265	17,146,308
2	24,597,485	3,486,593	611,377	43,226,429	71,921,884	48,901,222
3	40,750,971	5,597,163	1,371,931	93,547,316	141,267,381	103,077,084
4	56,615,892	7,405,156	2,601,269	167,582,485	234,204,802	181,103,556
5	86,491,803	11,549,070	4,791,244	350,452,583	453,284,700	371,548,385
6	117,603,845	15,876,637	9,223,121	635,433,265	778,136,868	665,551,017



Mesh: Level 2

wbh_aoa229_buffet_deformed_Level-2.b8.ugrid

Level	Tetrahedrons	Pyramids	Prisms	Hexahedrons	Total Cells	Nodes
1	12,389,064	1,808,169	271,557	14,292,475	28,761,265	17,146,308
2	24,597,485	3,486,593	611,377	43,226,429	71,921,884	48,901,222
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5	86,491,803	11,549,070	4,791,244	350,452,583	453,284,700	371,548,385
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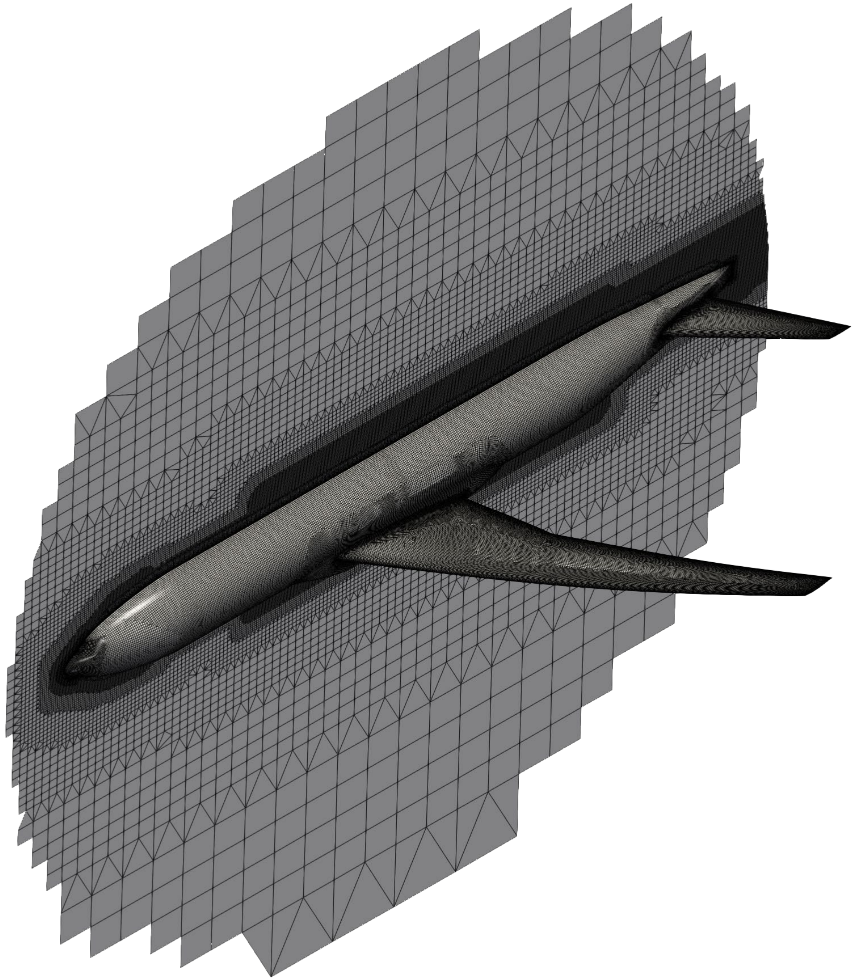
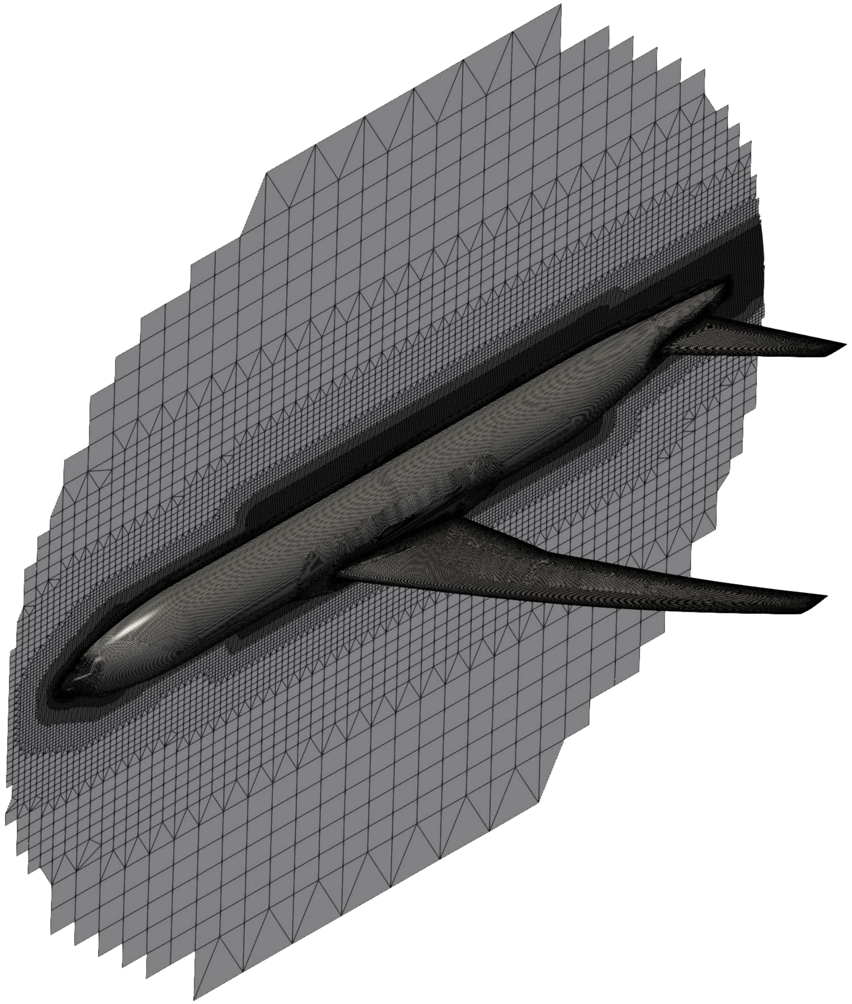


Mesh: Level 3

wbh_aoa229_buffet_deformed_Level-3.b8.ugrid

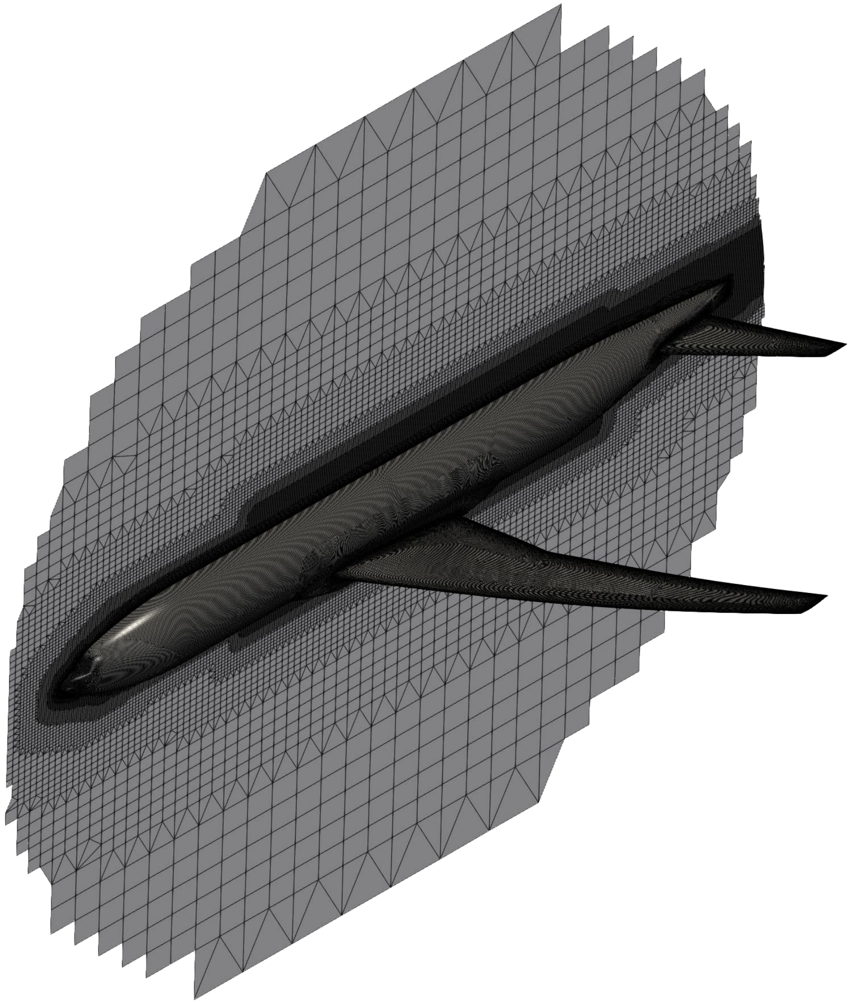
Level	Tetrahedrons	Pyramids	Prisms	Hexahedrons	Total Cells	Nodes
1	12,389,064	1,808,169	271,557	14,292,475	28,761,265	17,146,308
2	24,597,485	3,486,593	611,377	43,226,429	71,921,884	48,901,222
3	40,750,971	5,597,163	1,371,931	93,547,316	141,267,381	103,077,084
4	56,615,892	7,405,156	2,601,269	167,582,485	234,204,802	181,103,556
5	86,491,803	11,549,070	4,791,244	350,452,583	453,284,700	371,548,385
6	117,603,845	15,876,637	9,223,121	635,433,265	778,136,868	665,551,017



Mesh: Level 4

wbh_aoa229_buffet_deformed_Level-4.b8.ugrid

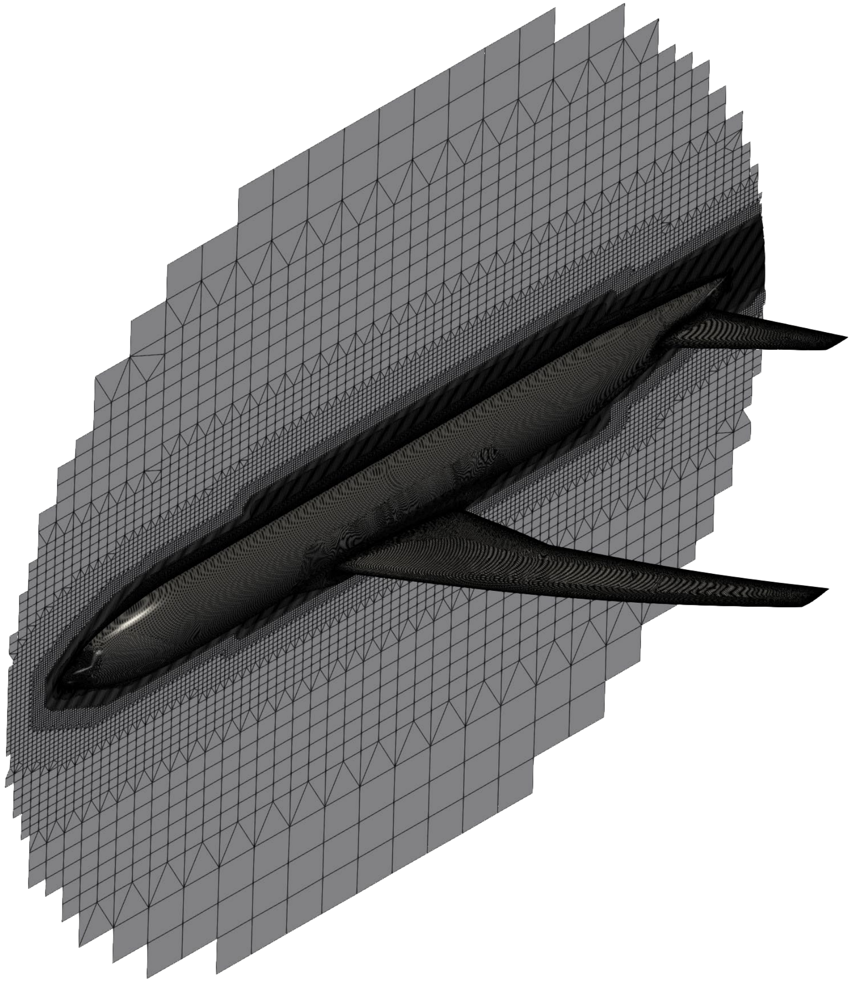
Level	Tetrahedrons	Pyramids	Prisms	Hexahedrons	Total Cells	Nodes
1	12,389,064	1,808,169	271,557	14,292,475	28,761,265	17,146,308
2	24,597,485	3,486,593	611,377	43,226,429	71,921,884	48,901,222
3	40,750,971	5,597,163	1,371,931	93,547,316	141,267,381	103,077,084
4	56,615,892	7,405,156	2,601,269	167,582,485	234,204,802	181,103,556
5	86,491,803	11,549,070	4,791,244	350,452,583	453,284,700	371,548,385
6	117,603,845	15,876,637	9,223,121	635,433,265	778,136,868	665,551,017



Mesh: Level 5

wbh_aoa229_buffet_deformed_Level-5.b8.ugrid

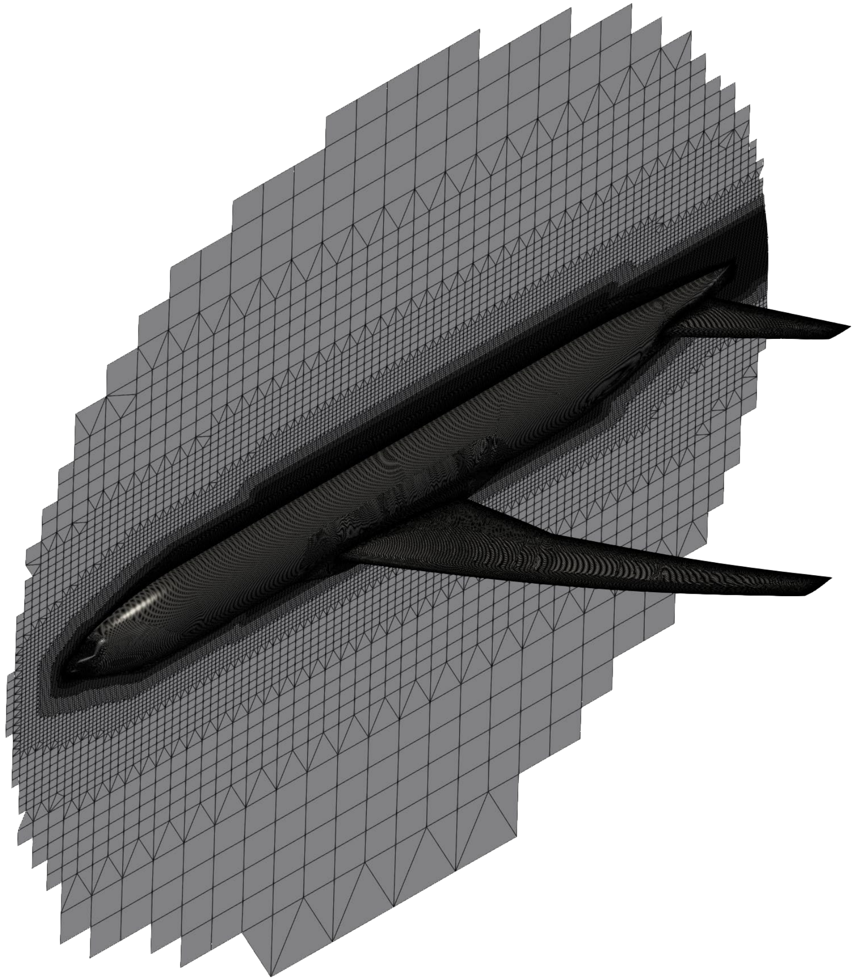
Level	Tetrahedrons	Pyramids	Prisms	Hexahedrons	Total Cells	Nodes
1	12,389,064	1,808,169	271,557	14,292,475	28,761,265	17,146,308
2	24,597,485	3,486,593	611,377	43,226,429	71,921,884	48,901,222
3	40,750,971	5,597,163	1,371,931	93,547,316	141,267,381	103,077,084
4	56,615,892	7,405,156	2,601,269	167,582,485	234,204,802	181,103,556
5	86,491,803	11,549,070	4,791,244	350,452,583	453,284,700	371,548,385
6	117,603,845	15,876,637	9,223,121	635,433,265	778,136,868	665,551,017



Mesh: Level 6

wbh_aoa229_buffet_deformed_Level-6.b8.ugrid

Level	Tetrahedrons	Pyramids	Prisms	Hexahedrons	Total Cells	Nodes
1	12,389,064	1,808,169	271,557	14,292,475	28,761,265	17,146,308
2	24,597,485	3,486,593	611,377	43,226,429	71,921,884	48,901,222
3	40,750,971	5,597,163	1,371,931	93,547,316	141,267,381	103,077,084
4	56,615,892	7,405,156	2,601,269	167,582,485	234,204,802	181,103,556
5	86,491,803	11,549,070	4,791,244	350,452,583	453,284,700	371,548,385
6	117,603,845	15,876,637	9,223,121	635,433,265	778,136,868	665,551,017



Mesh: DPW-6 M (For Steady State Comparison)

V2-NASA.GEOLAB.WB.ae2.75.UNS.M.VGRID.merged.lb8.ugrid

Level	Tetrahedrons	Pyramids	Prisms	Hexahedrons	Total Cells	Nodes
1	12,389,064	1,808,169	271,557	14,292,475	28,761,265	17,146,308
2	24,597,485	3,486,593	611,377	43,226,429	71,921,884	48,901,222
3	40,750,971	5,597,163	1,371,931	93,547,316	141,267,381	103,077,084
4	56,615,892	7,405,156	2,601,269	167,582,485	234,204,802	181,103,556
5	86,491,803	11,549,070	4,791,244	350,452,583	453,284,700	371,548,385
6	117,603,845	15,876,637	9,223,121	635,433,265	778,136,868	665,551,017
M	143,061,902	220,782	38,754,839	0	182,037,523	44,263,902
U	463,643,443	705,551	142,298,011	0	606,647,005	151,342,190

Mesh: DPW-6 U (For Steady State Comparison)

V2-NASA.GEOLAB.WB.ae2.75.UNS.U.VGRID.merged.lb8.ugrid

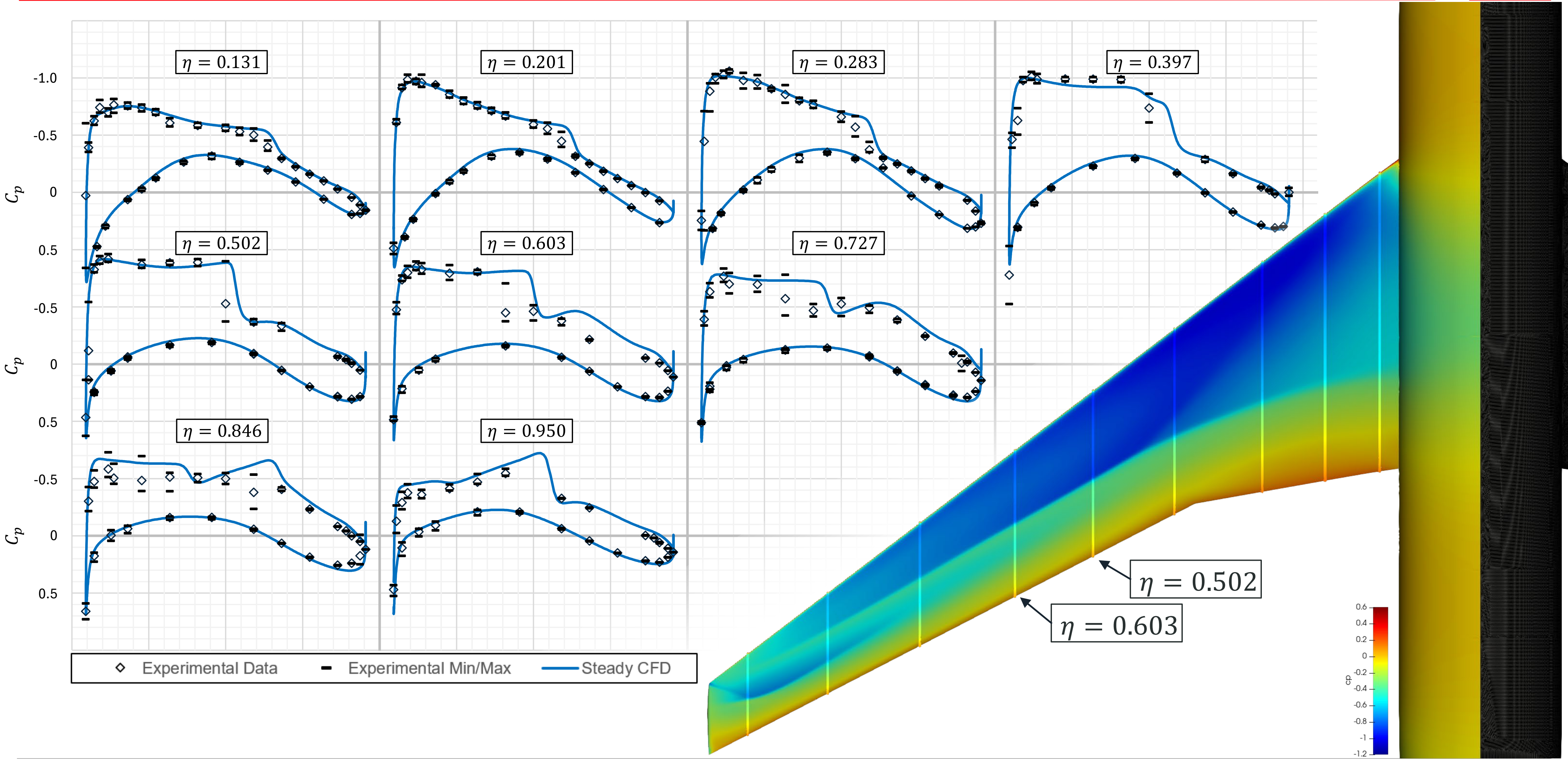
Level	Tetrahedrons	Pyramids	Prisms	Hexahedrons	Total Cells	Nodes
1	12,389,064	1,808,169	271,557	14,292,475	28,761,265	17,146,308
2	24,597,485	3,486,593	611,377	43,226,429	71,921,884	48,901,222
3	40,750,971	5,597,163	1,371,931	93,547,316	141,267,381	103,077,084
4	56,615,892	7,405,156	2,601,269	167,582,485	234,204,802	181,103,556
5	86,491,803	11,549,070	4,791,244	350,452,583	453,284,700	371,548,385
6	117,603,845	15,876,637	9,223,121	635,433,265	778,136,868	665,551,017
M	143,061,902	220,782	38,754,839	0	182,037,523	44,263,902
U	463,643,443	705,551	142,298,011	0	606,647,005	151,342,190

Steady State CFD Groundwork

Classic DPW Case: M=0.85 Re_c=5M C_L=0.50

Mesh: DPW-6 V2-NASA.GEOLAB.WB.ae2.75.UNS.U.VGRID.merged

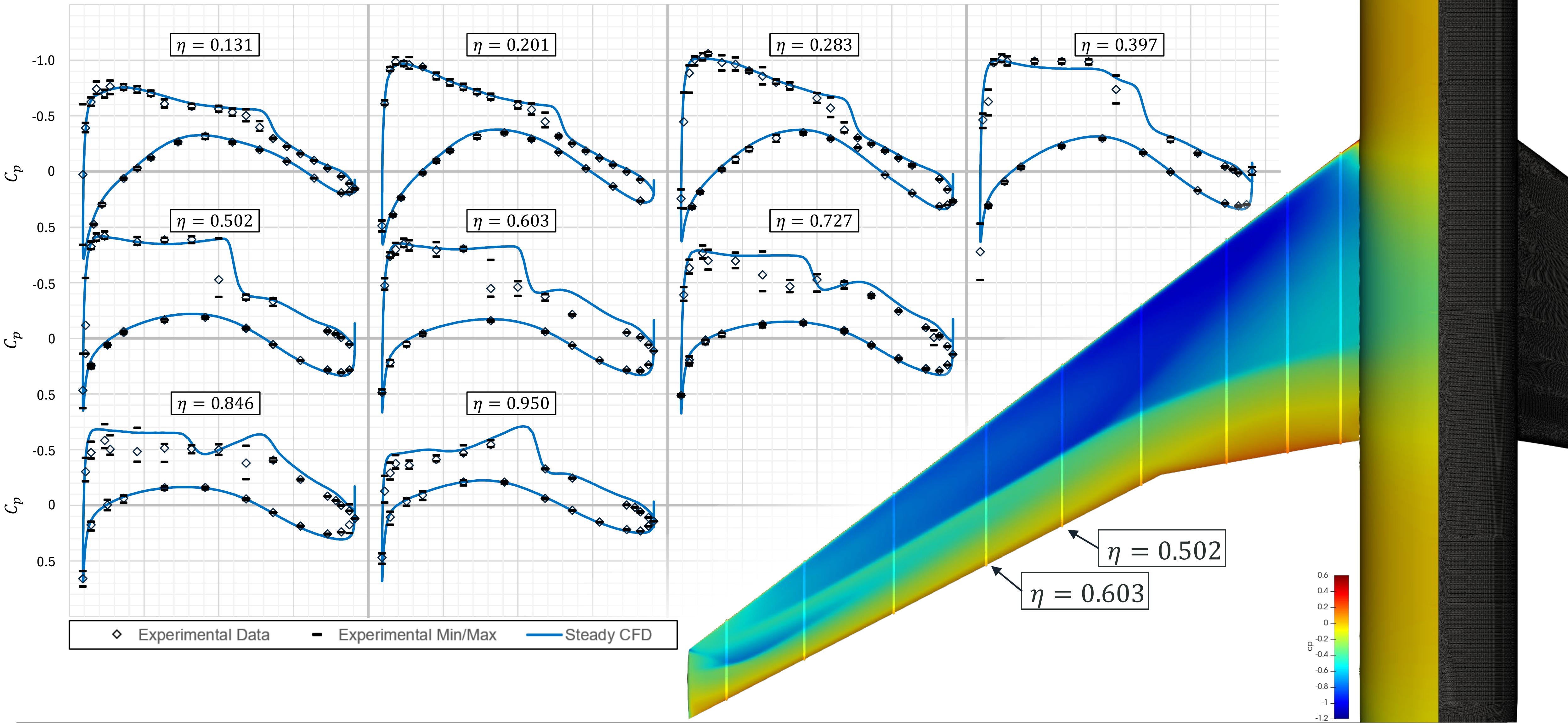
Steady



Classic DPW Case: M=0.85 Re_c=5M C_L=0.50

Mesh: DPW-6 V2-NASA.GEOLAB.WB.ae2.75.UNS.M.VGRID.merged

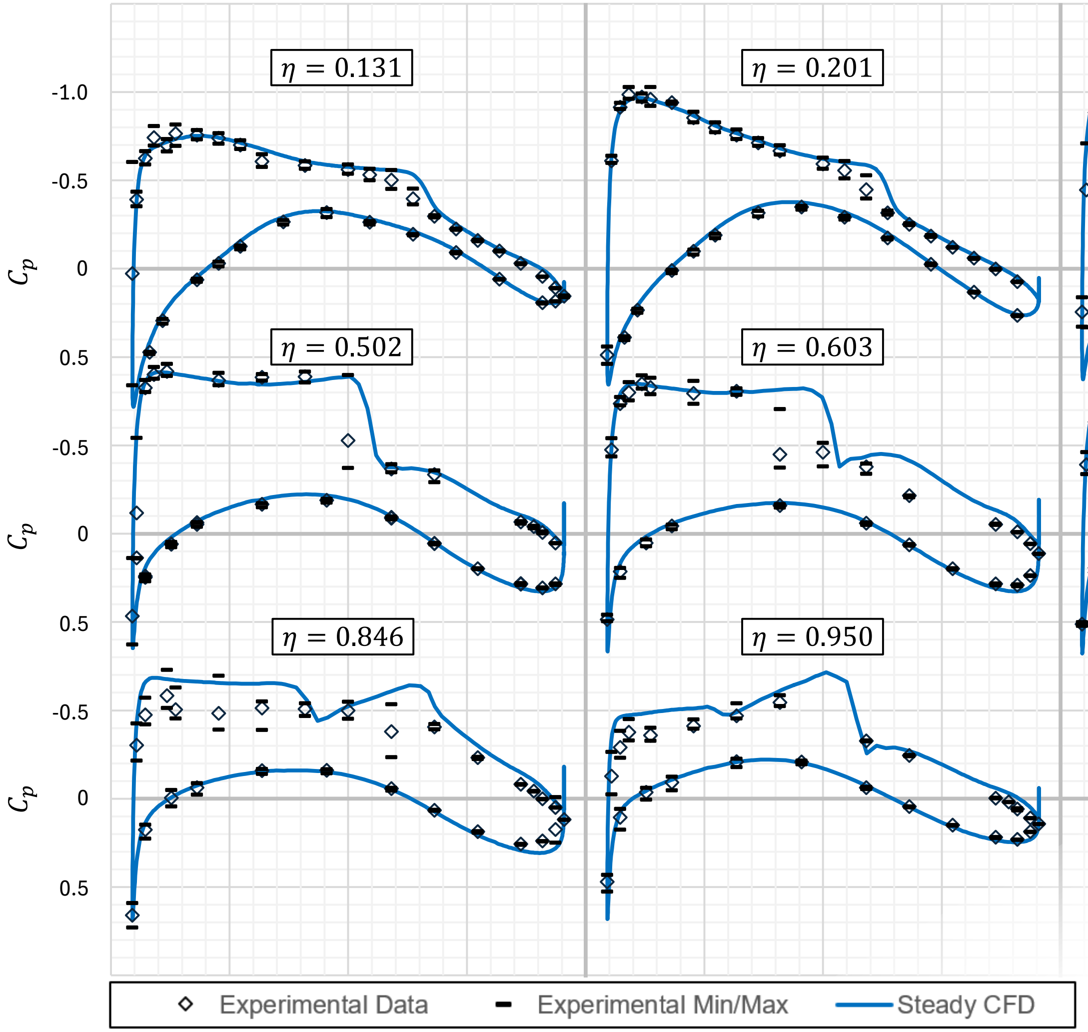
Steady

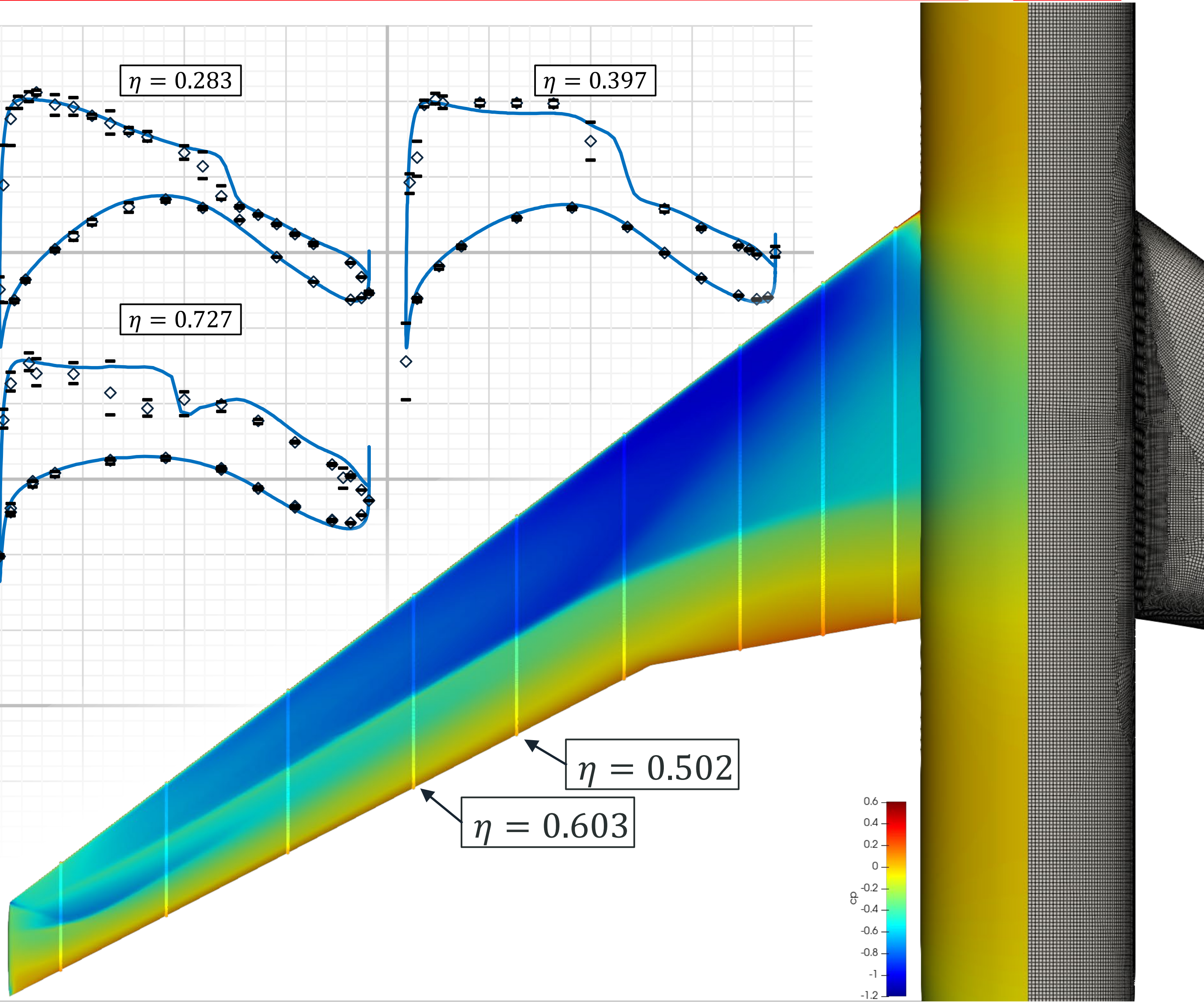


Classic DPW Case: M=0.85 Re_c=5M C_L=0.50

Mesh: DPW-7_CRM_wbt_182_2.500deg_02_03_2021__WeP_in_Level-3

Steady

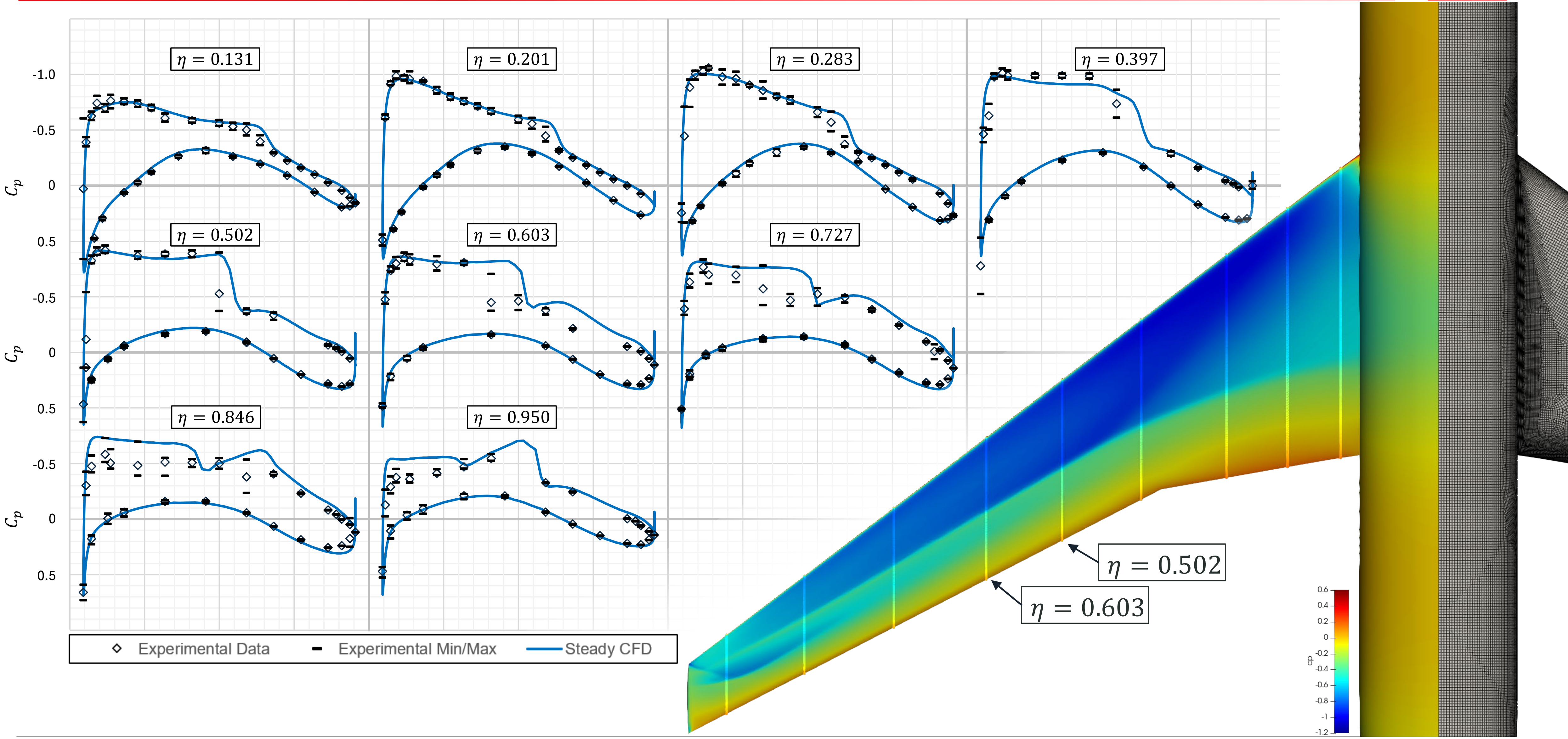




Classic DPW Case: M=0.85 Re_c=5M C_L=0.50

Mesh: wbh_aoa229_buffet_deformed_Level-3

Steady



Conclusions

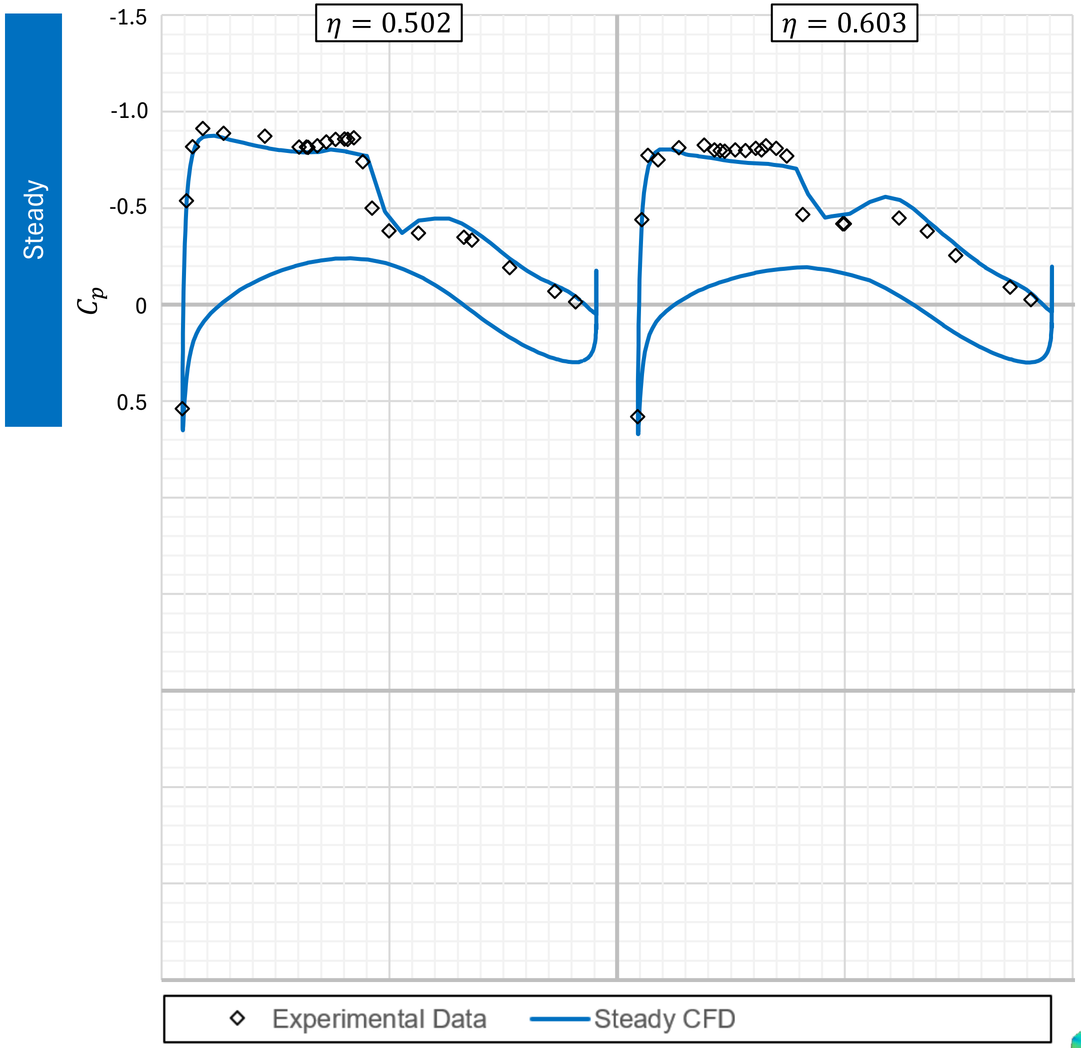
- Geometry differences are most pronounced in outboard most section cuts
- Solution influence from surface mesh resolution is notable outboard of 50% semispan

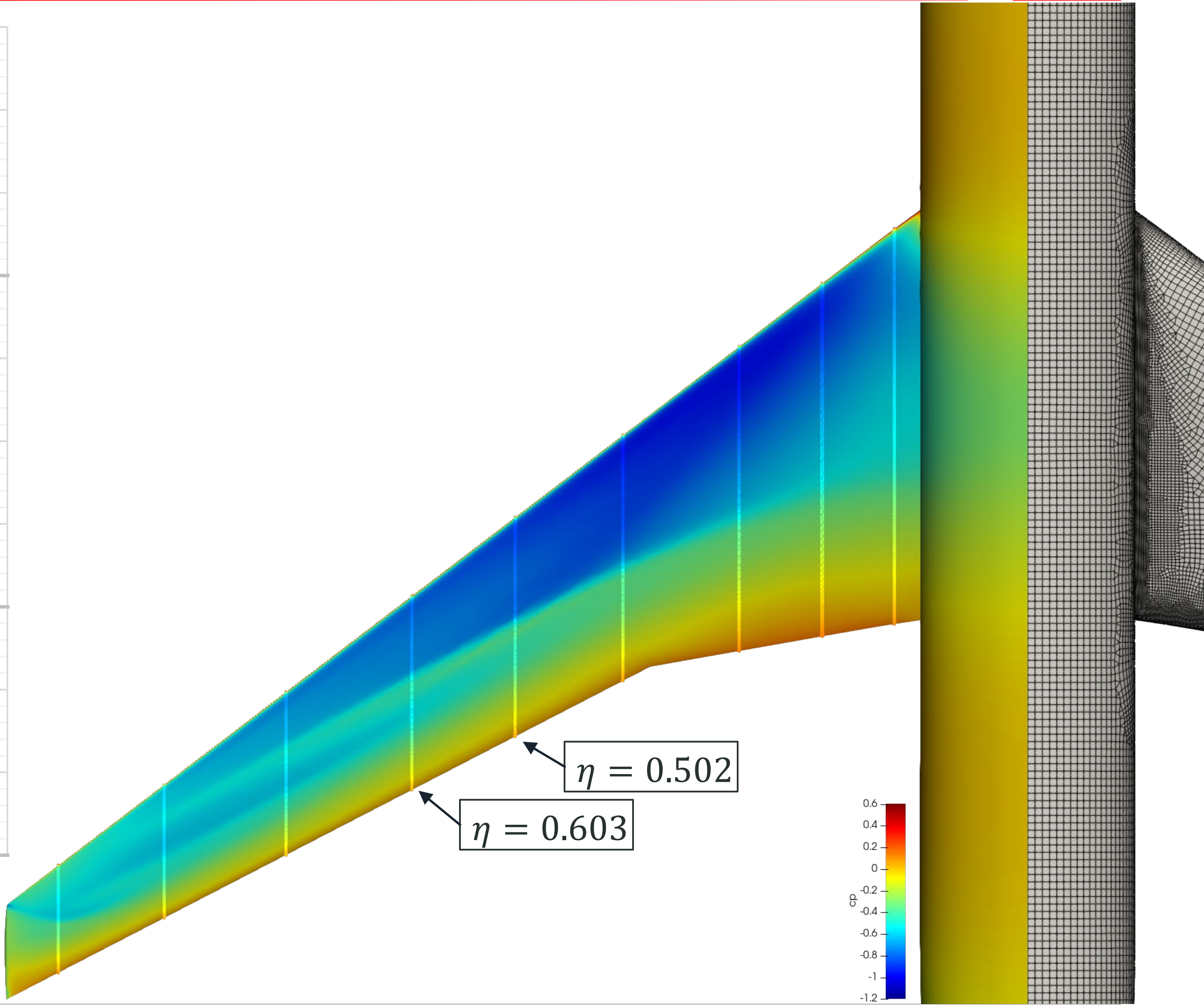
DPW8 Test Case 2 AoA=2.29 Mesh Sensitivity

FUN3D, Steady State RANS

DPW8 Test Case 2 AoA=2.29

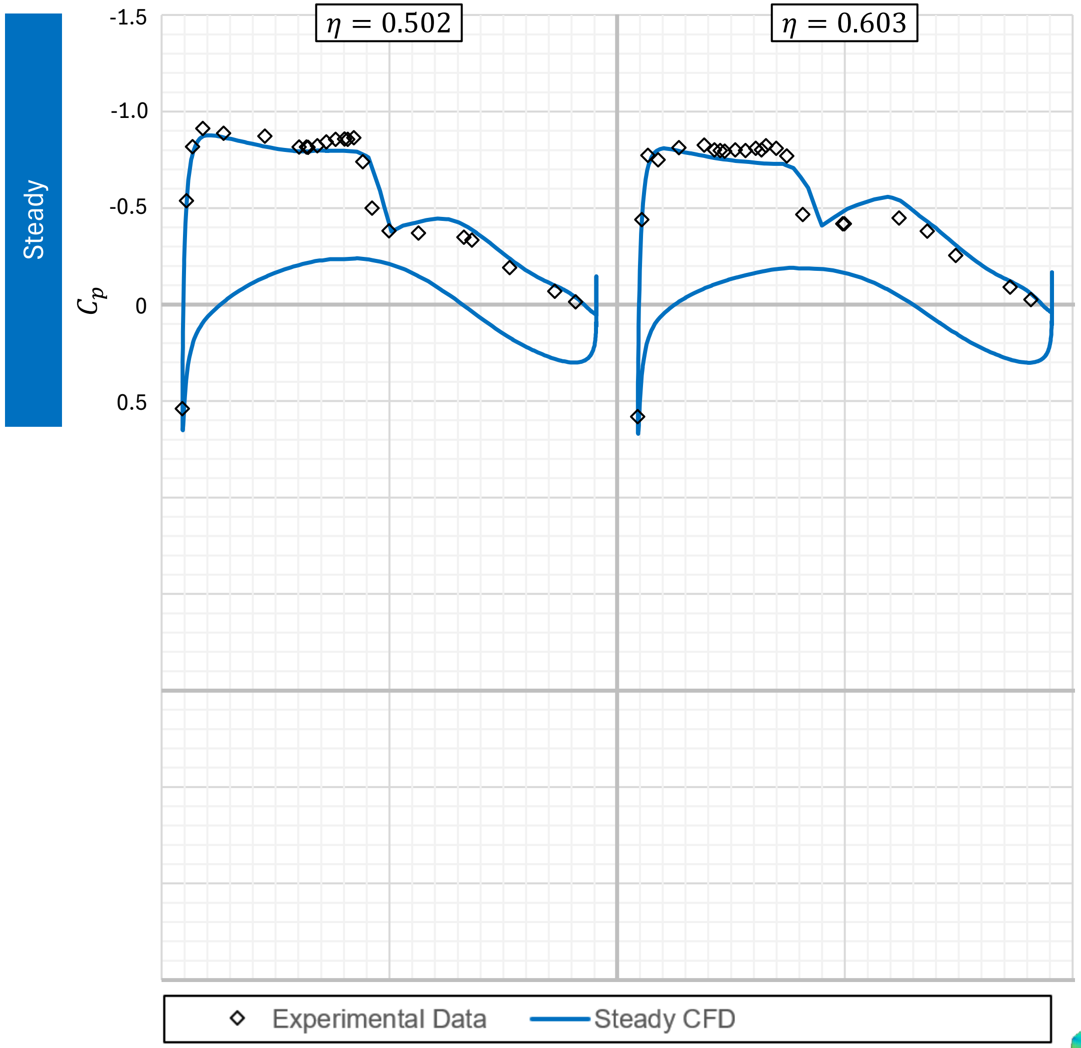
Mesh: wbh_aoa229_buffet_deformed_Level-1

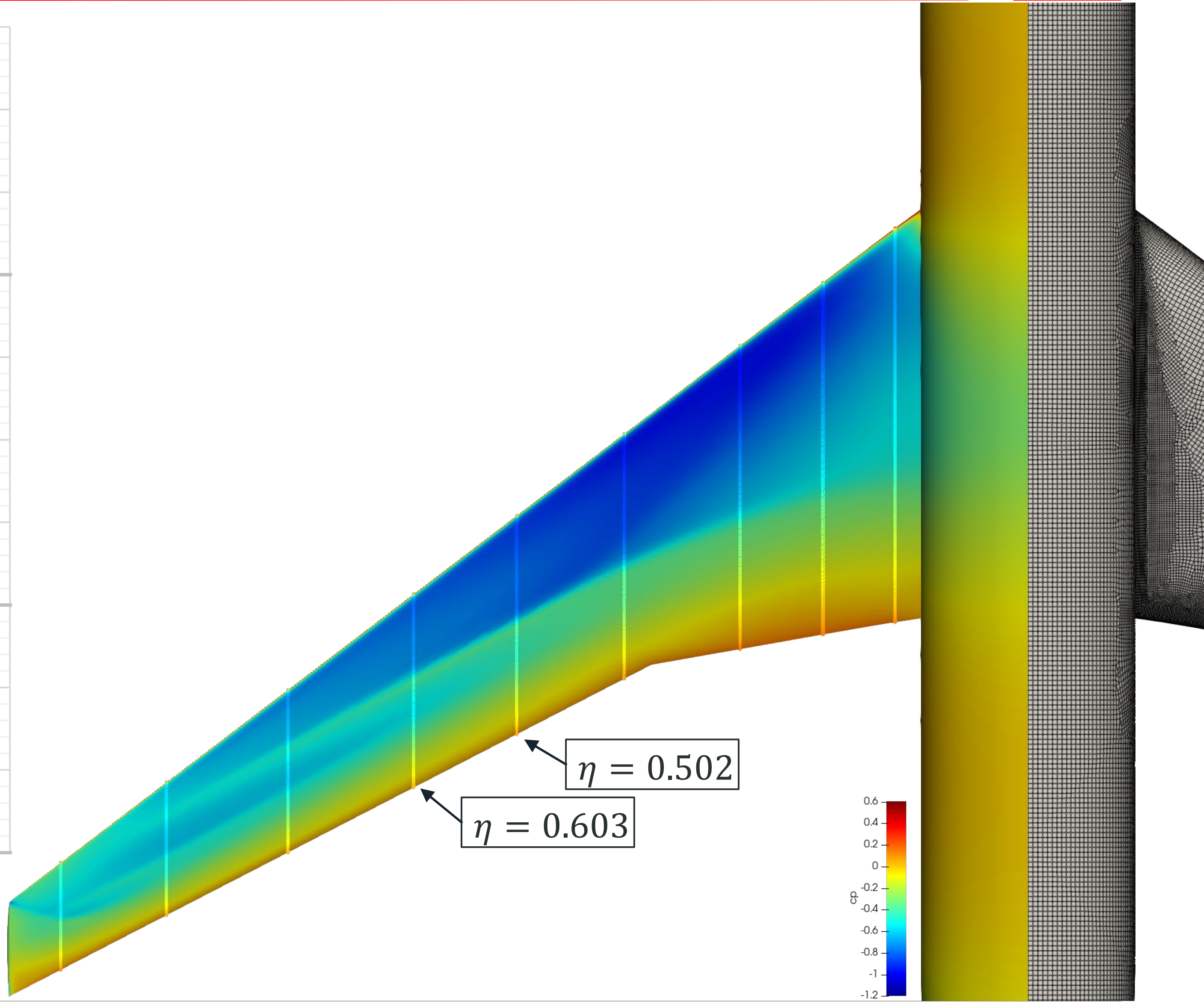




DPW8 Test Case 2 AoA=2.29

Mesh: wbh_aoa229_buffet_deformed_Level-2

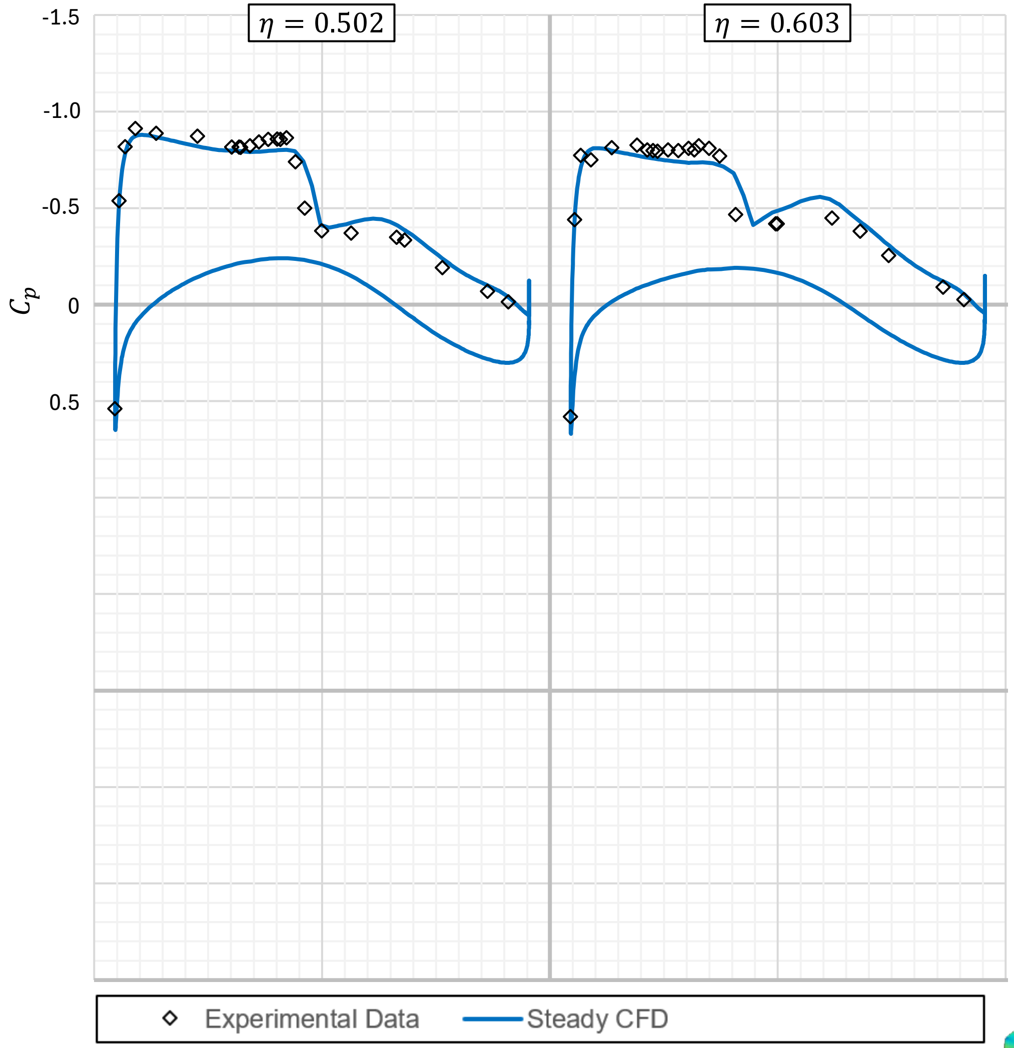


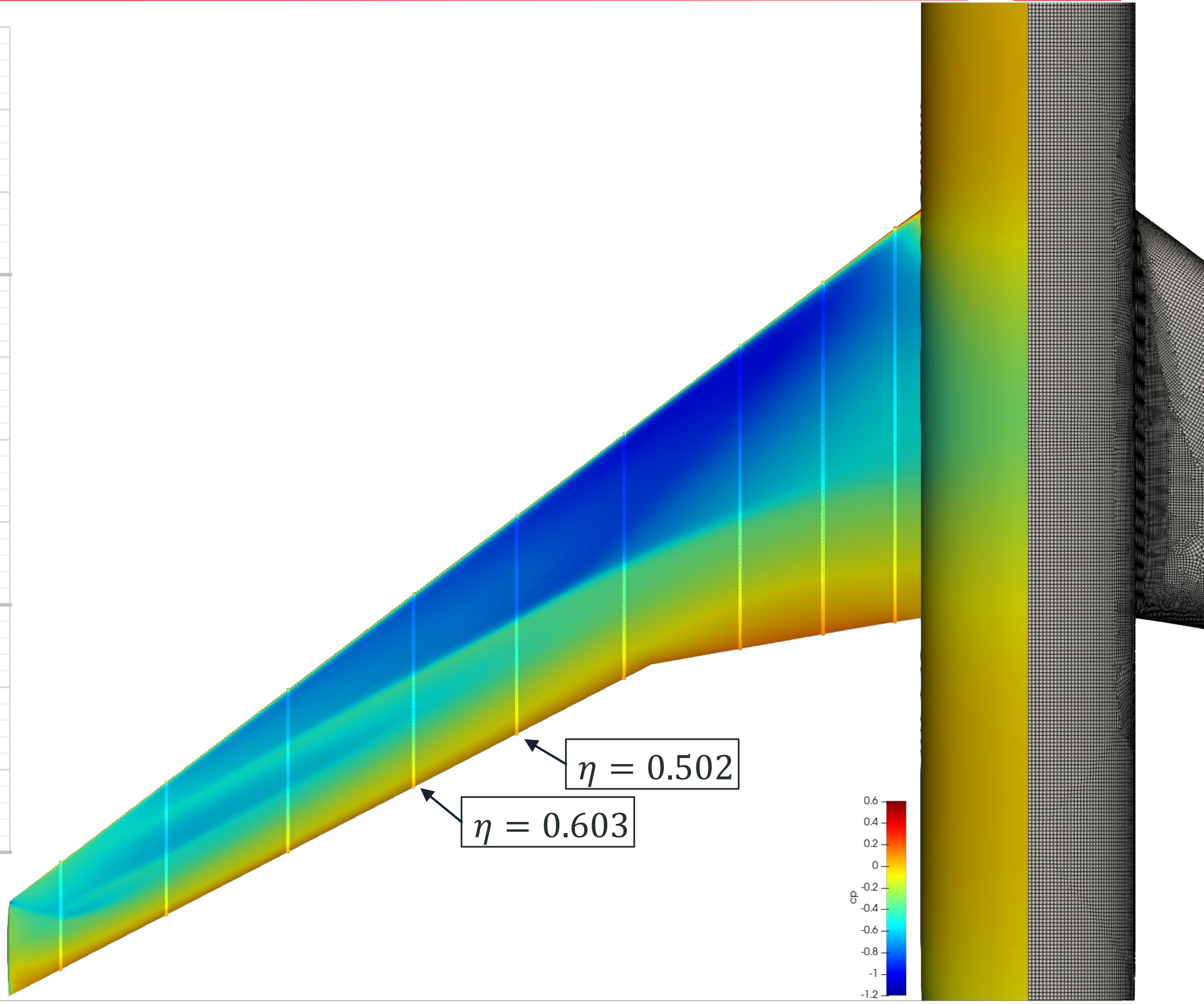


DPW8 Test Case 2 AoA=2.29

Mesh: wbh_aoa229_buffet_deformed_Level-3

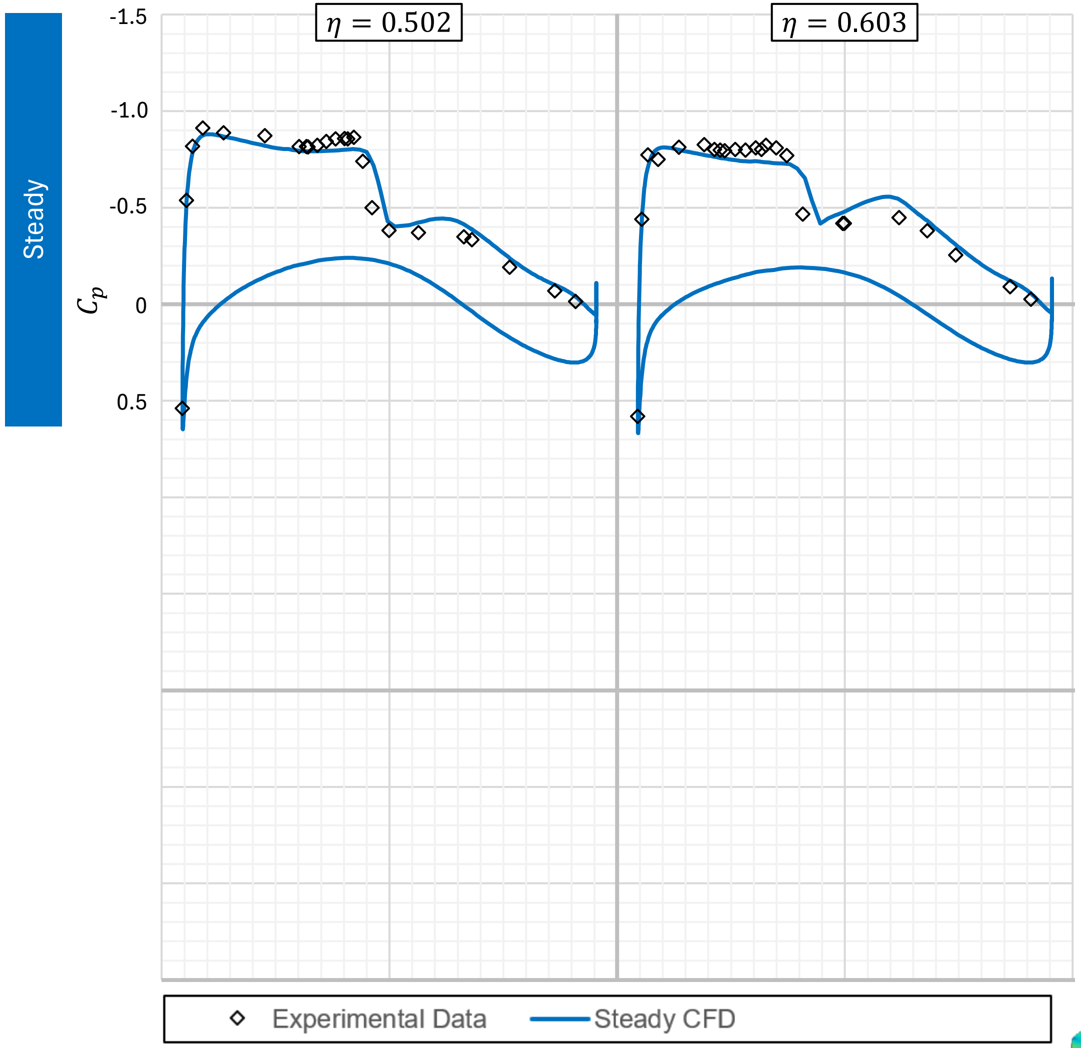
Steady

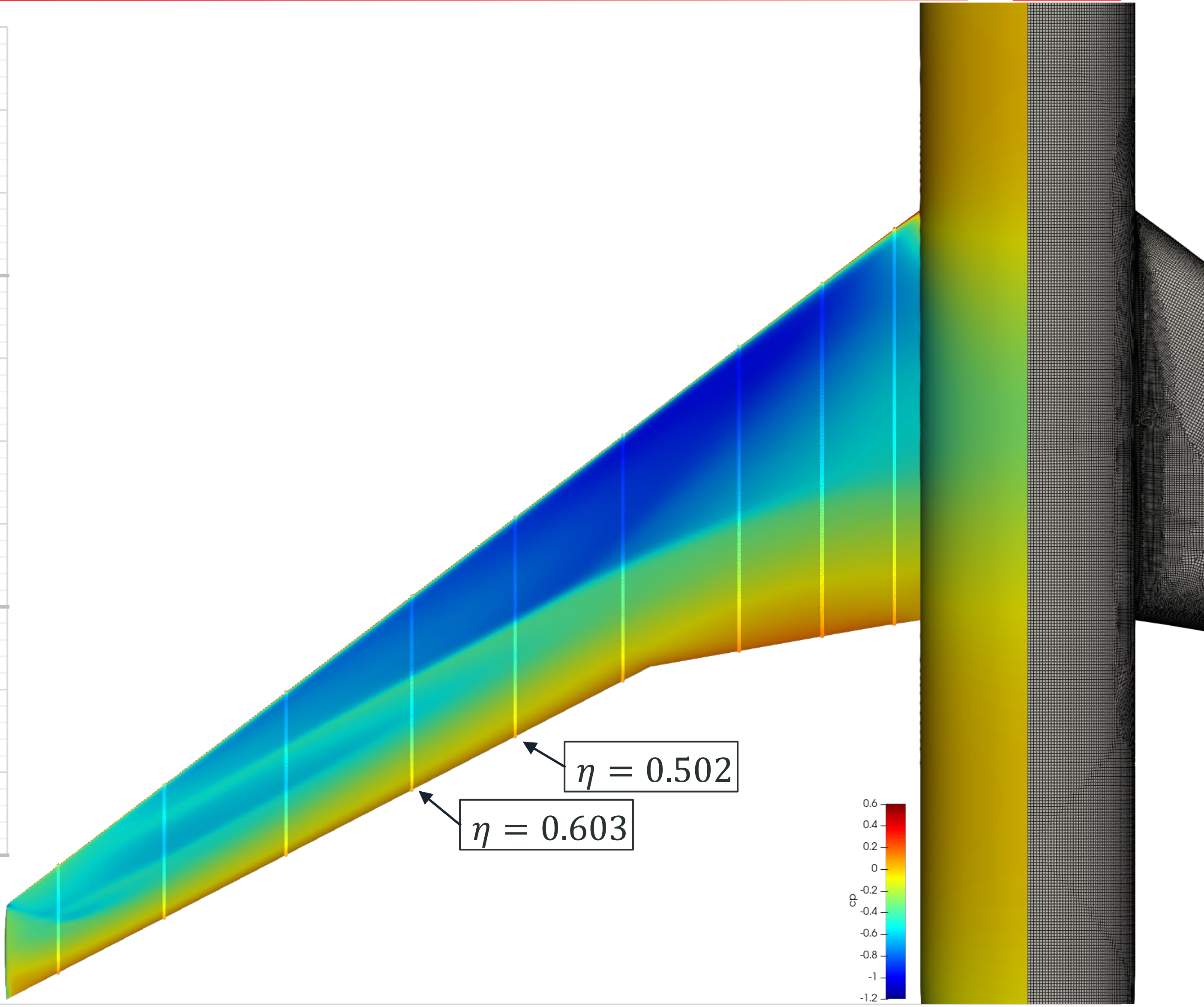




DPW8 Test Case 2 AoA=2.29

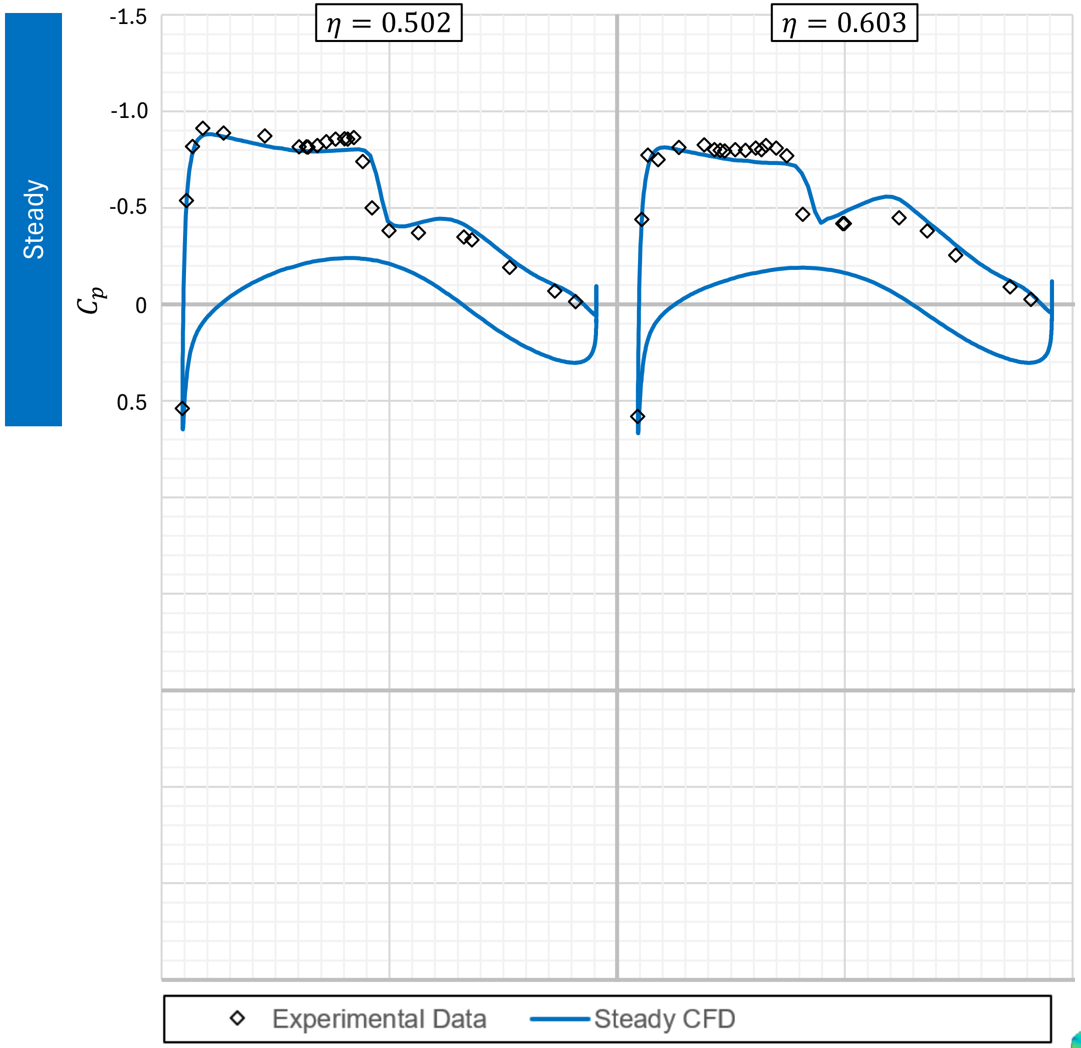
Mesh: wbh_aoa229_buffet_deformed_Level-4

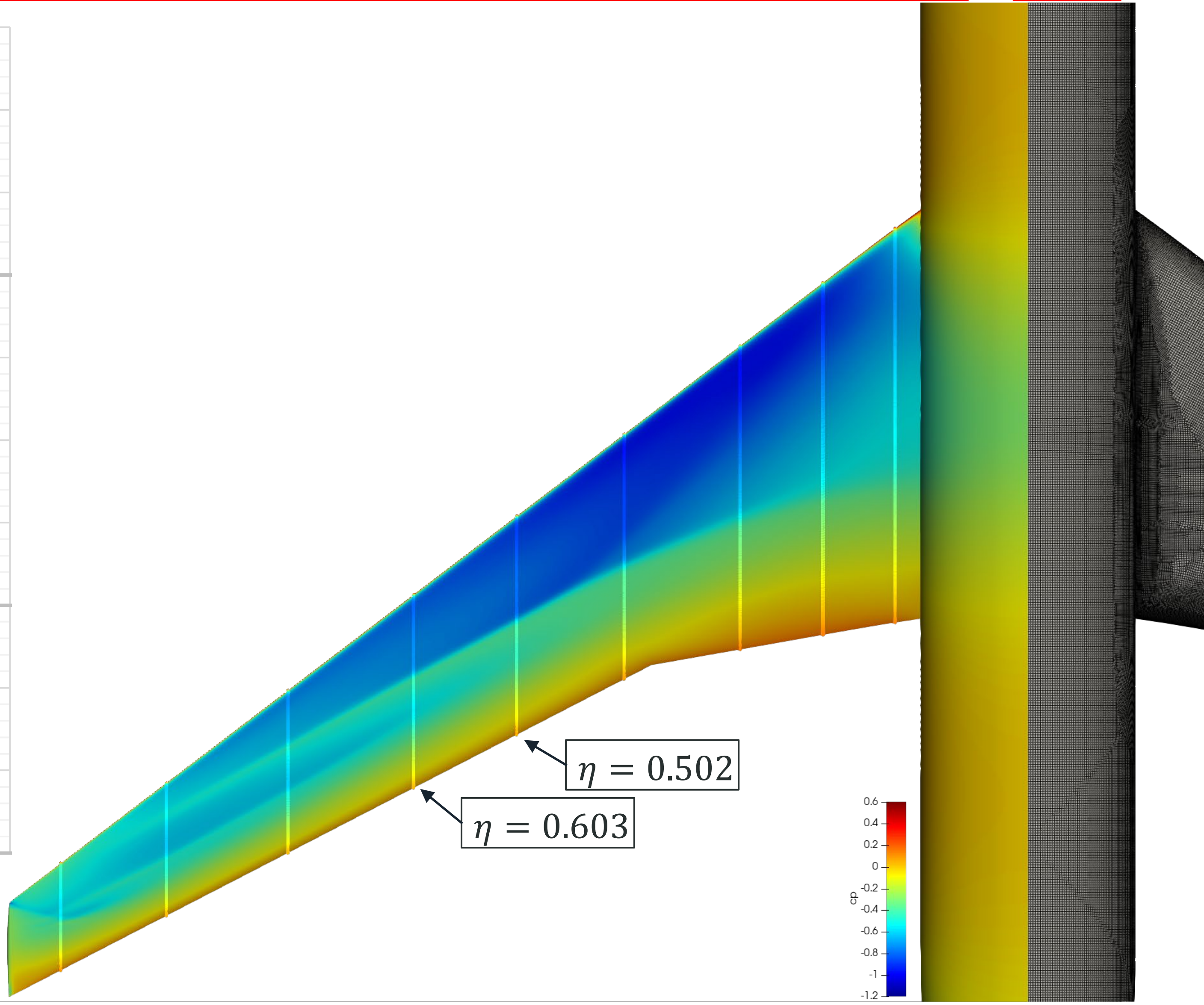




DPW8 Test Case 2 AoA=2.29

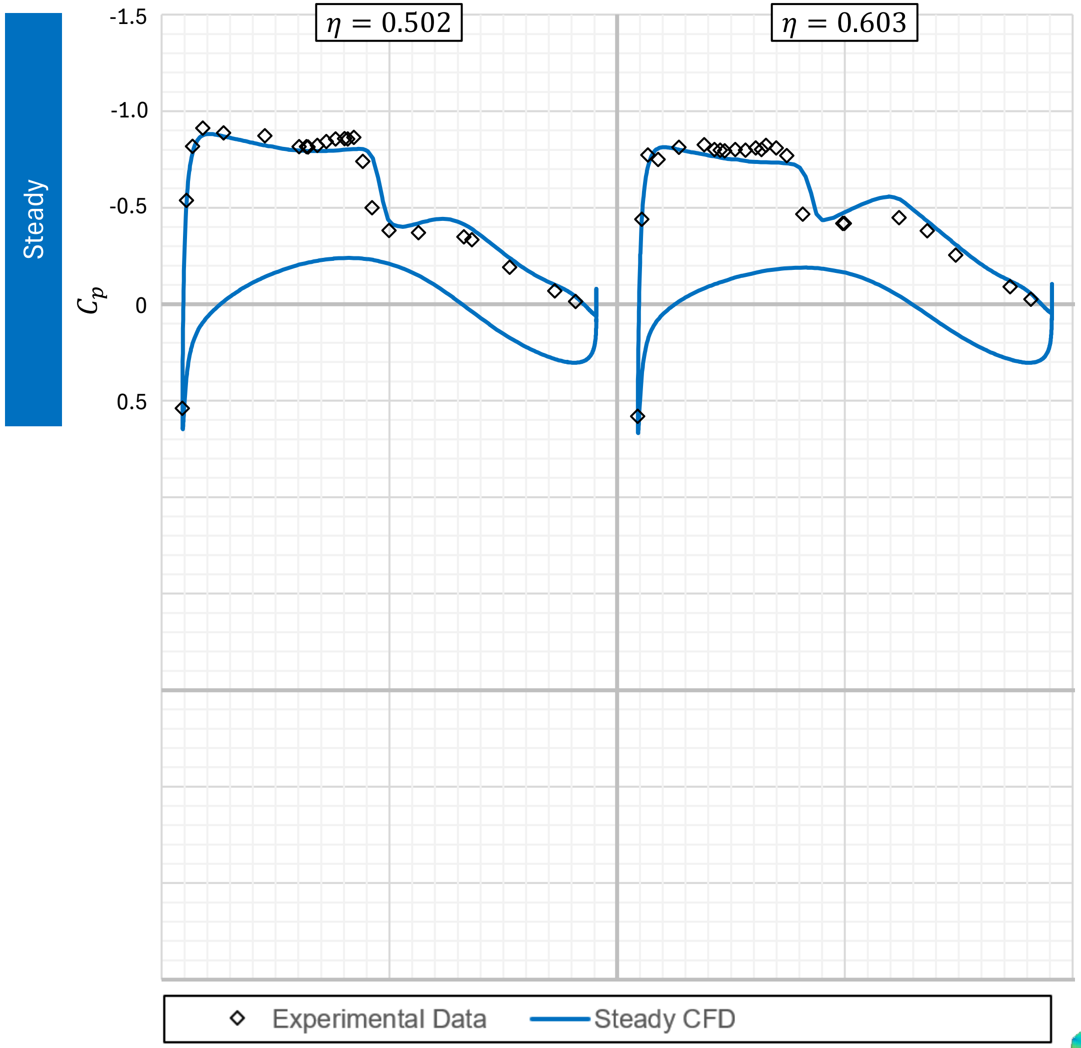
Mesh: wbh_aoa229_buffet_deformed_Level-5

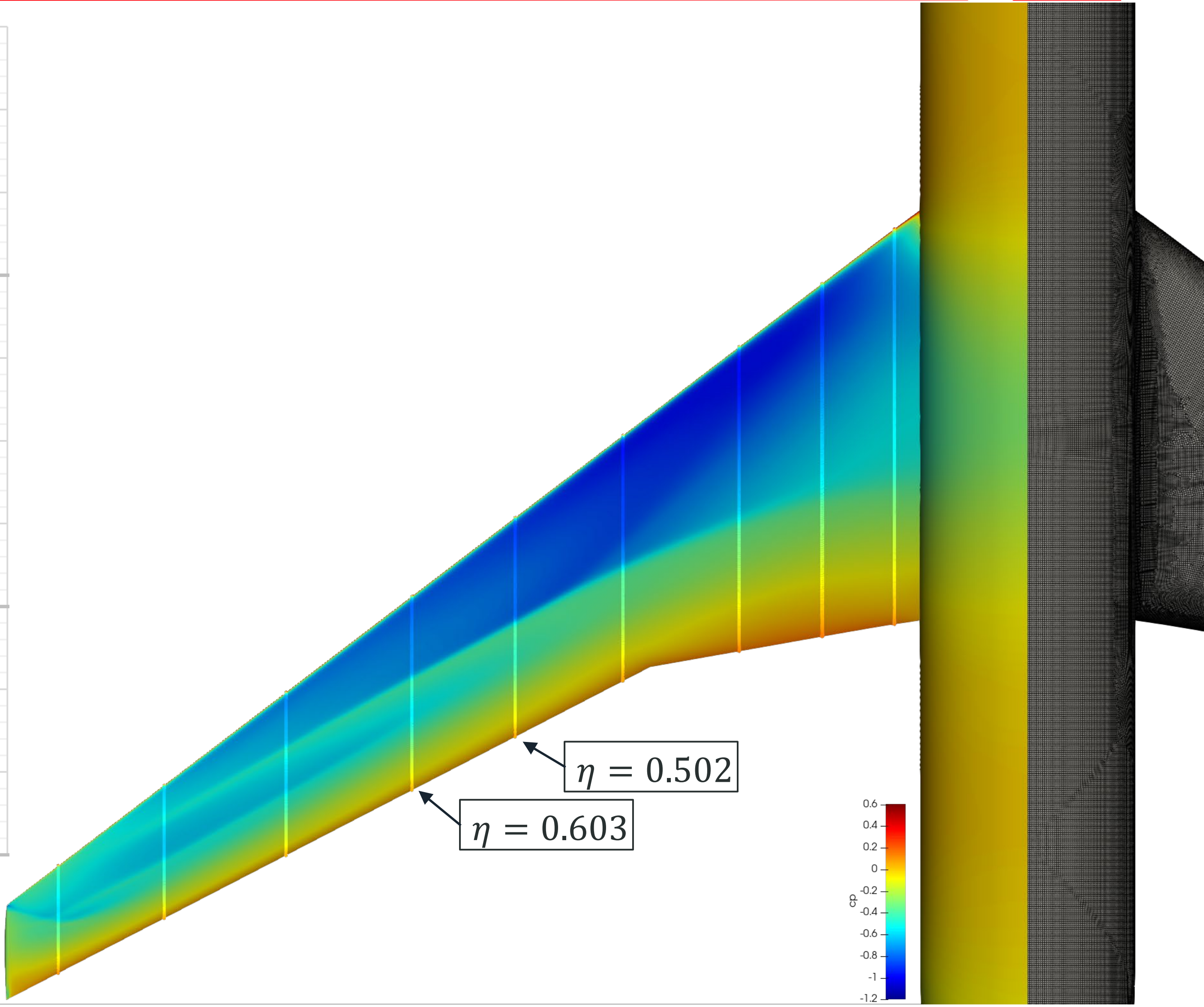




DPW8 Test Case 2 AoA=2.29

Mesh: wbh_aoa229_buffet_deformed_Level-6





Steady State Grid Study Conclusions

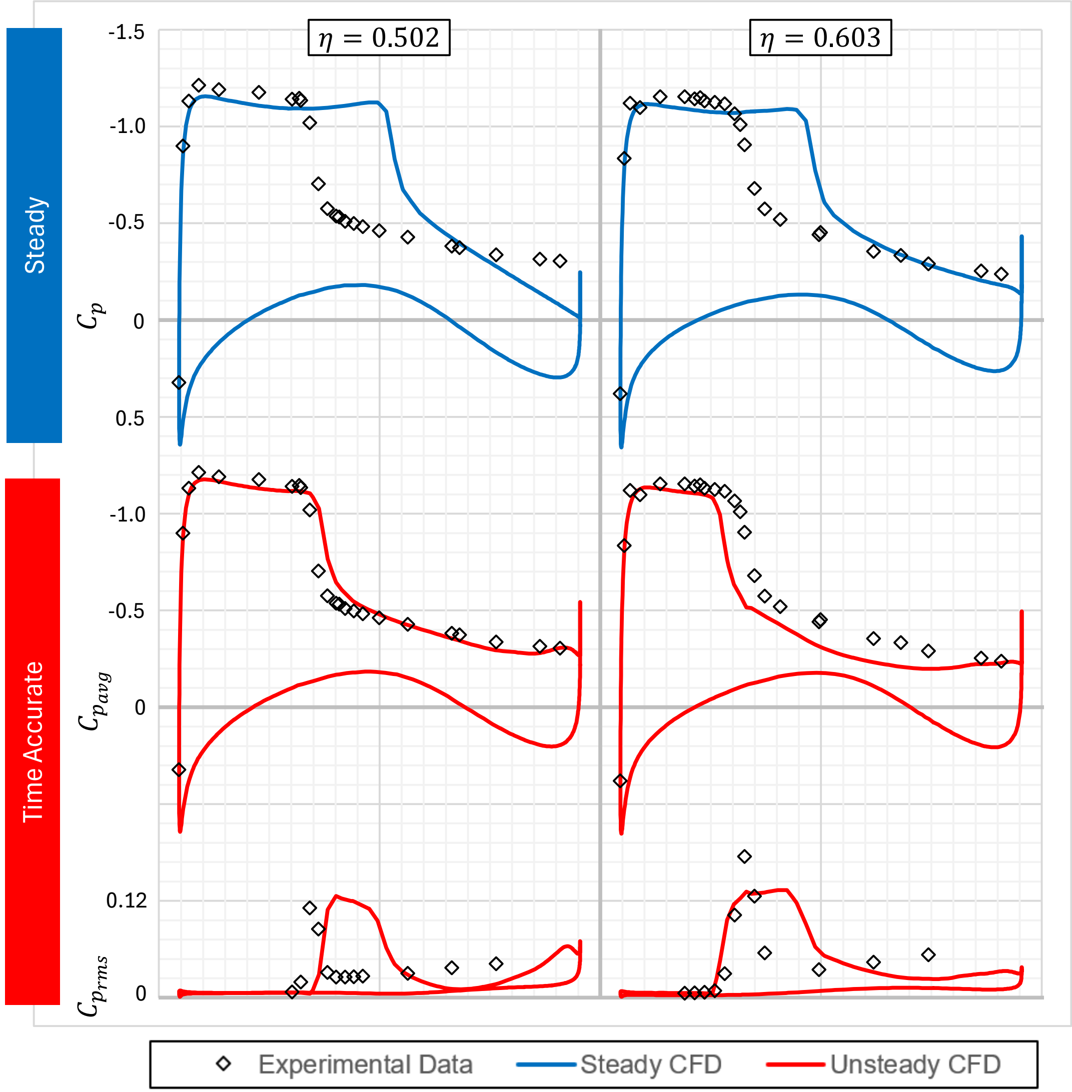
- Mesh level 1 has notable influence on steady state RANS solution
- Mesh levels 2 thru 6 provide reasonable resolution for steady state RANS
- Mesh level 3 will be used for Unsteady CFD analysis

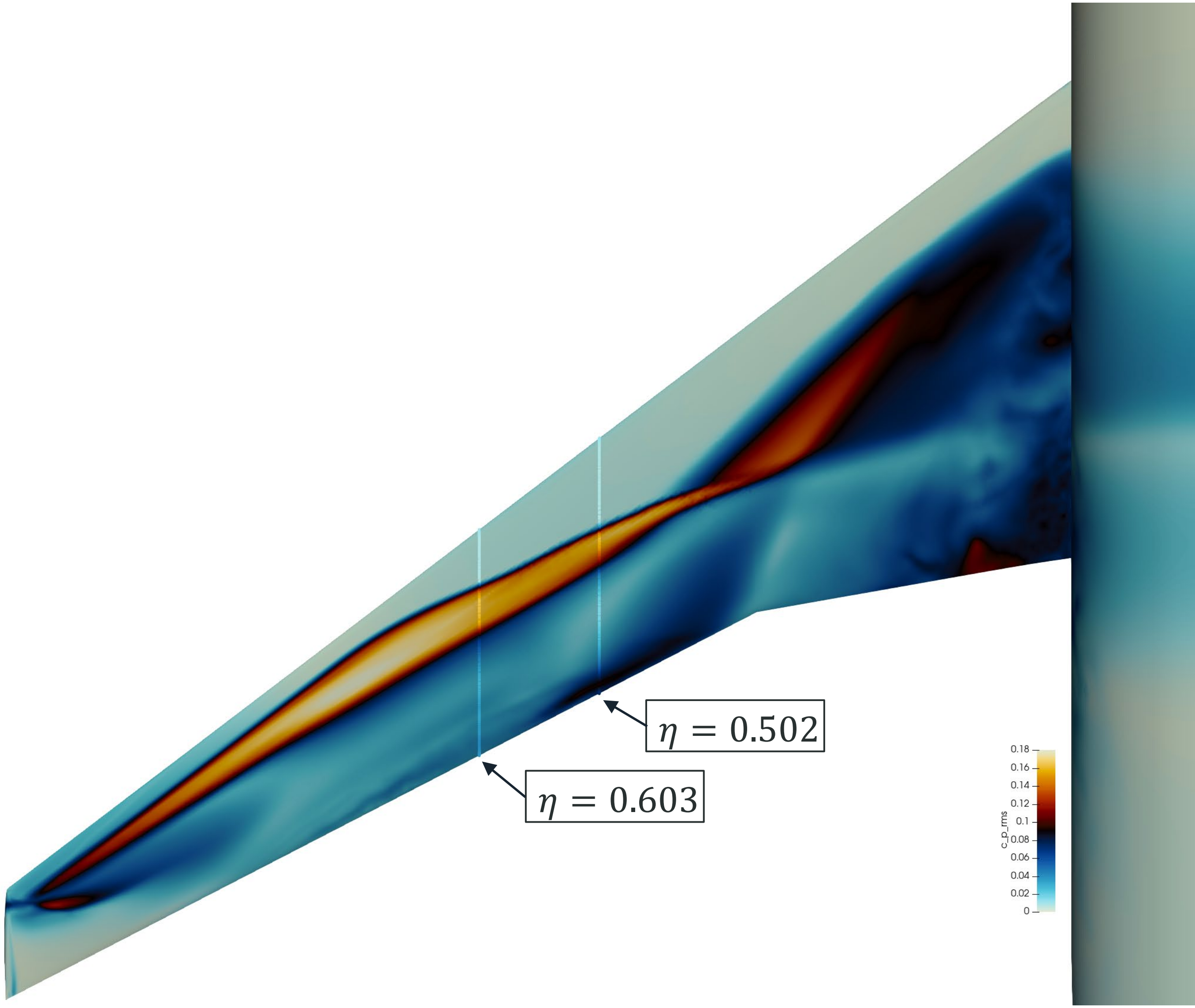
DPW8 Test Case 2 AoA=4.84

FUN3D, Time Accurate DDES

DPW8 Test Case 2 AoA=4.84

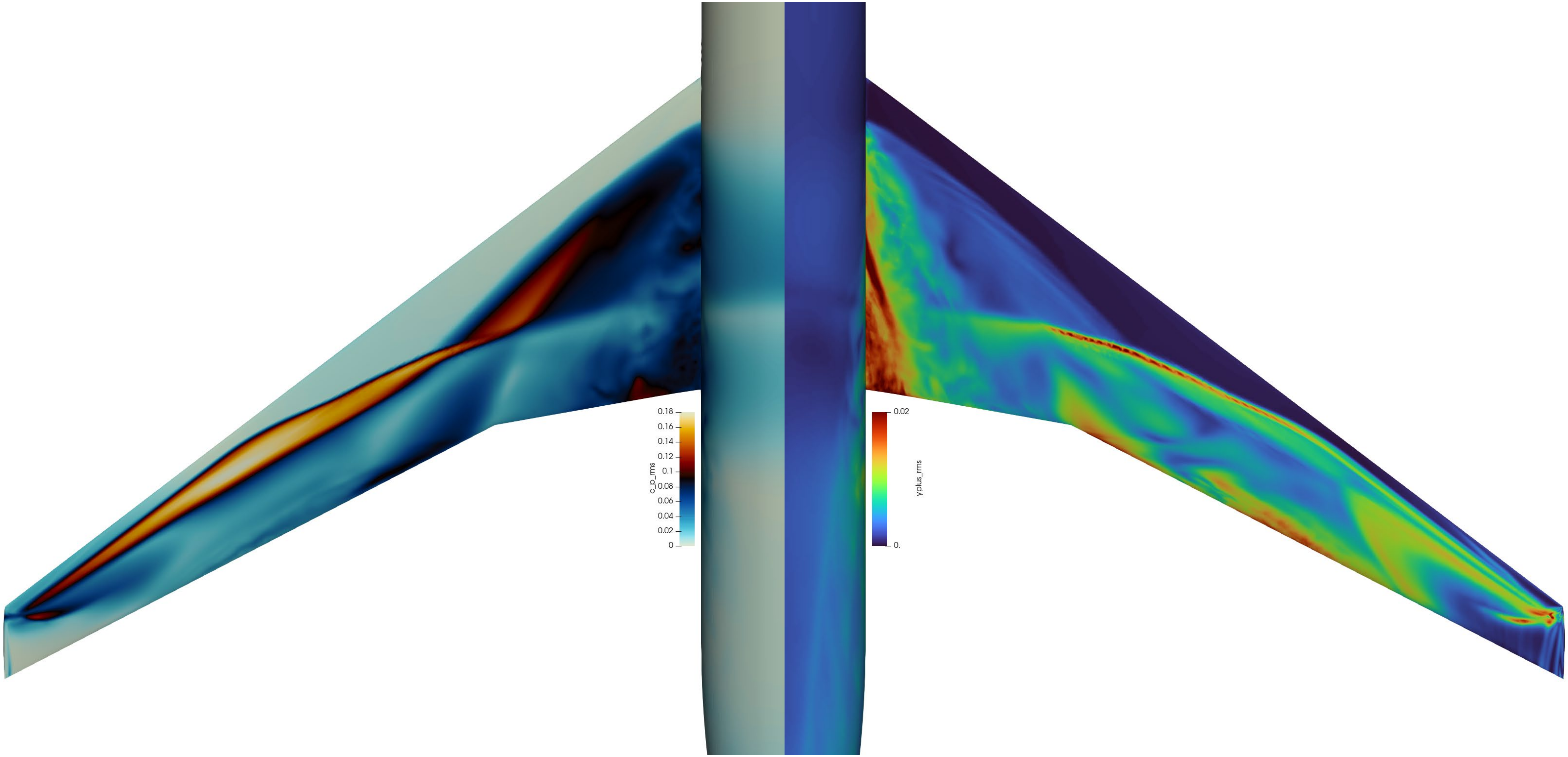
Mesh: wbh_aoa484_buffet_deformed_Level-3





DPW8 Test Case 2 AoA=4.84

Mesh: wbh_aoa484_buffet_deformed_Level-3



Test Case 2: Unsteady CFD Study Conclusions

- Similar findings as those for Case 1a/1b with unsteady CFD providing improved prediction of time averaged pressures
- Pressure fluctuation chordwise spatial extent over-predicted.

Thank You!