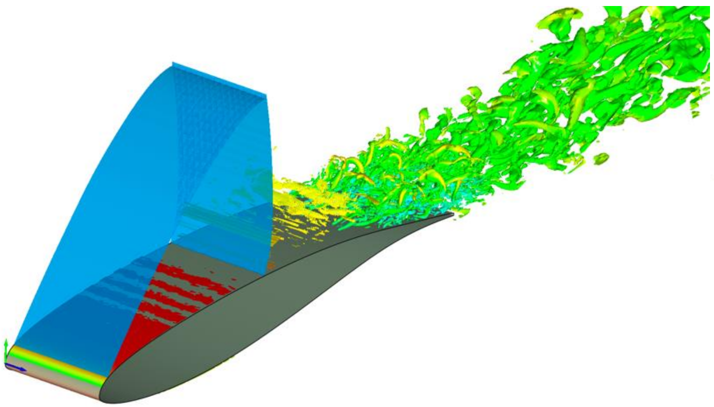
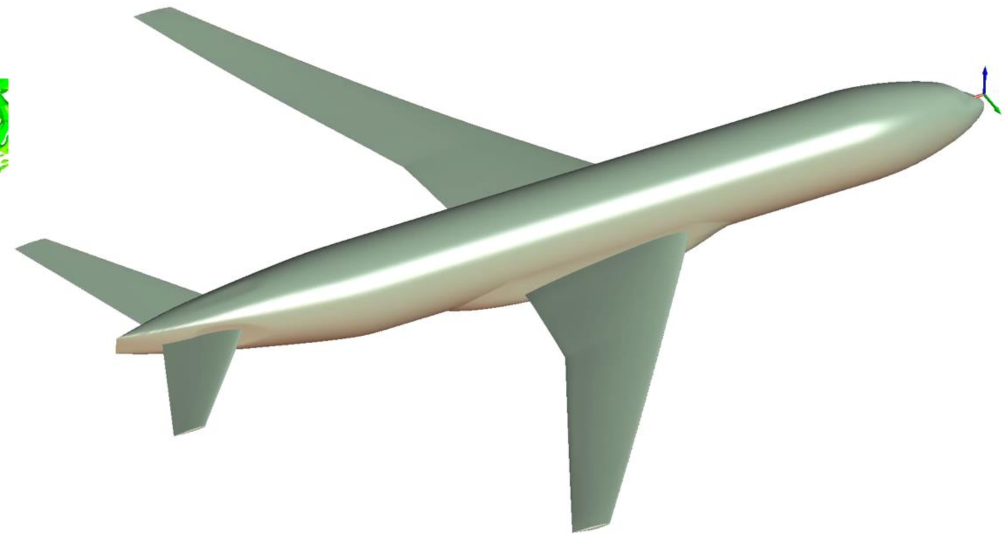
CFD++ Computations of DPW8 Case 3 (with a Summary of Case 1)





Paul Batten, Beerinder Singh, Ravi Kovvali, Oshin Peroomian
& Nili Bachchan
Metacomp Technologies, Inc.

AIAA Aviation, June 2026

Overview

- Solver & Settings
- Test Case 1 – Recap & Motivation
- FSI Approach
- Test Case 3
- Summary

Solver & Settings

- CFD++ version 22.5
- Nodal-reconstruction transport scheme
- HLLC Riemann solver with Smart SGS
- NNDB TVD limiter (low diffusion, but *bounded*)
- Implicit DTS solver & algebraic multi-grid
- Self-tuning far-field absorbing layers
- SA-based DDES (+ Deck/Renard EPSF and large time-step SGS filter augmentation)

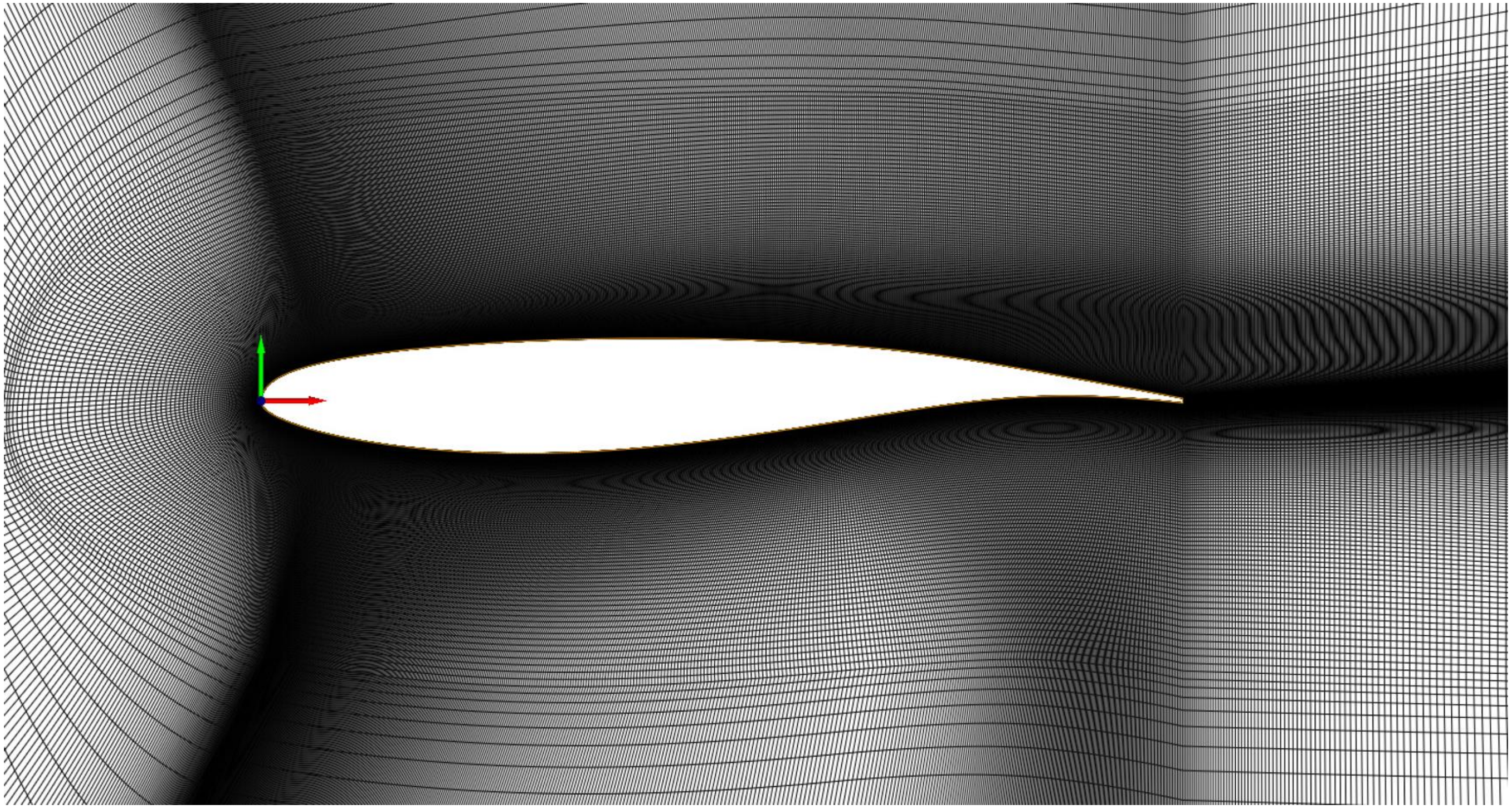
TC1: ONERA OAT15A Airfoil

1. Widely-studied aerodynamic benchmark case based on 2D supercritical airfoil geometry
2. Transition at x/c=7% on both upper & lower surfaces
3. Re(chord) = 3e6
4. M=0.73
5. AoAs = 1.36°, 1.5°, 2.5°, 3.0°, 3.1°, 3.25°, 3.4°, **3.5°**, 3.6°, **3.9°**
6. Pressure/time histories recorded from:
   probe 1 (x/c=0.9 on upper surface)
   probe 2 (x/c=0.55 on lower surface)
   probe 3 (x/c=0.45 on upper surface)
7. Shock-oscillation period is ~ 0.012 s or ~ 13 CTUs

*__Data available__ from Jacquin et al., *Experimental Study of Shock Oscillation over a Transonic Supercritical Profile*, AIAA J. Vol. 47, No. 9, 2009

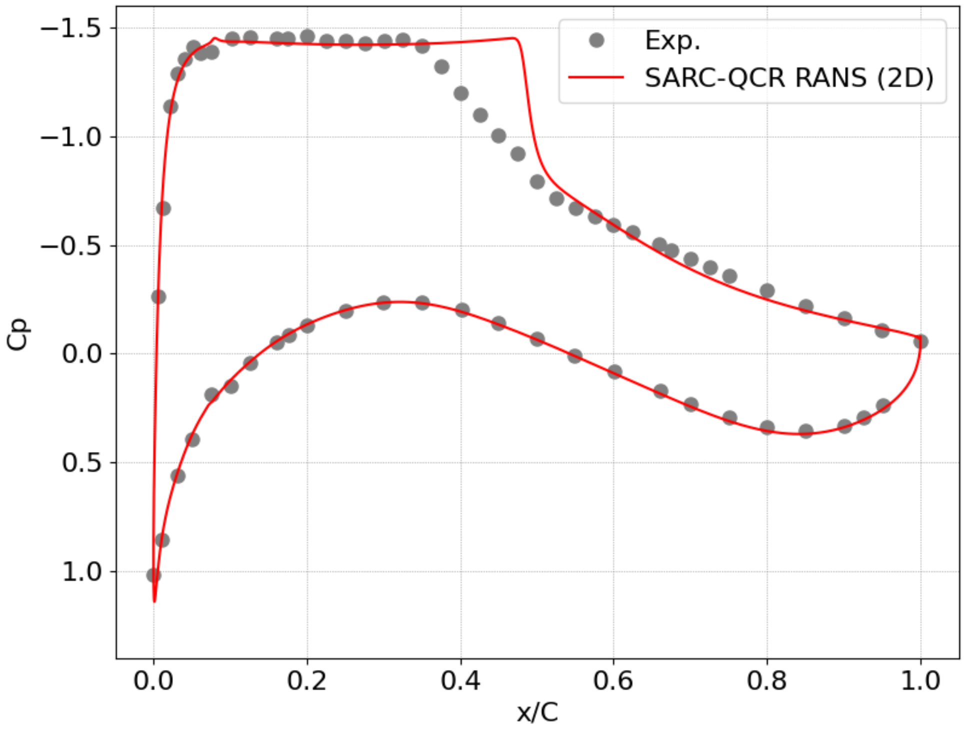
ONERA Structured Mesh

- 2D mesh with 397,640 cells:

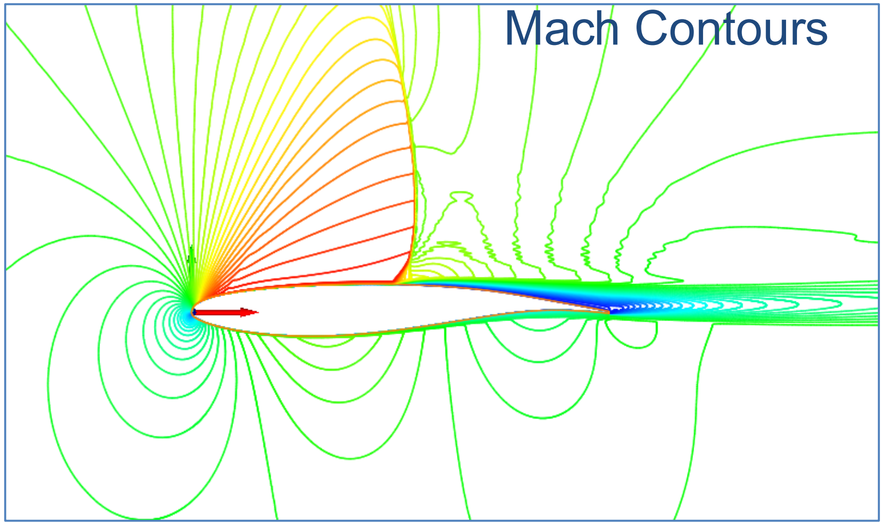


*Extruded through 145 planes for HRLES mesh with Δz = 0.00139c (~57.3 M cells)

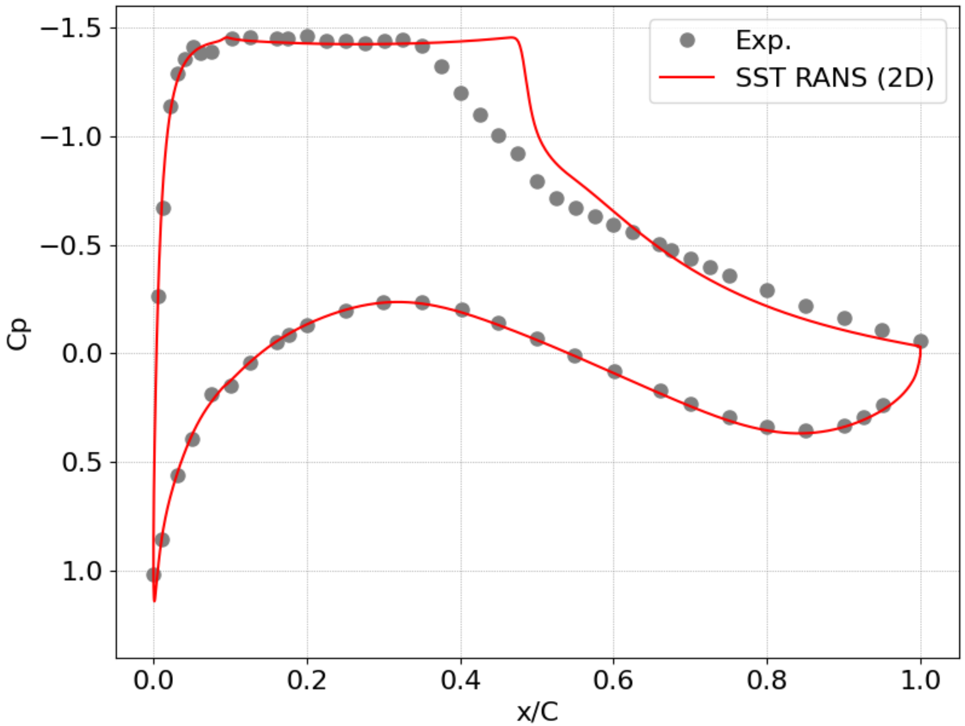
RANS – SA(neg)RC-QCR (AoA=3.5°)



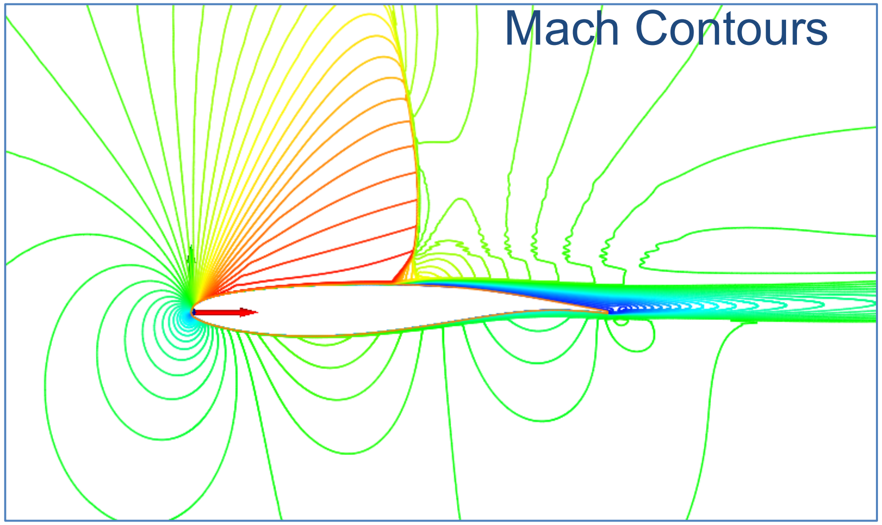
Surface Cp distribution



RANS – SST (AoA=3.5°)

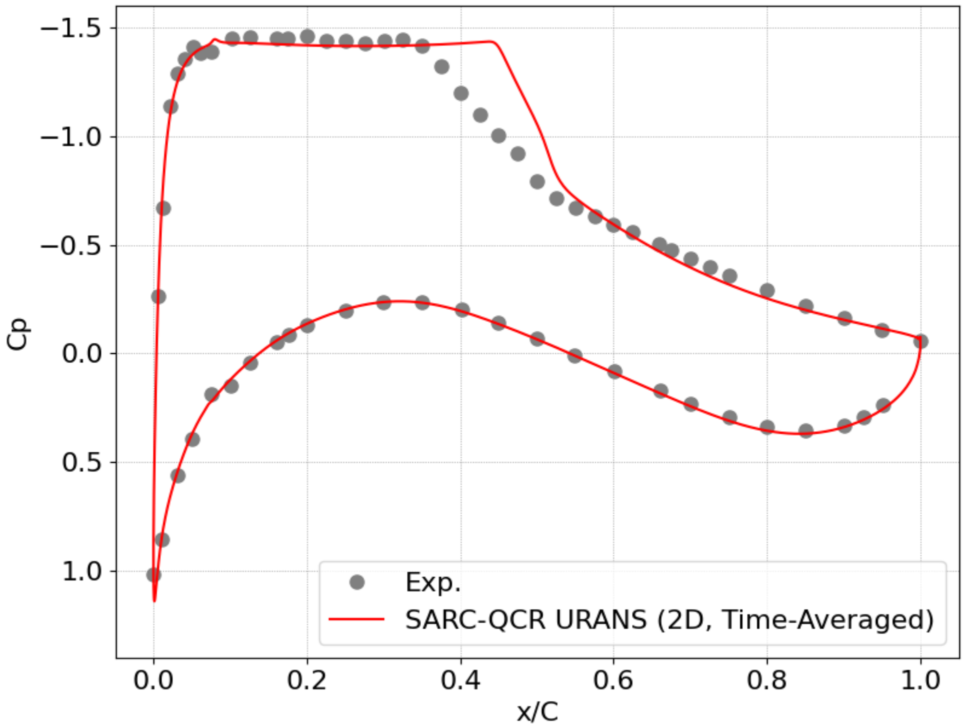


Surface Cp distribution

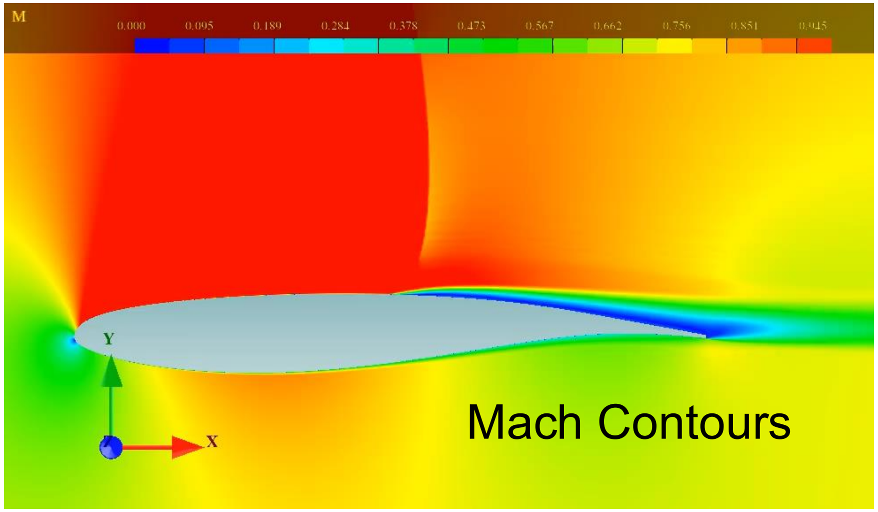


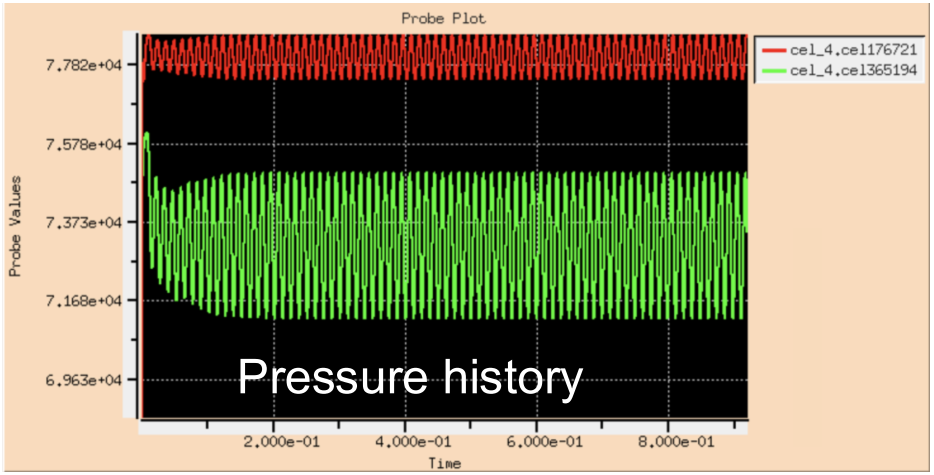
URANS – SA(neg)RC-QCR (AoA=3.5°)

Δt = 9.2e-6 s (100 steps/CTU)



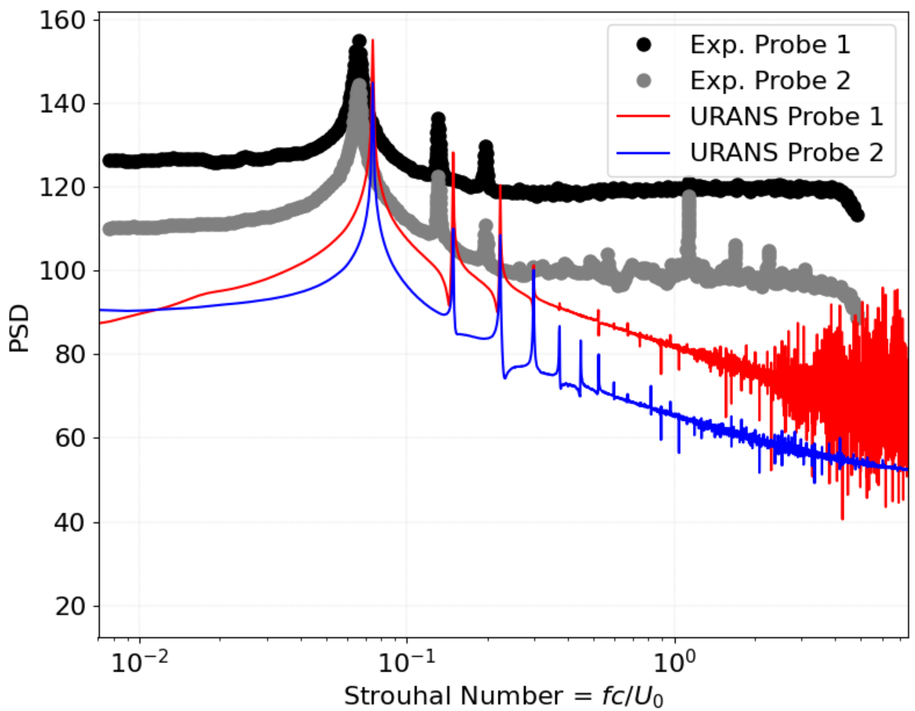
Surface Cp distribution
(time-averaged)



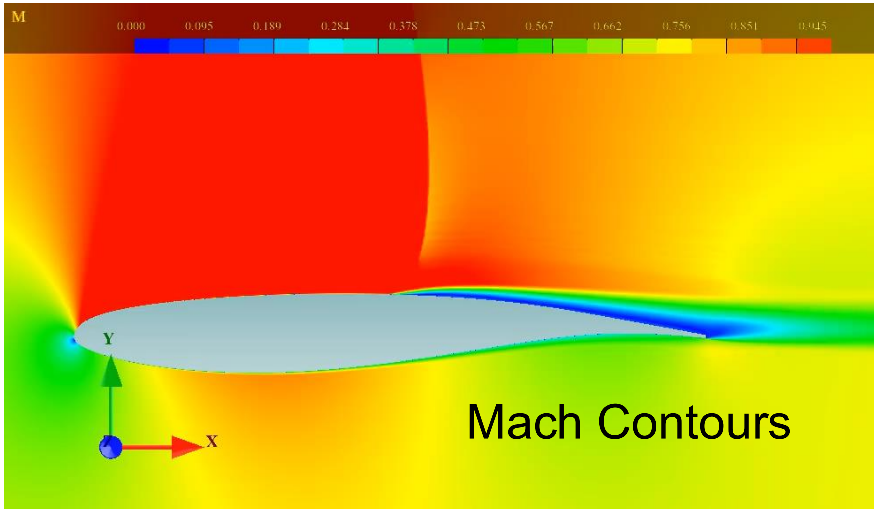


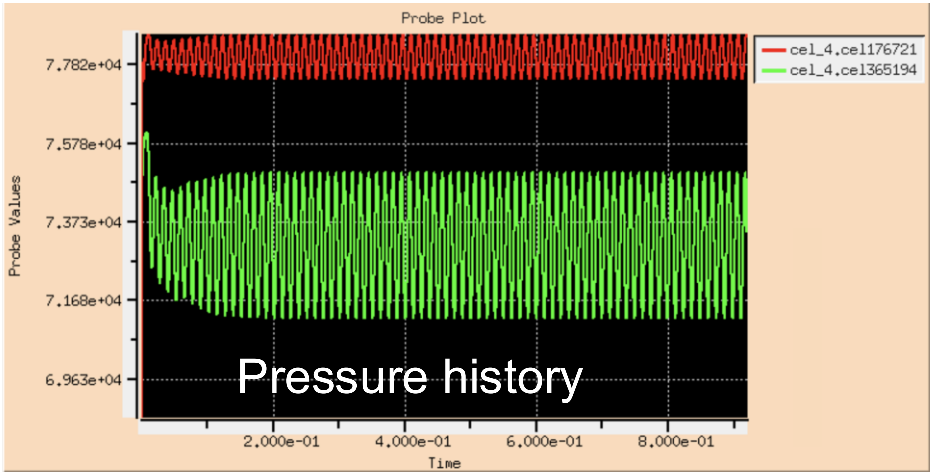
URANS – SA(neg)RC-QCR (AoA=3.5°)

Δt = 9.2e-6 s (100 steps/CTU)



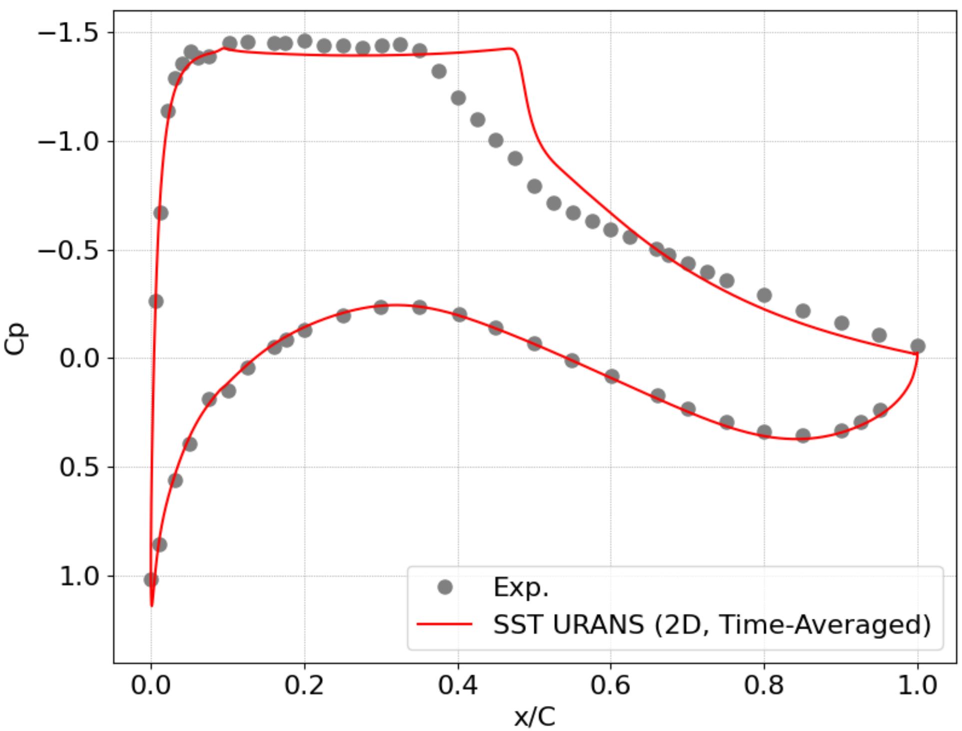
Pressure power spectral density



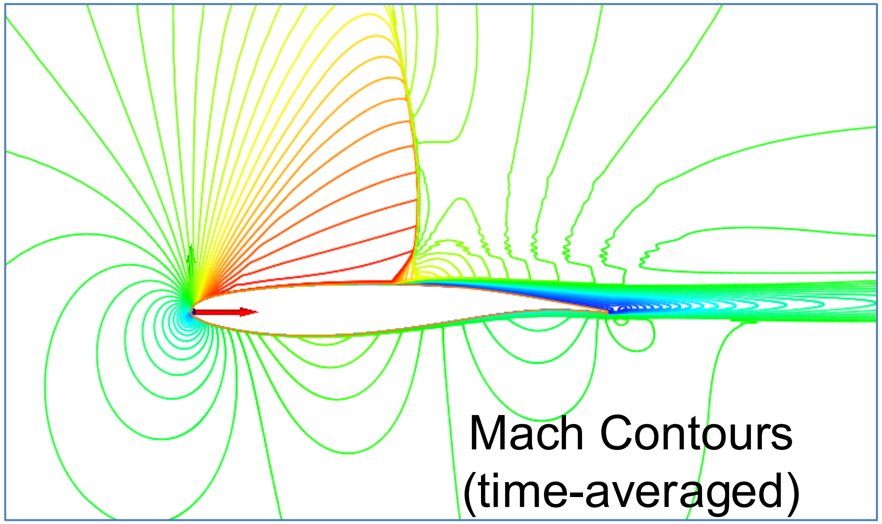


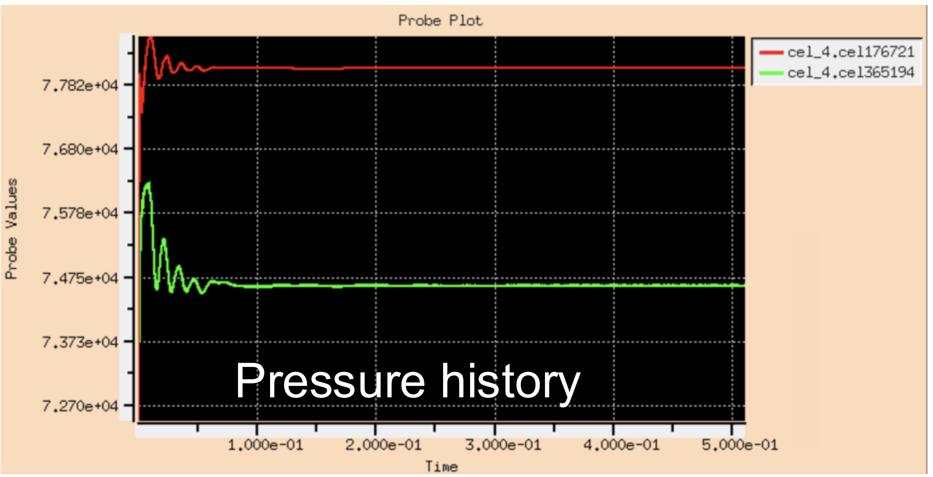
URANS – SST (AoA=3.5°)

No unsteadiness achieved

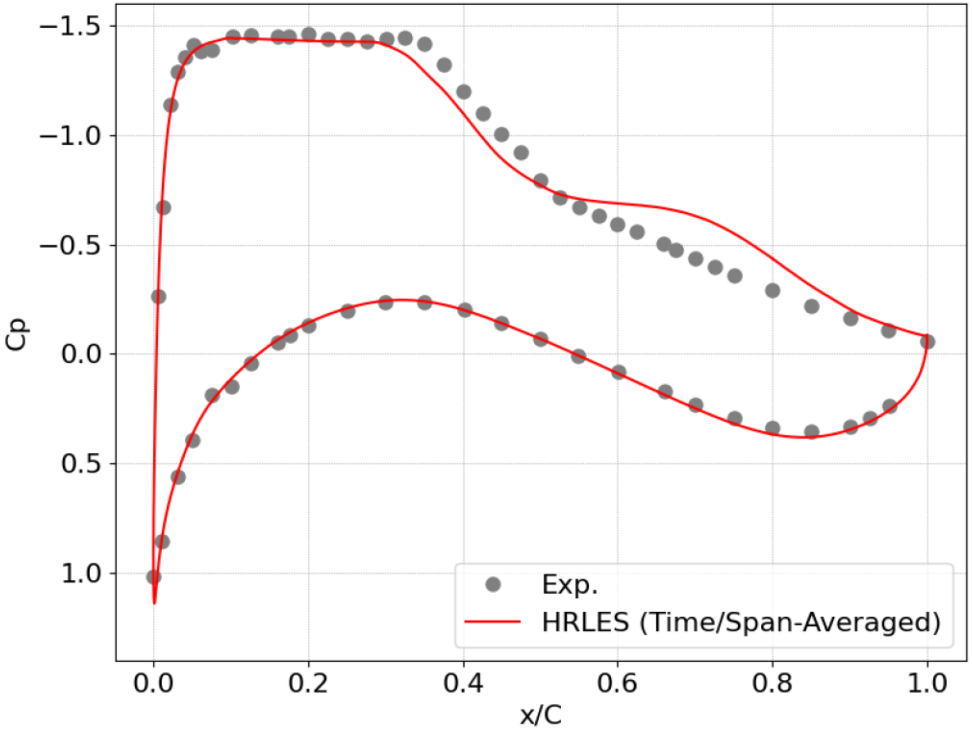


Surface Cp distribution
(time-averaged)

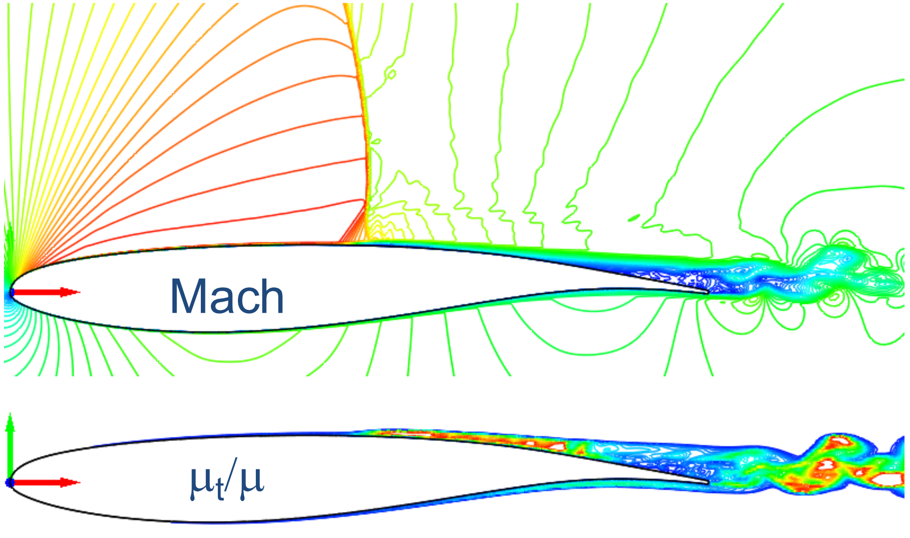


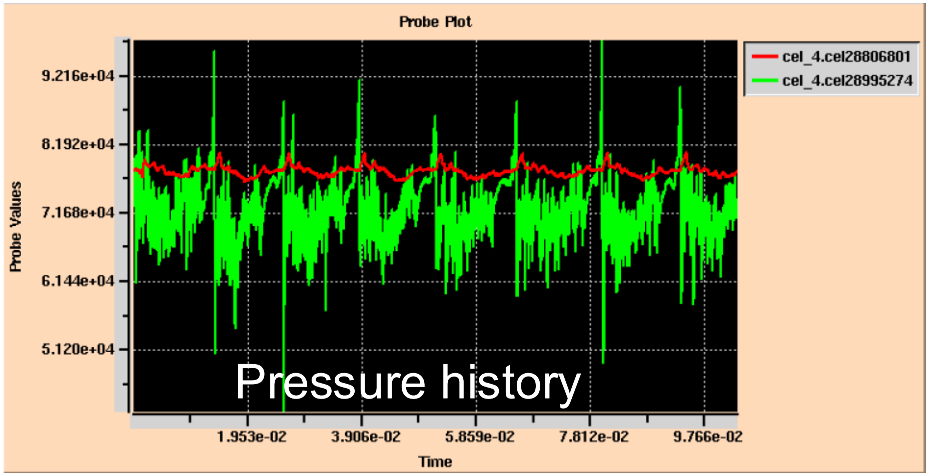


HRLES – SARC-QCR-DDES+DR (AoA=3.5°)

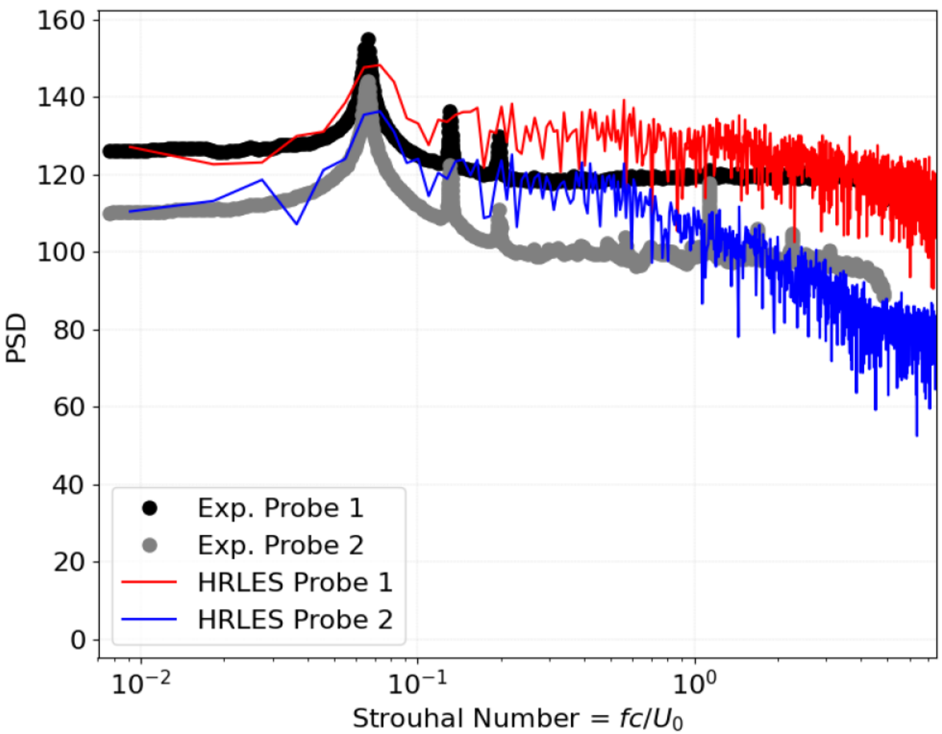


Surface Cp distribution
(time- & span-averaged,
~100 CTUs, ~8 periods, 57.3 M cell
ONERA mesh)

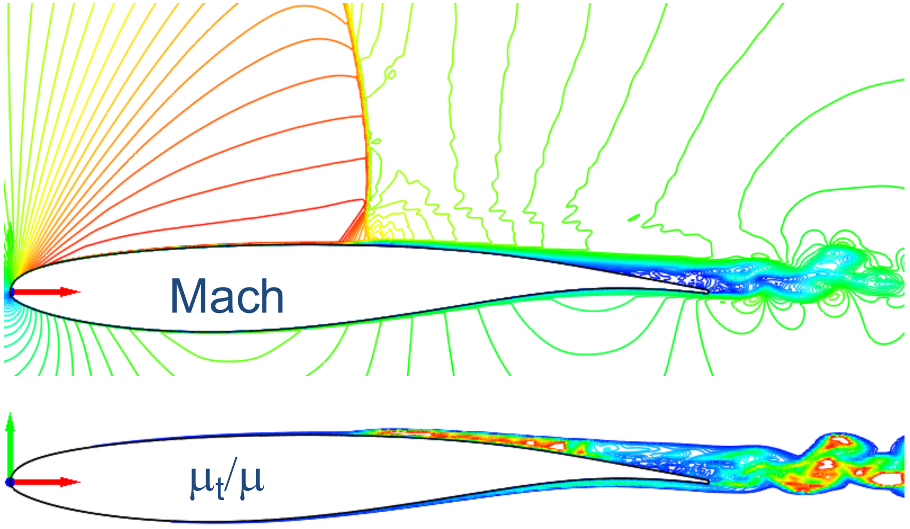


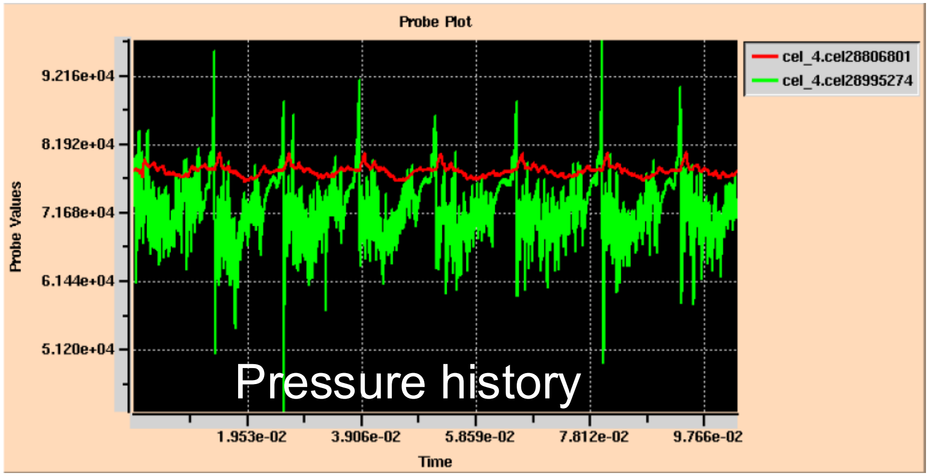


HRLES – SARC-QCR-DDES+DR (AoA=3.5°)



Pressure power spectral density
~100 CTUs, ~8 periods





Cost Overview

1. **URANS**: 100 steps/CTU*, 1 buffet cycle ~ 0.012 s, or about 13 CTUs
2. Recommended minimum of 8 buffet cycles to average over (ONERA)
3. Need about 13 cycles/periods of start-up transient to reach phase stationarity
4. (8+13)*13 = 273 CTUs, or 27,300 URANS time steps (spectral resolution suffers with shorter histories) – remember 2D mesh had only ~400,000 cells
5. **HRLES**: 3D extruded ONERA mesh (same Δz as Deck/Renard, 57.3 M elements) results in much larger grid and smaller Δt – results in ~1440 times the effort to simulate the same history length

*Suggested by Jeff Housman and Daniel Maldonado, **Evaluation of a Physics-Based Unsteady RANS Method for Buffet Onset Prediction**, NASA Advanced Supercomputing AMS seminar, **September 26, 2024**

The Problem with URANS

Has questionable general reliability…

For example, SARC-QCR gives good convergence in RANS mode, but predicts unsteady flow in URANS mode; SST gives poor convergence in RANS mode, but predicts no unsteadiness in URANS mode

How can we know *a priori* what type of RANS model is appropriate, or *would even give an unsteady solution* for any given flow scenario?

1. There's no guarantee that URANS will even become unsteady
2. When resolved-scale structures do appear in URANS, decay rates, amplitudes and bifurcation behavior aren't guaranteed to be correct:

D. Israel, 'The Myth of URANS', Journal of Turbulence, Vol. 24, pp. 367-392, 2023.

The Problem with HRLES, WMLES, WRLES and DNS

Each of these approaches generally require a convective CFL of ~1 in regions of resolved-scale turbulence for accurate prediction of resolved Reynolds stresses

Numerical resolution requirements set Δx, Δy, Δz, from which Δt is carved in stone (because of accuracy restriction on CFL)

The total number of steps, n, required for the simulation is then also carved in stone:

$$\mathbf{n} = \frac{\textbf{start–up transient time + time to gather sufficient history for reliable statistics}}{\Delta t}$$

For these buffet problems, the numerator becomes large, leading to a large number of physical steps

A Large Δt Approach to Simulation Cost-Reduction in HRLES

It's appealing to use large Δt in HRLES, similar to that used in URANS

… but large Δt in LES limits the ability to directly capture resolved-scale turbulence – ***so we cannot just naively increase Δt***

Potential solution is to sensitize the filter width to *Δt* so that we don't remove as much modeled stress as Δt increases:

$$\tilde{\Delta}^{II} = (1 - test_{\Delta})\tilde{\Delta}_{max} + test_{\Delta}\left(\tilde{\Delta}_{\omega}\right),$$

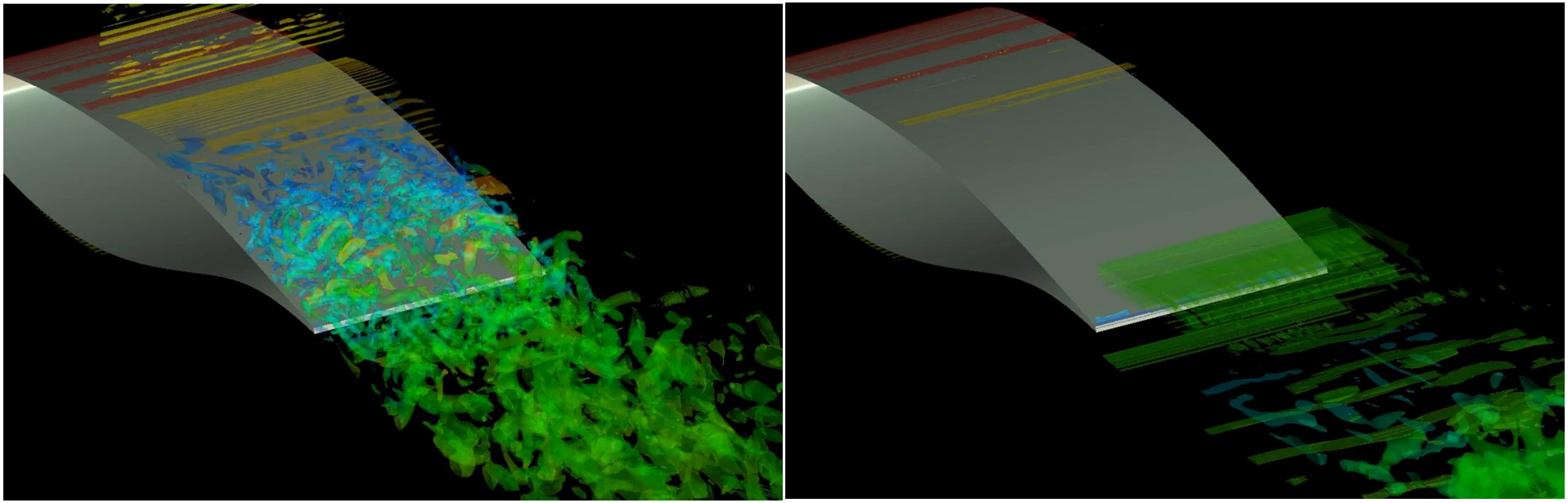
$$\tilde{\Delta}_{max} = \max(\Delta x, \Delta y, \Delta z, \sqrt{(u_i - \dot{x}_i)^2}\delta t)$$

$$\tilde{\Delta}_{\omega} = \max(\Delta_{\omega}, \sqrt{(u_i - \dot{x}_i)^2}\delta t)$$

*Deck & Renard's `enhanced dissipation' option is not used here, as its goal is destruction of μ_t at separation, regardless of Δt

Traditional HRLES vs Large Δt HRLES

The following comparison was made on the same extruded (ONERA-supplied) mesh:

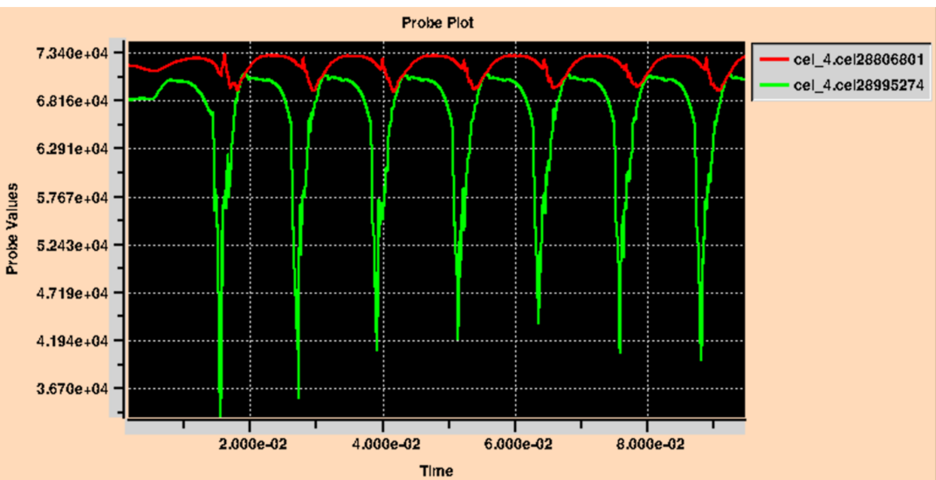


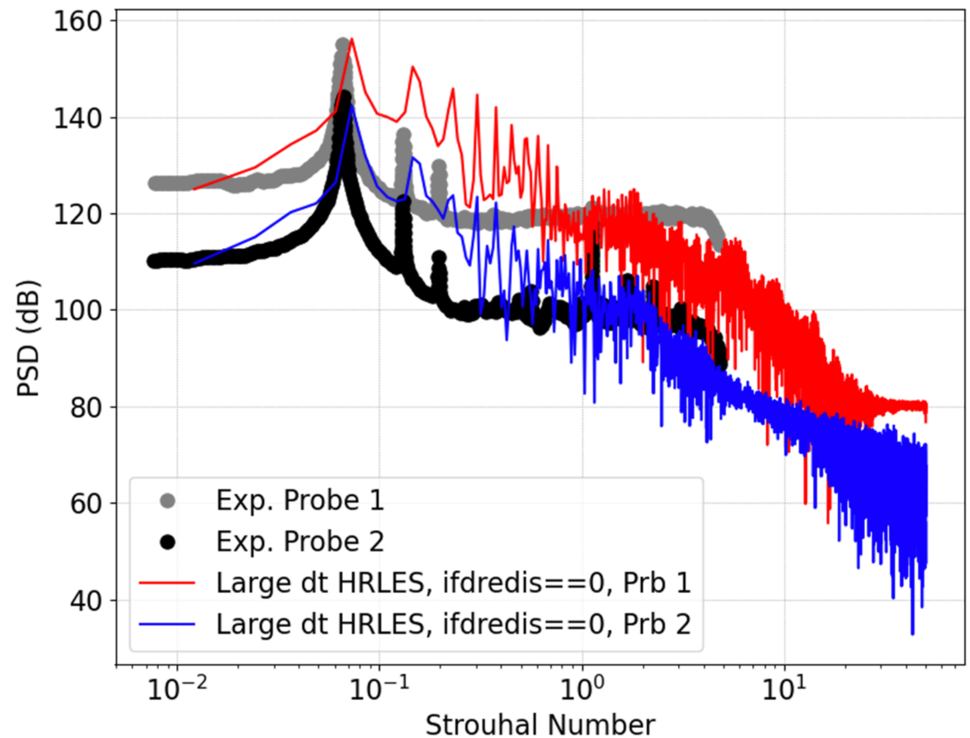
a) Traditional (CFL~1) DDES-DR **b) Large Δt DDES-DR**

- Solution b) is severely lacking in resolved-scale content
- Usual assumption would be that solution a) is superior, however…

Large Δt DDES-DR HRLES Results

SWBLI motion is still apparent in large Δt DDES-DR and spectra (at least at lower st) are still reasonable:

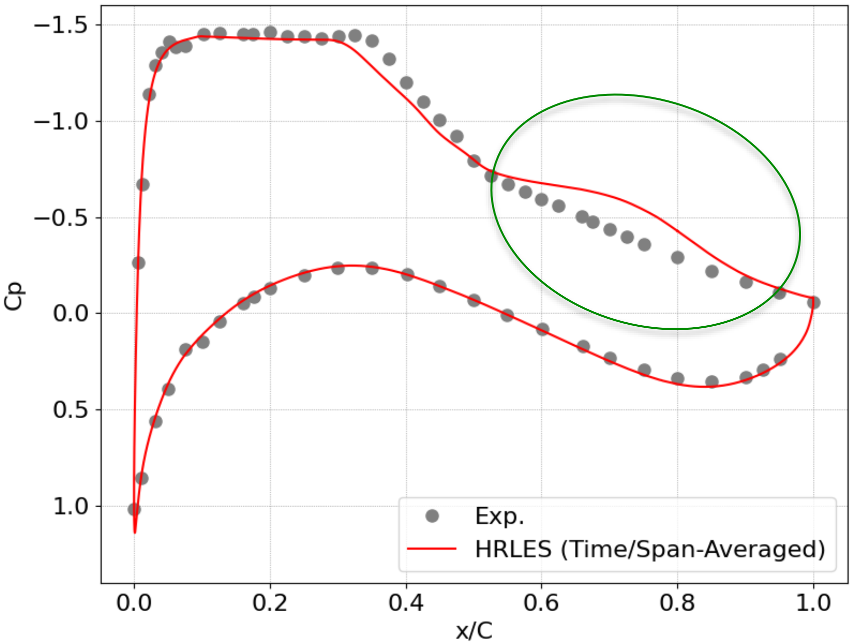




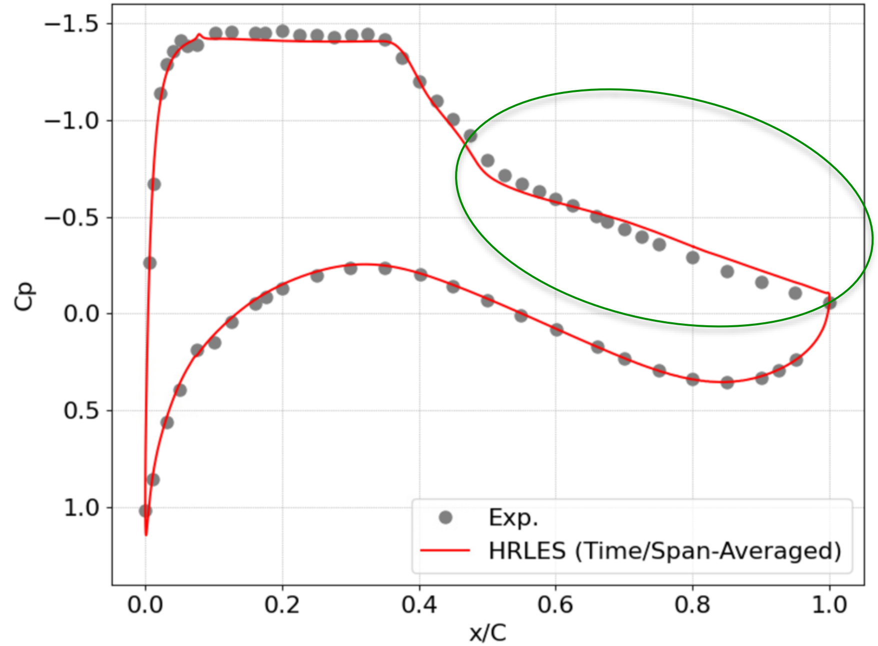
DDES-DR with Courant-sensitive filter width and URANS-sized (9.6e-6 s) Δt:

*Enhanced dissipation off

Comparison of Traditional DDES-DR and Large Δt DDES-DR



Traditional DDES-DR

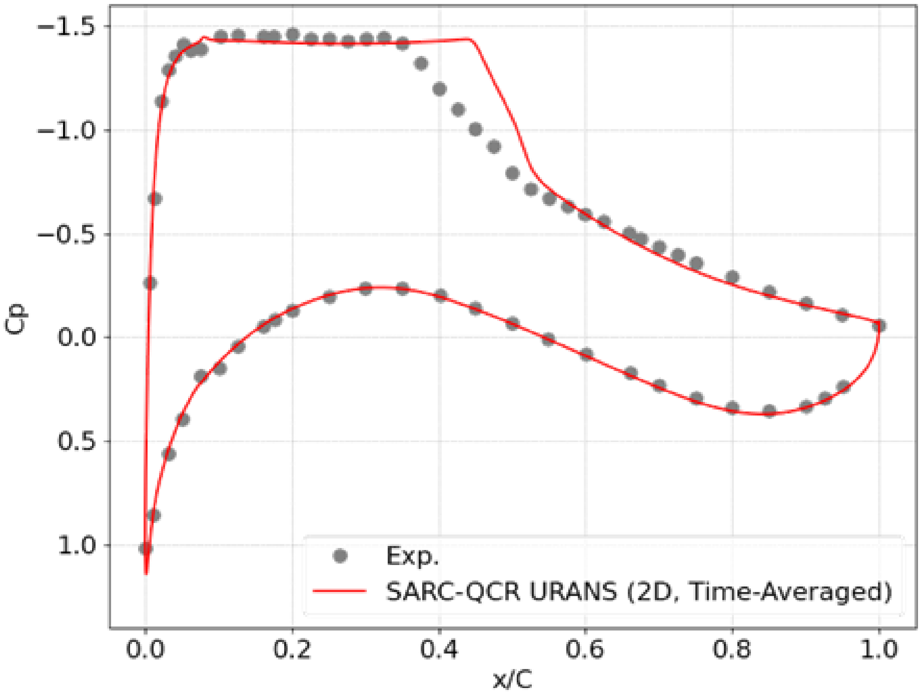


Large Δt DDES-DR

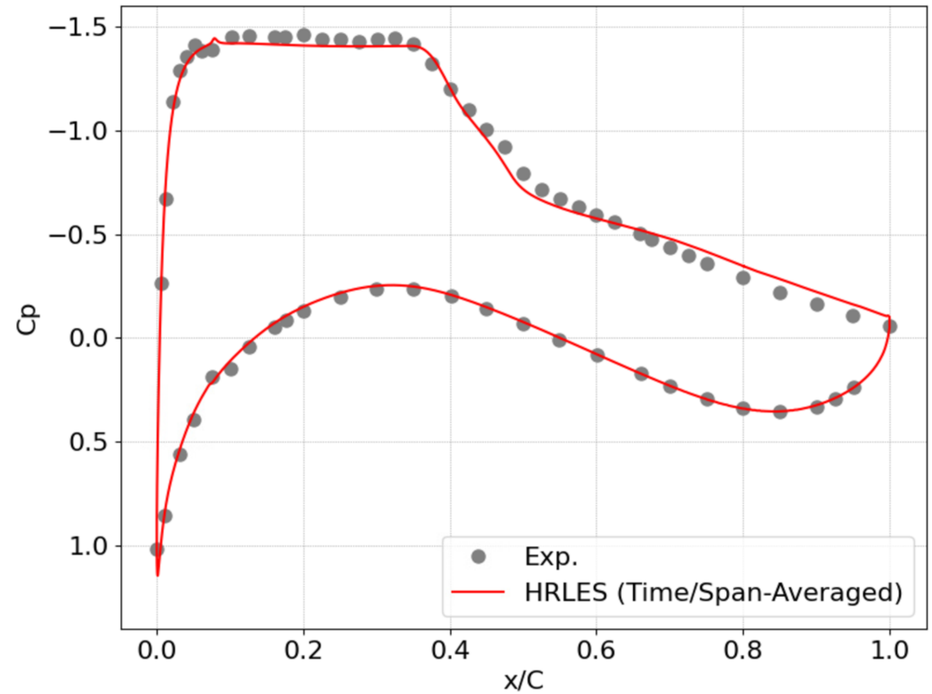
Note absence of modeled-stress depletion effects in large Δt DDES-DR

URANS vs Large Δt HRLES

- 2D URANS vs DDES-DR* with Courant-sensitive filter width (in both cases, Δt=9.6e-6 s)



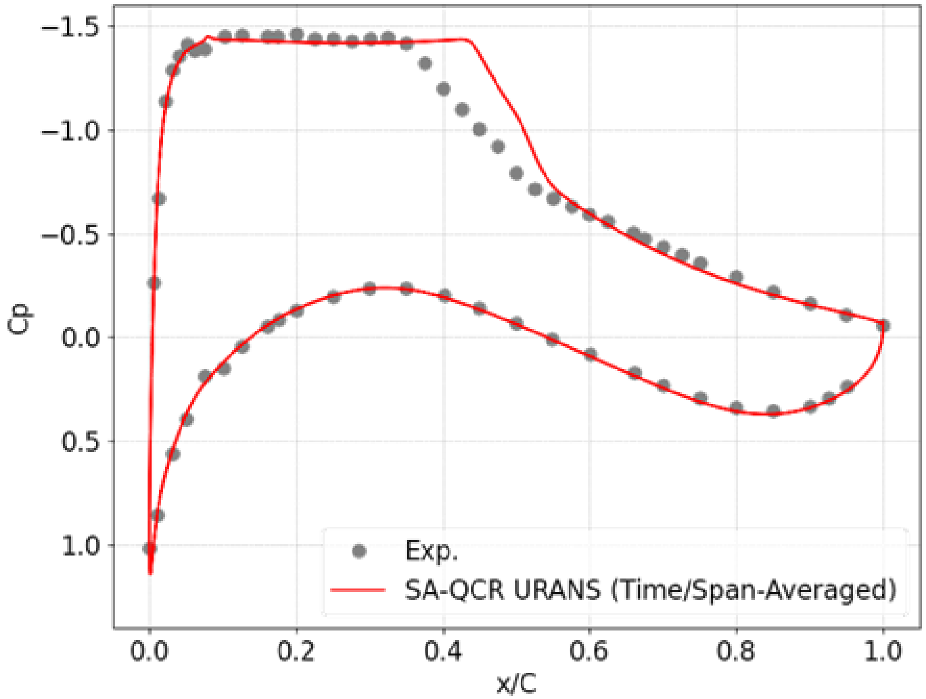
URANS, 2D ONERA mesh



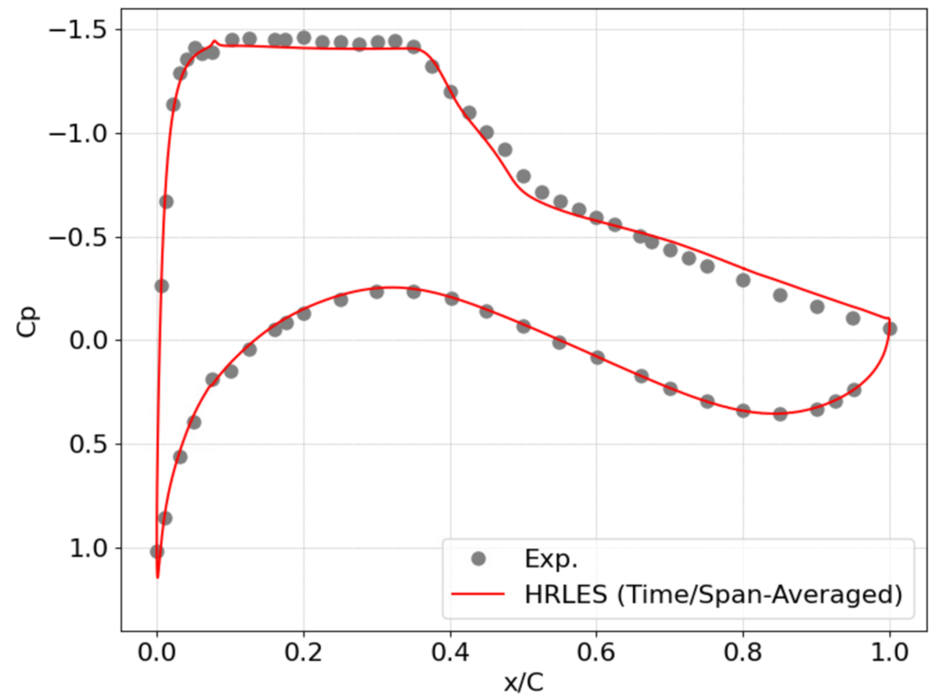
Large Δt HRLES, 3D ONERA mesh

3D URANS vs Large Δt HRLES

- 3D URANS vs DDES-DR* with Courant-sensitive filter width (in both cases, Δt=9.6e-6 s, identical 57.2 M cell ONERA mesh)



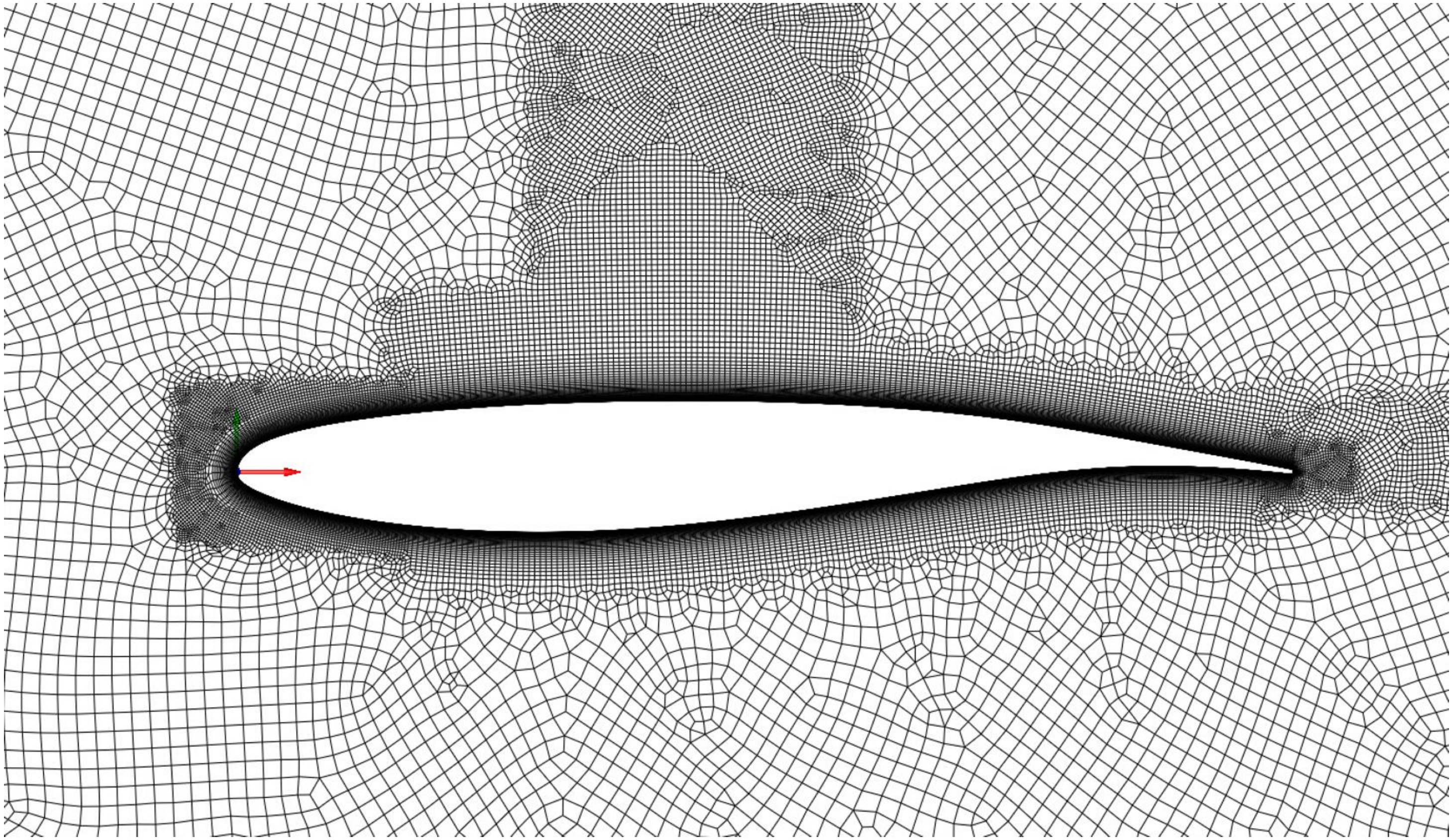
URANS, 3D ONERA mesh



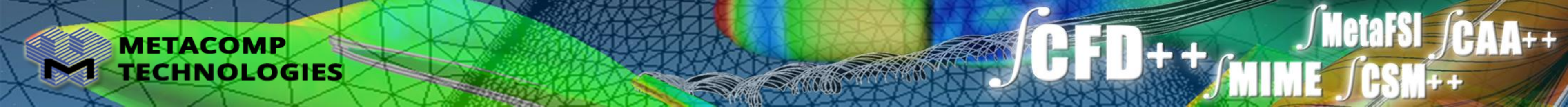
Large Δt HRLES, 3D ONERA mesh

MIME Mesh

If we're using a larger Δt (and therefore a larger filter width, couldn't we also get away with using a coarser (even RANS-like) mesh?

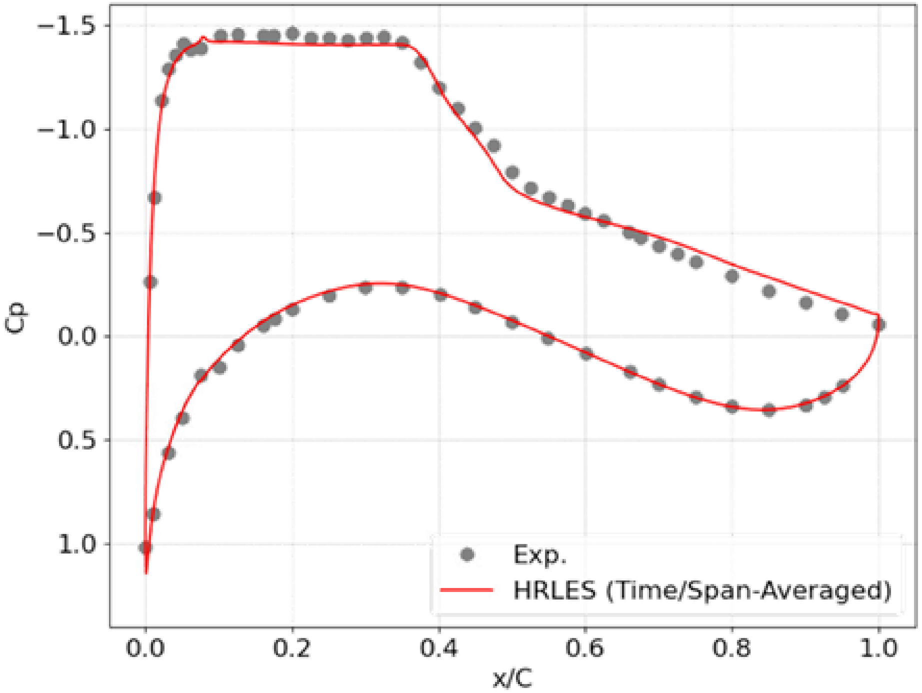


*Extruded over the same span, 3D MIME mesh has only ~2.2 M elements

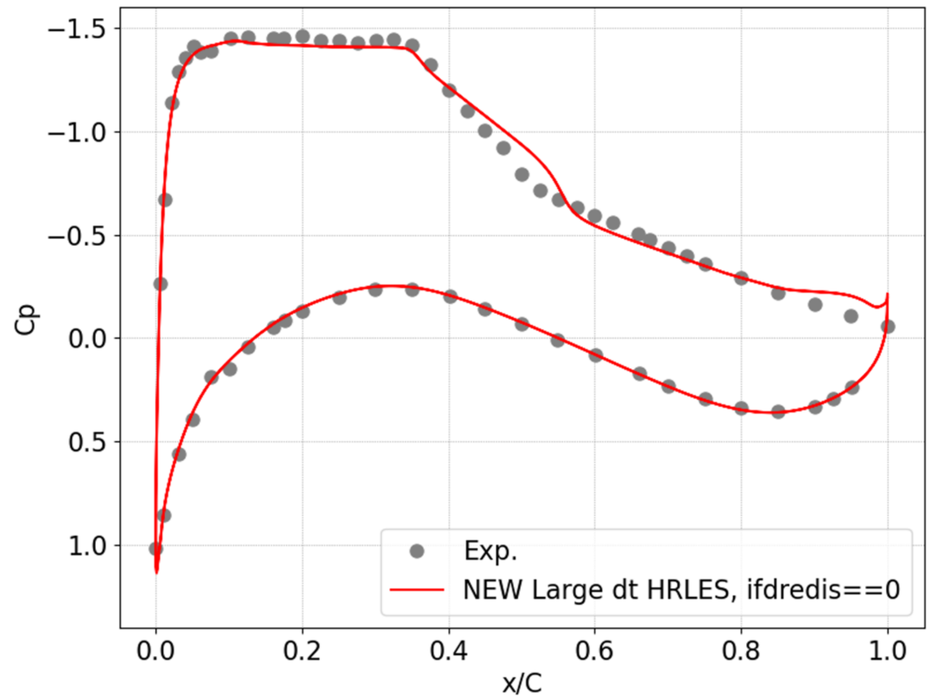


Large Δt HRLES: ONERA vs MIME Mesh Results

- Rather similar results (Δt=9.6e-6 s in both simulations)

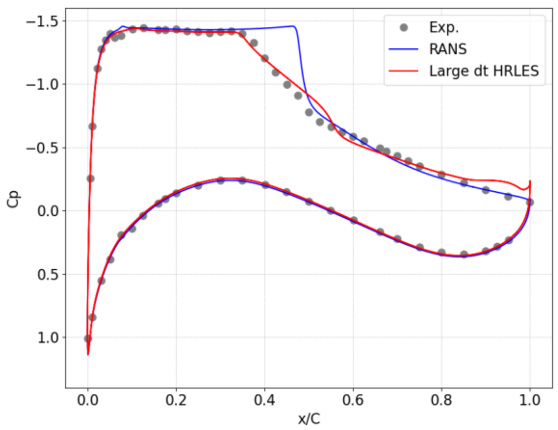


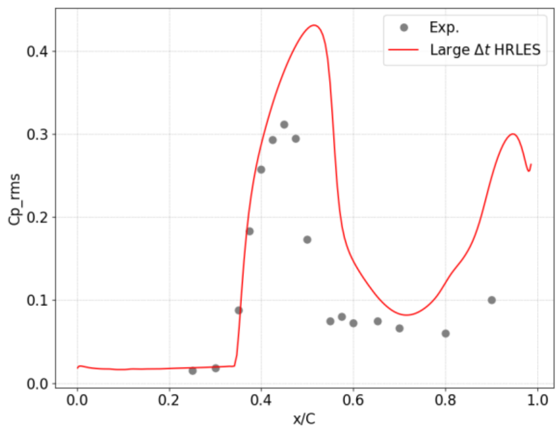
Large Δt HRLES, 3D ONERA mesh (57 M cells)

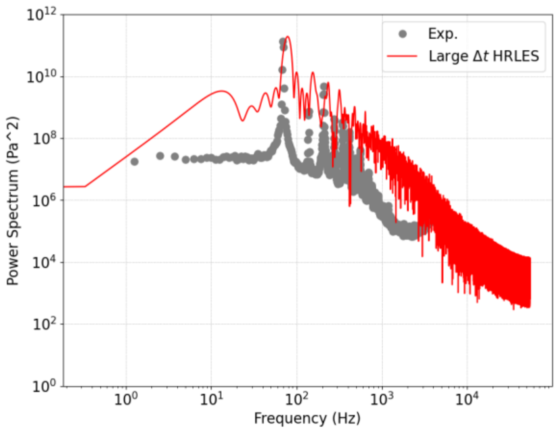


Large Δt HRLES, 3D MIME mesh (2.2 M cells)

MIME/Large Δt DDES-DR Alpha Sweep





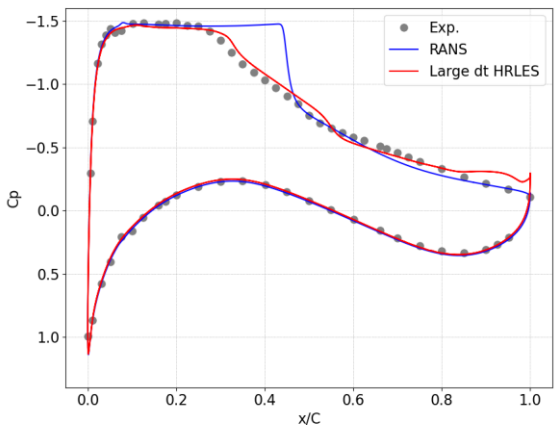


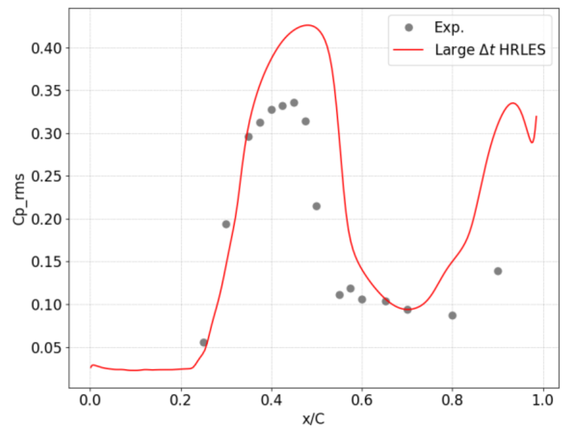
Angle of Attack: α = 3.50°

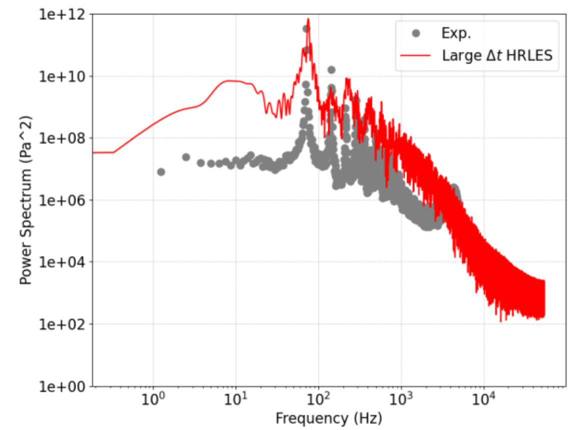
***All power spectra (incl. those from Jacquin et al.) computed from E. Molina's script with:**
compute_psd_10212024.py -f filename -o 0.50 -d 1.0

****RANS solutions computed from finest Cadence-supplied mesh**

MIME/Large Δt DDES-DR Alpha Sweep







Angle of Attack: α = 3.90°

***All power spectra (incl. those from Jacquin et al.) computed from E. Molina's script with:**
compute_psd_10212024.py -f filename -o 0.50 -d 1.0

****RANS solutions computed from finest Cadence-supplied mesh**

Case 1 Recap

RANS is inaccurate for these SWBLI cases (shock too sharp/too far aft); URANS is unreliable, and even when using dubious mechanisms to force unsteadiness, results aren't as accurate as those of HRLES

Traditional scale-resolving methods requiring convective CFL ~1 can become very expensive due to this huge number:

$$\mathbf{n} = \frac{\text{start–up transient + time to gather sufficient history over all frequencies}}{\Delta \boldsymbol{t}}$$

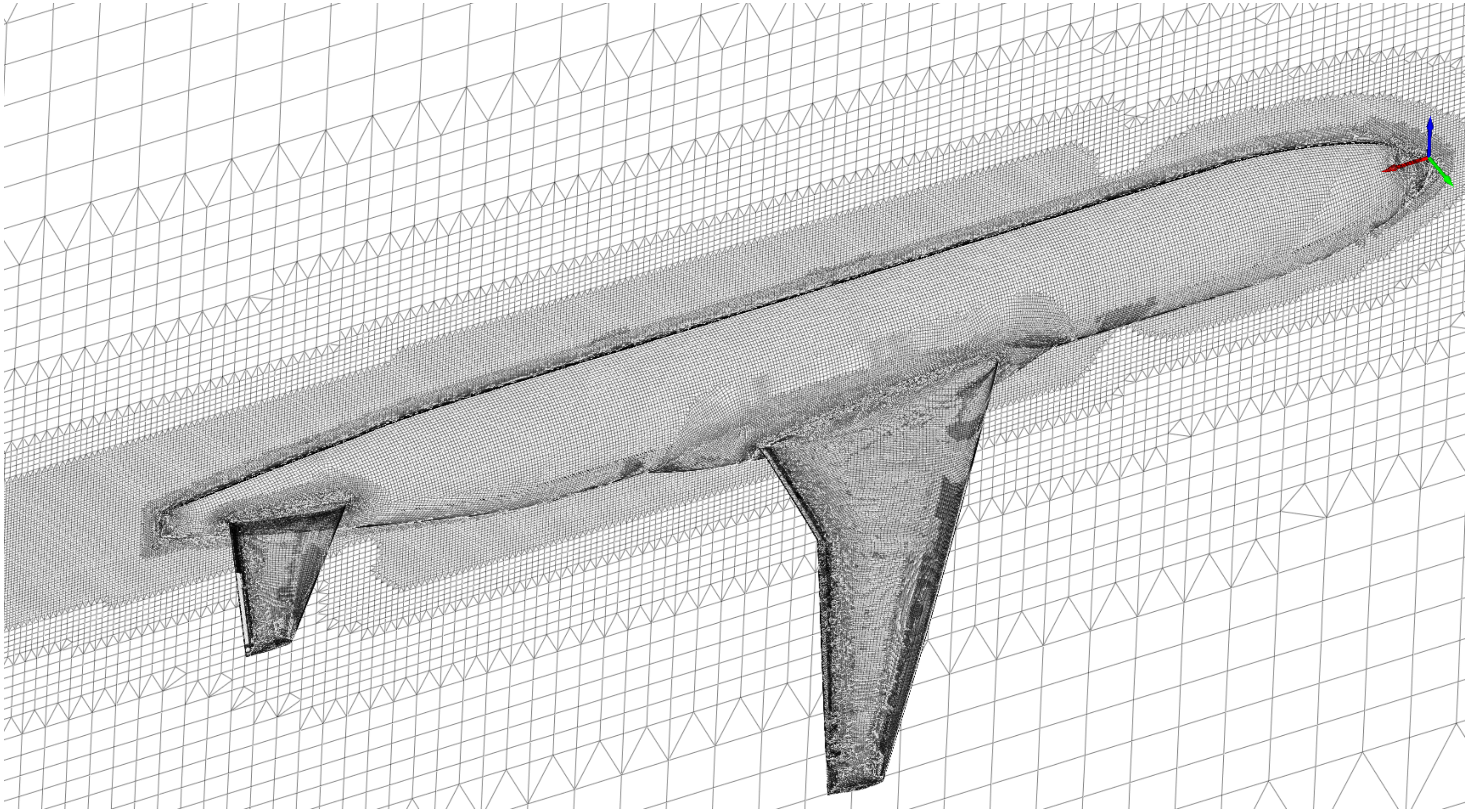
Large Δt HRLES offers an affordable approach to SWBLI modeling

For the ONERA OAT15A test case, large Δt HRLES is substantially faster (cost factor of ~250), and gave *better agreement* with mean Cp, than traditional HRLES (because it avoids most RANS->LES MSD issues)

This is the motivation for using this approach for Case 3…

Case 3

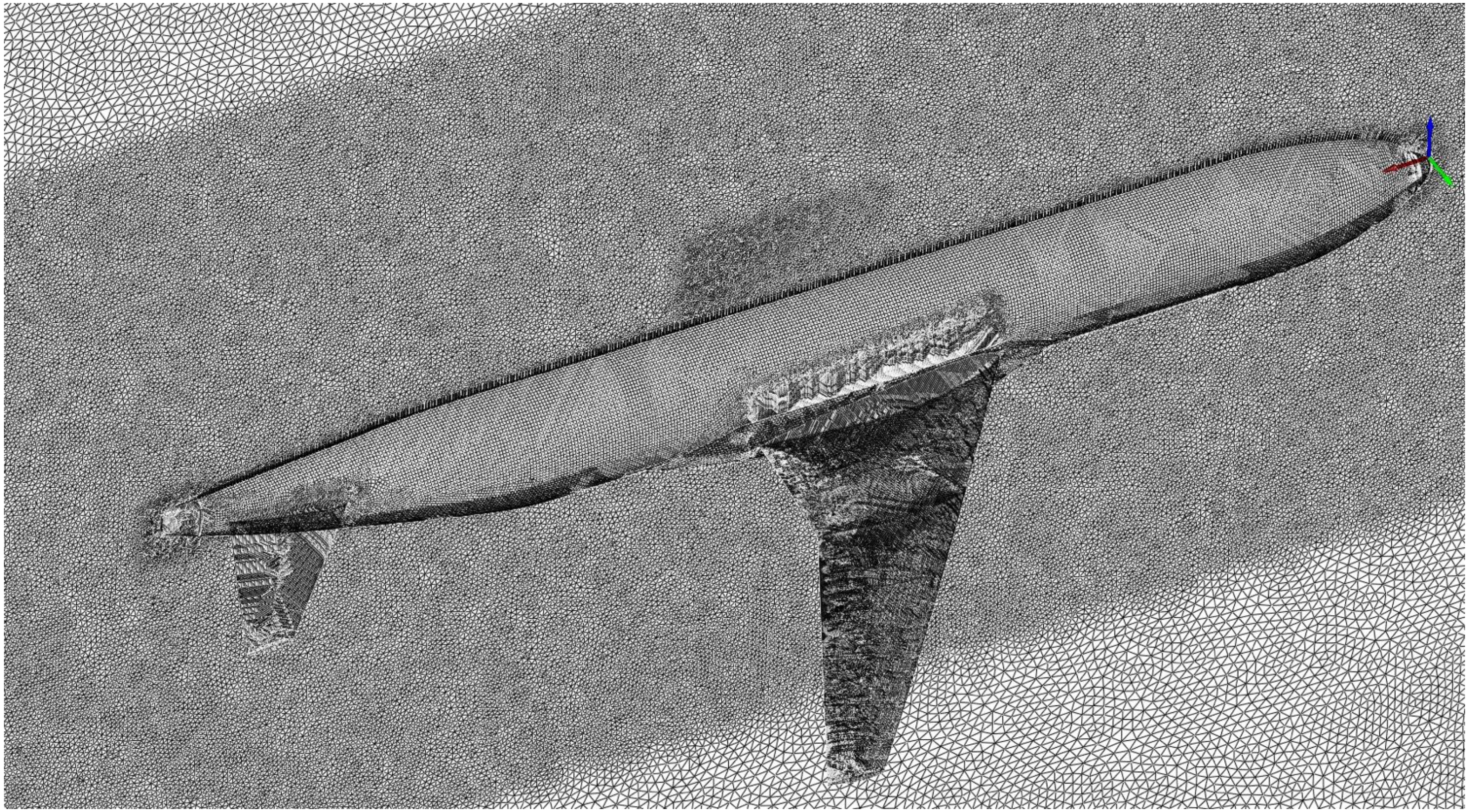
CRM: Reynolds number = 2.22e6, Mach number = 0.848, AoA = 4.71º



Cadence L2 Mesh (~52 M elements, y+ ~0.1)

Case 3

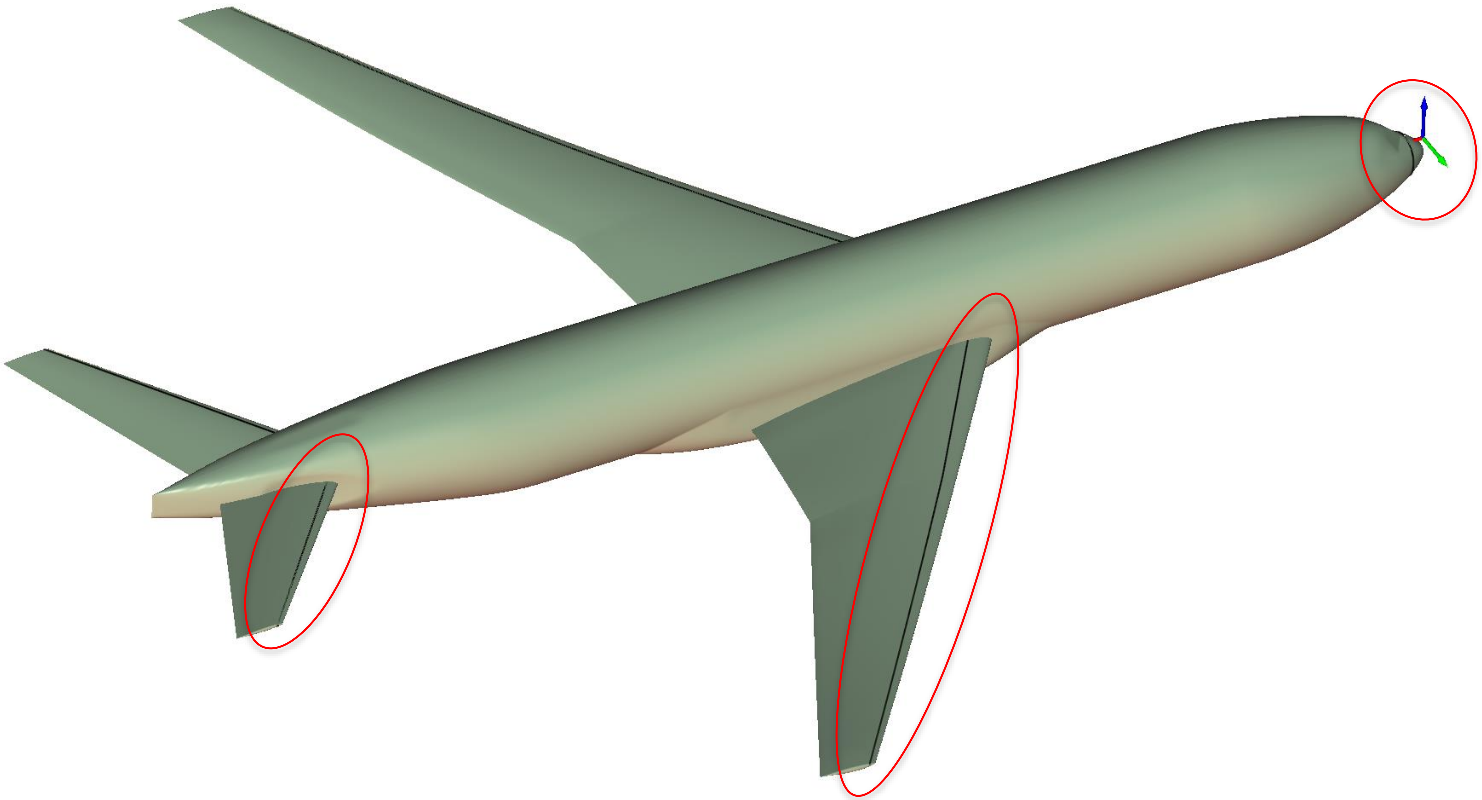
CRM: Reynolds number = 2.22e6, Mach number = 0.848, AoA = 4.71º



Preliminary MIME Mesh (~61 M elements, y+ ~ 1)

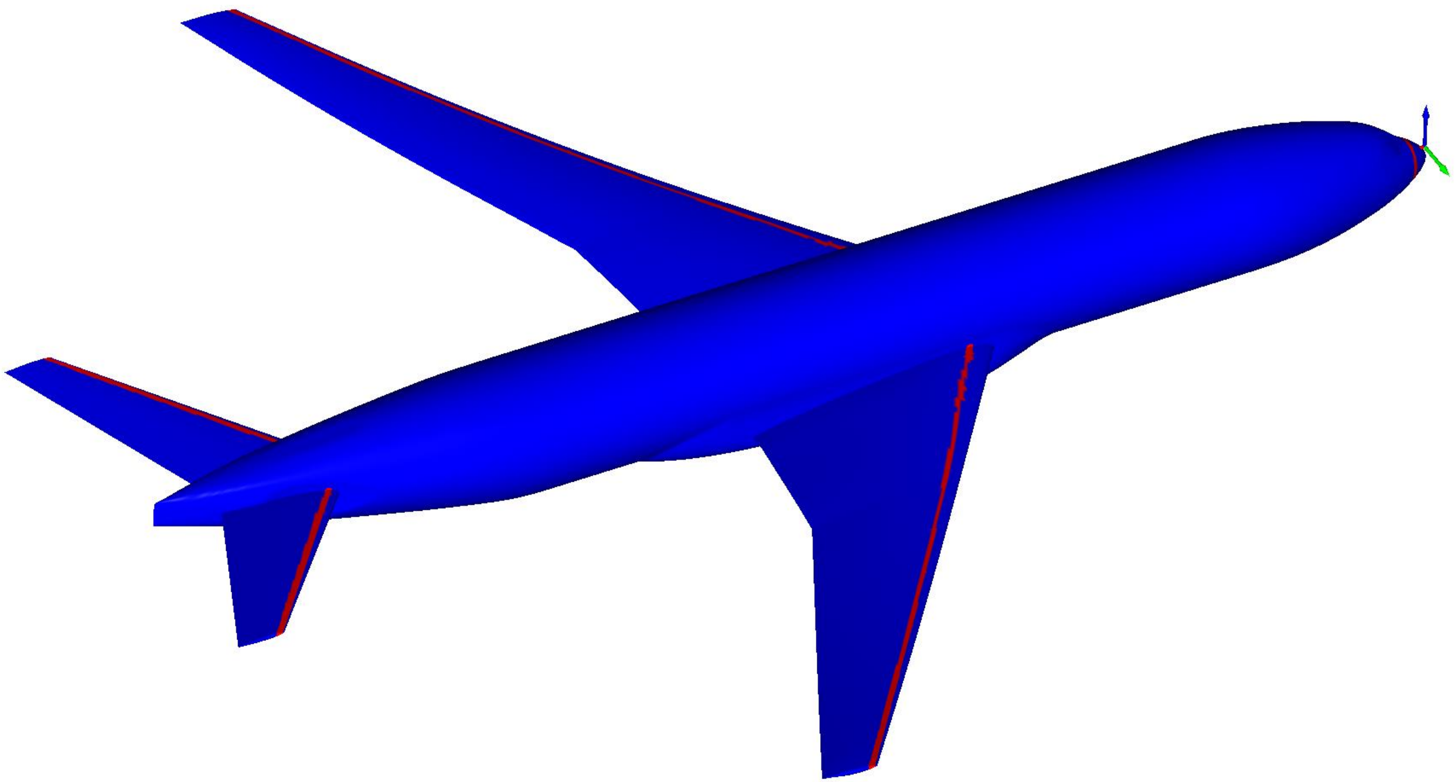
Case 3 – Triplines

Polylines defining nose, wing and horizontal-tail trips:



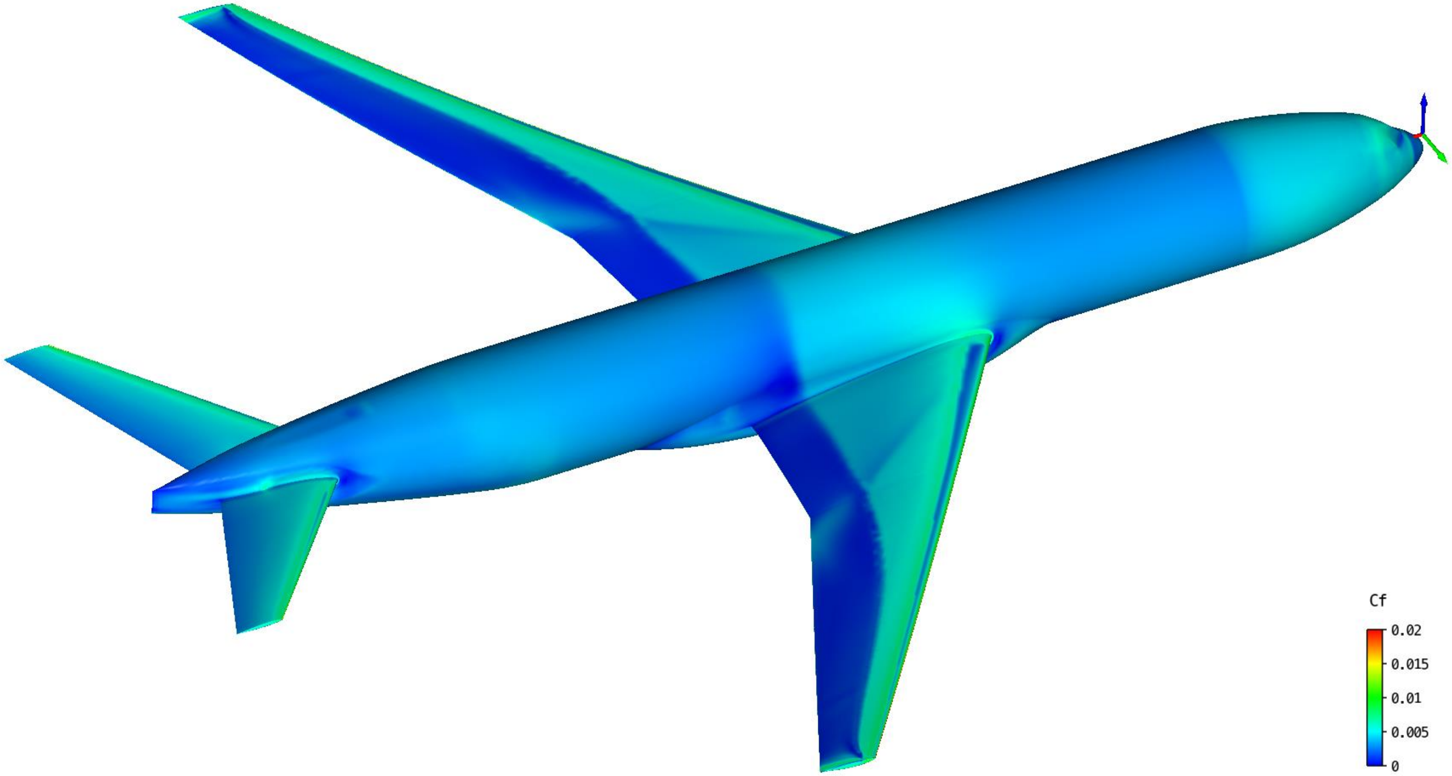
Trip sources are intended to approximate the experimental 10% chord transition strips; effective numerical trip width & strength remain mesh-dependent

Case 3 – Trip Function



Cells marked for transition trip sources

Resulting Skin Friction

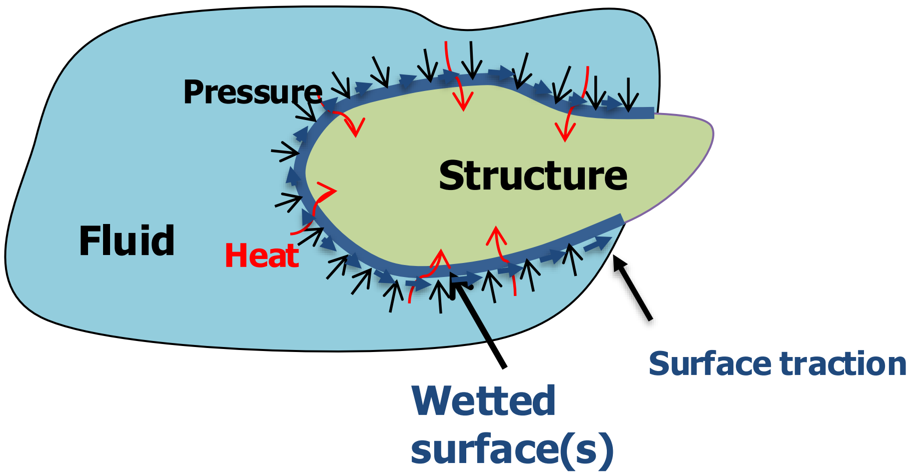


Time-averaged HRLES (Cadence L2 mesh)

Fluid-Structure Interaction

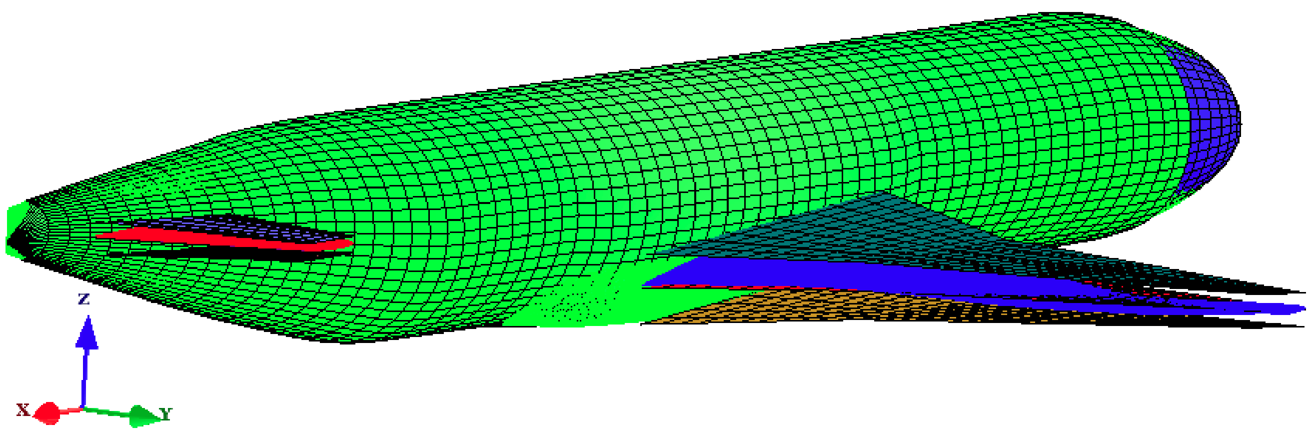
MetaFSI:

- Transfers loads from CFD++ to CSM++ (similar or dissimilar meshes), *preserving total load and center of pressure*
- Thermal loads to a CSM++ thermal model (optional)
- Transfers deformations and rotations to control points in the CFD++ volume
- Mesh morphing: No change in CFD mesh connectivity



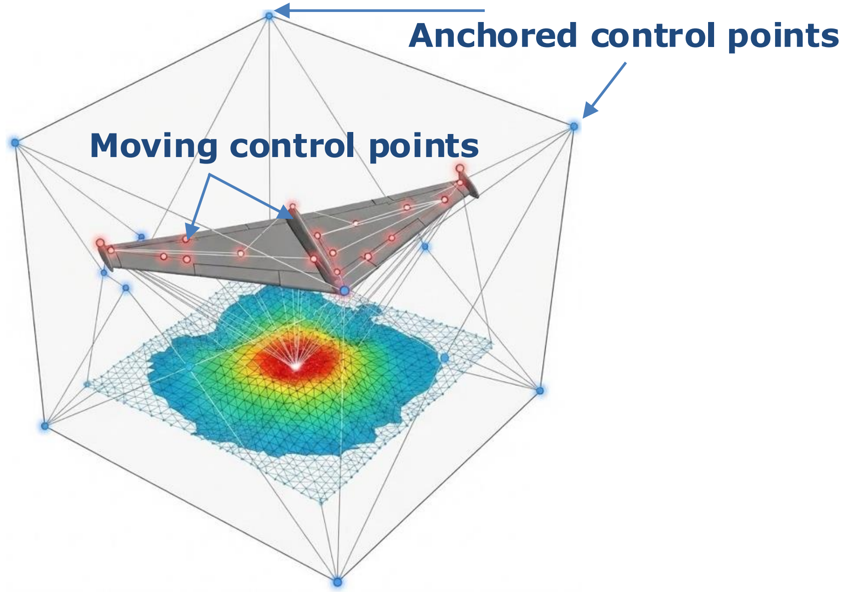
Control Points

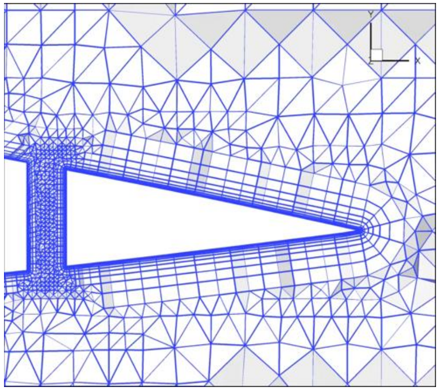
- Points on a structured grid used as RBF control points
- Surfaces above, below and at the mid-plane of the wing and horizontal tail
- Two surfaces around the fuselage with a small offset



Mesh Morphing 1

- **3D interpolant using Radial Basis Functions (RBF) on control points**
- $\delta x = \sum_{i=1}^{n} \lambda_i \phi(|\vec{x} - \vec{x}_i|) + p_1(\vec{x})$
- **Linear polynomial captures constant/linear motion**
- **Global RBF: every point influences entire domain**
- **Mesh topology preserved**





Modal FSI

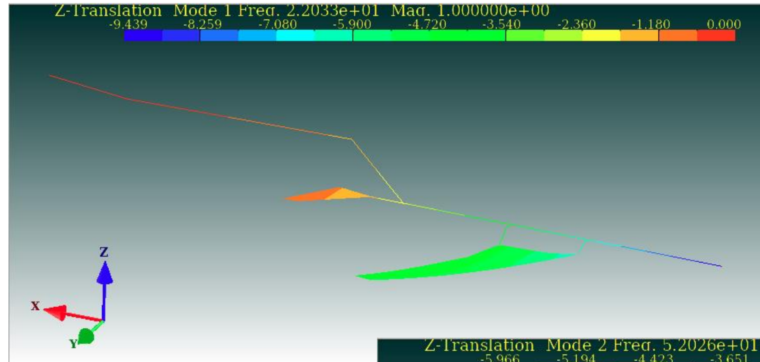
$$[M]\{\ddot{x}\} + [K]\{x\} = \{f_{aero}\}$$

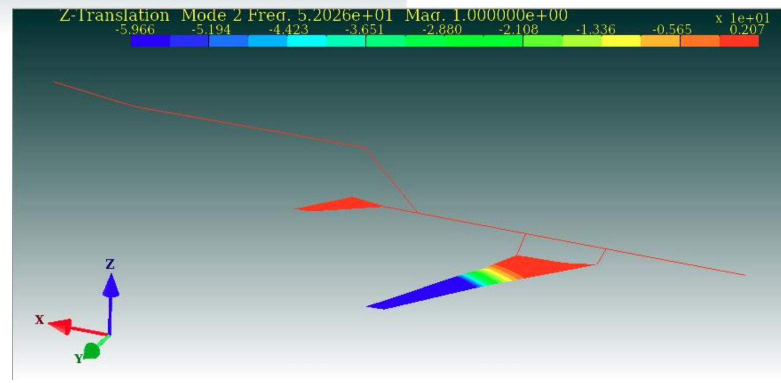
$$\{x\} = [\Phi]\{q\}$$

$$[\bar{M}]\{\ddot{q}\} + [\bar{K}]\{q\} = [\Phi]^T\{f_{aero}\}$$

Φ – Mode shapes

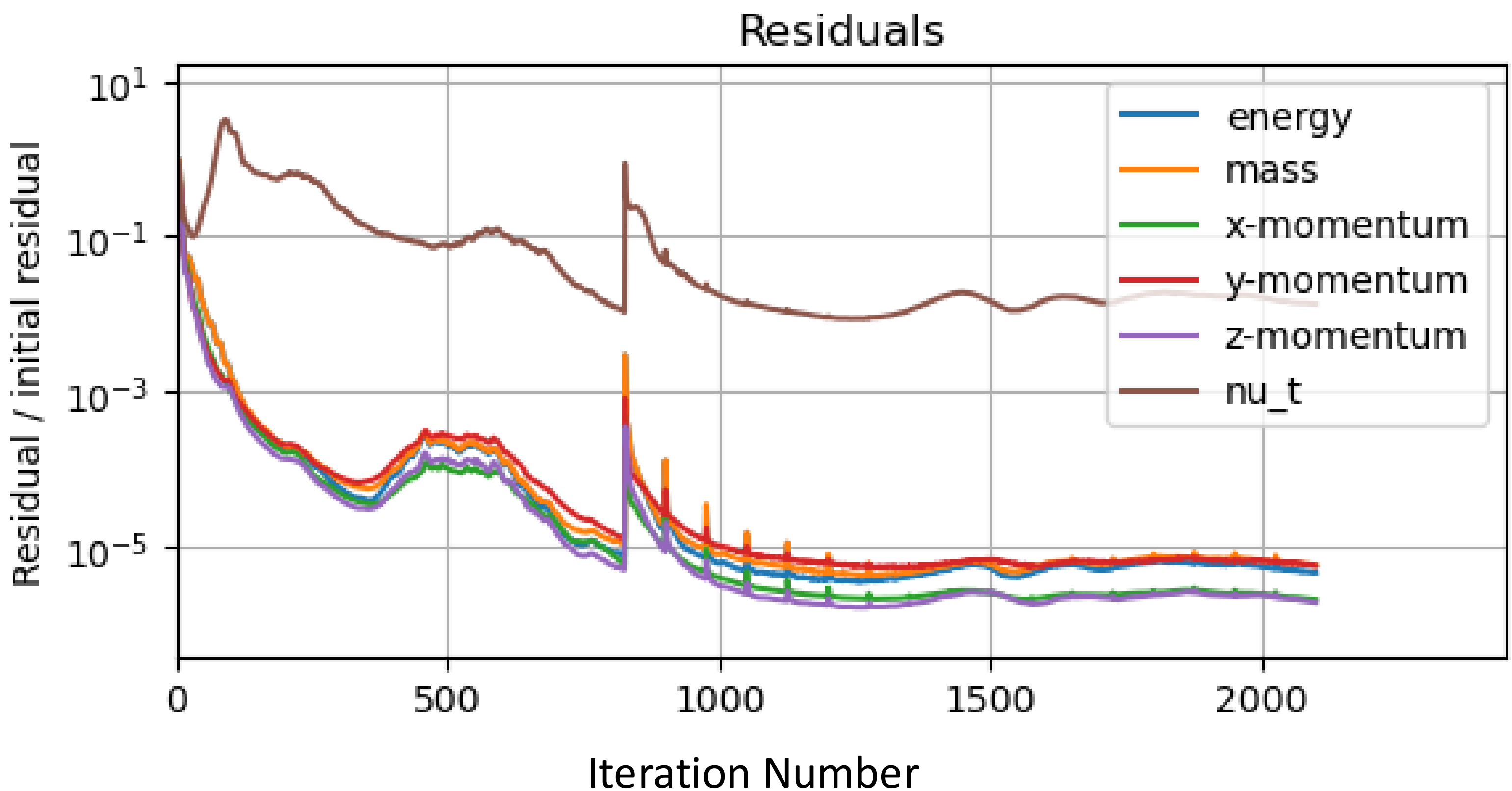
q - Generalized displacements





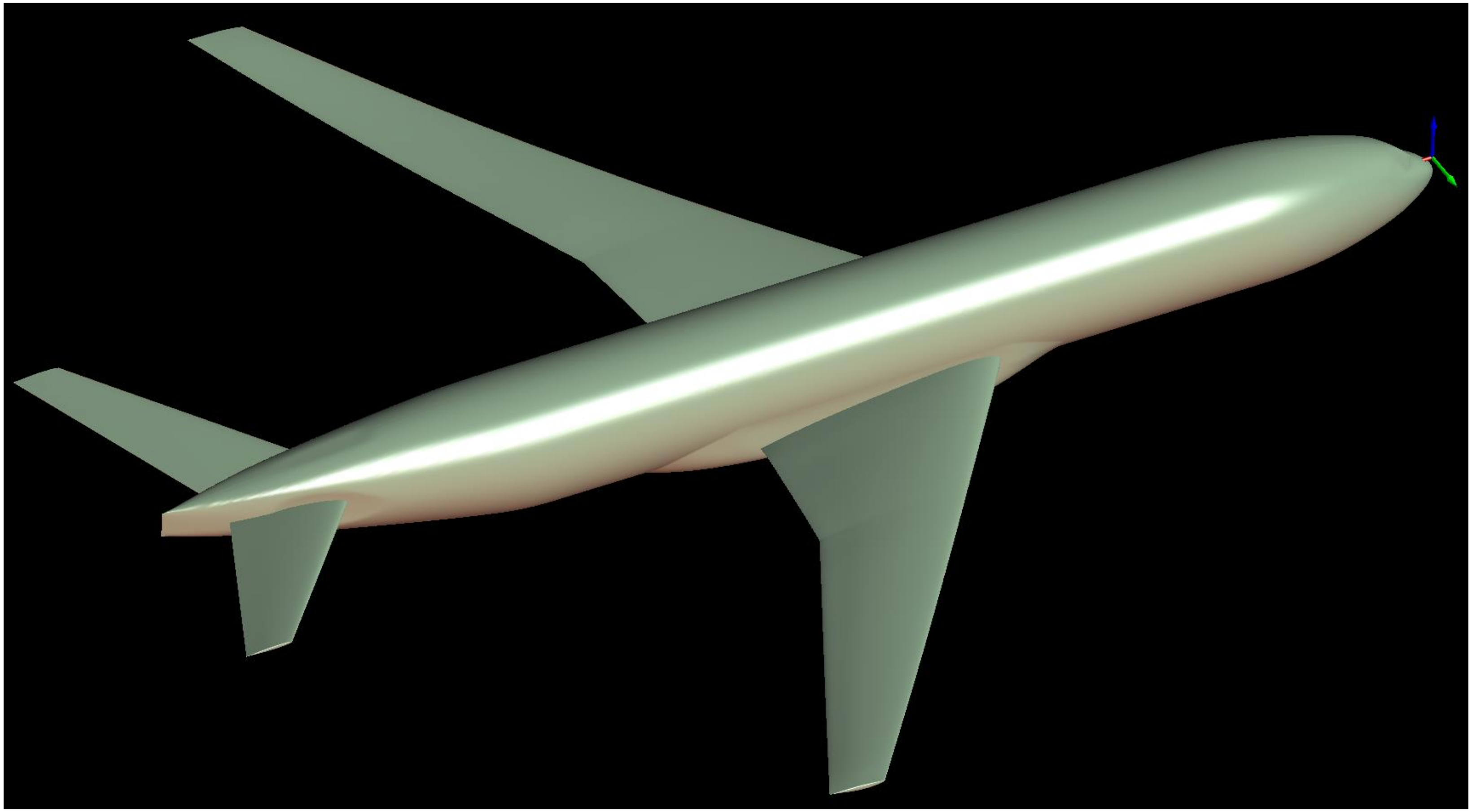
- **Modal mesh morphing:**
  - **Mesh-morphing displacement *precomputed* for each structural mode prior to the coupled FSI analysis**
  - **During transient FSI run, mesh node displacement fields are scaled by generalized displacements (q) and linearly superimposed (no RBF interpolation required at runtime)**

Initial RANS Steady-State Deflection*

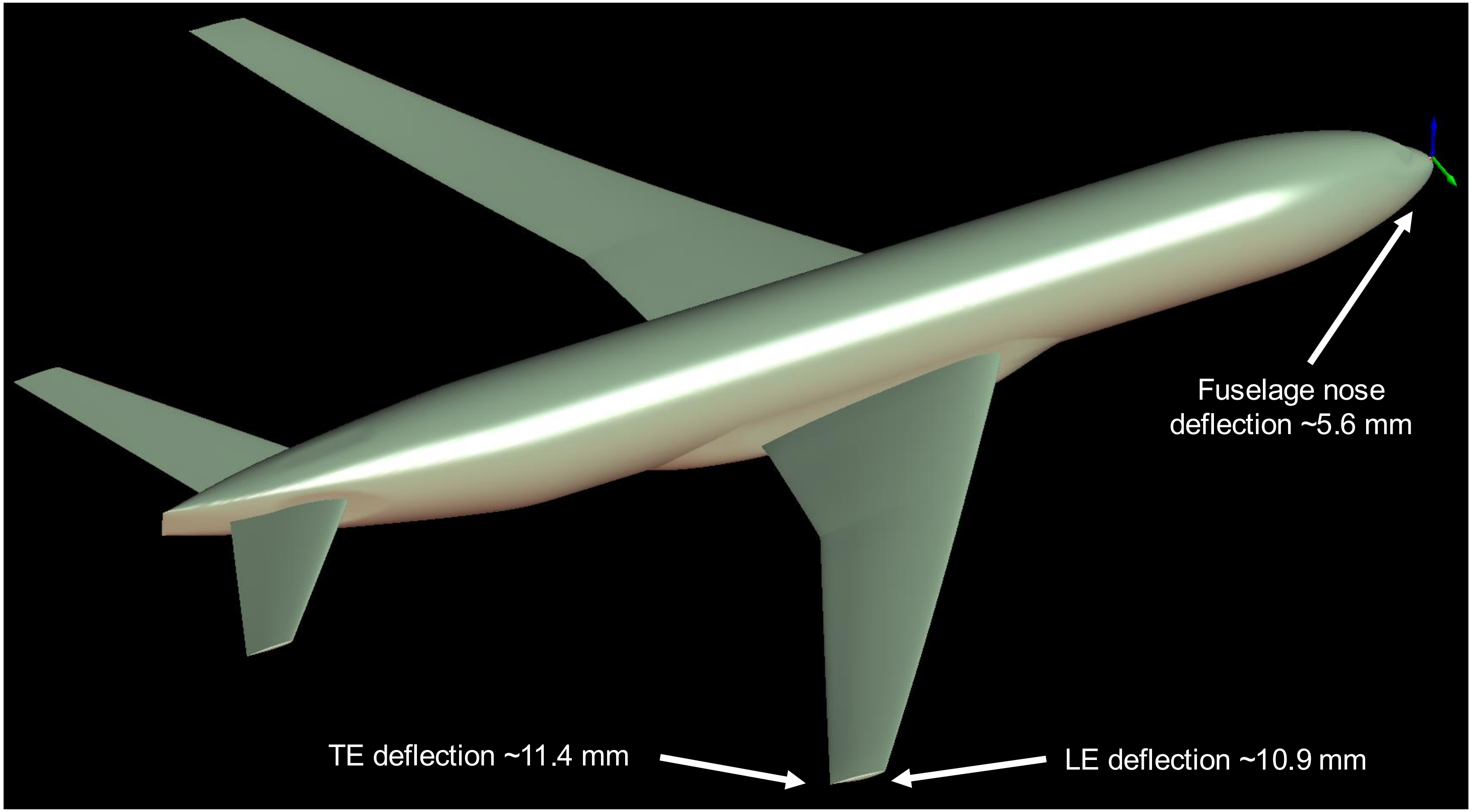


***Solution (and deformations) used as initial conditions for transient FSI**

Undeflected Jig Geometry

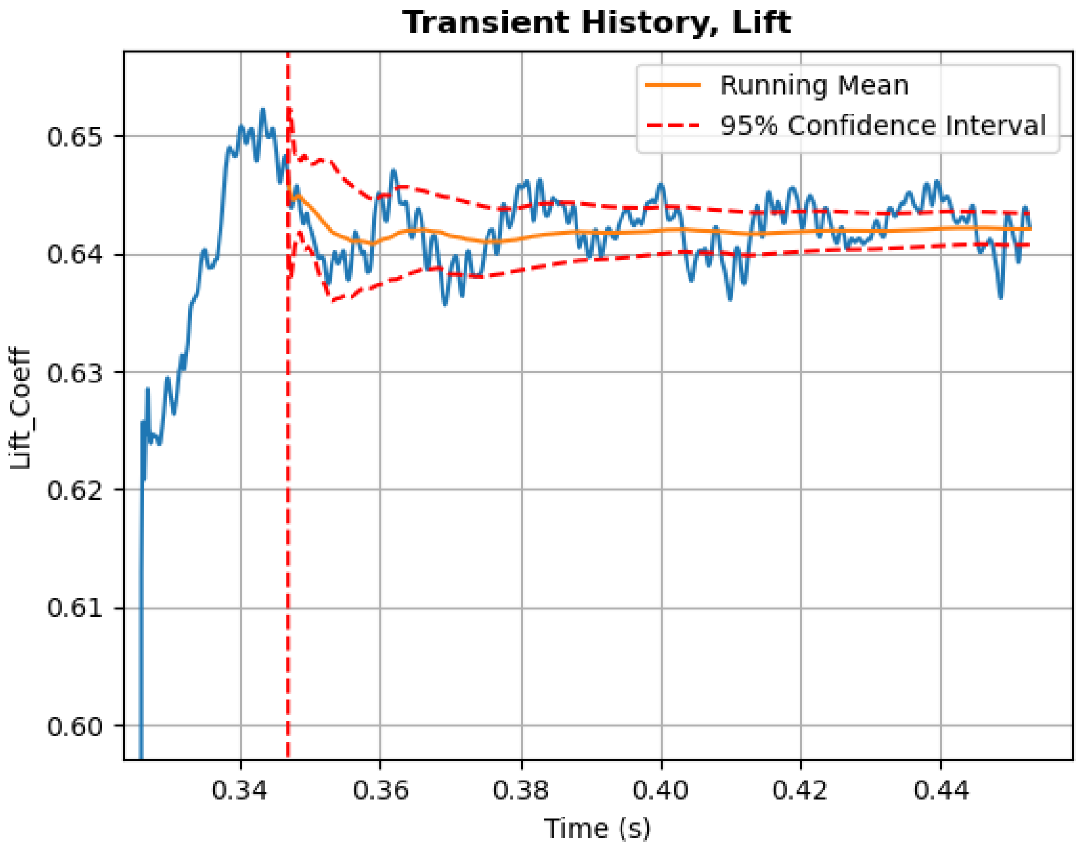


RANS Steady-State Deflection



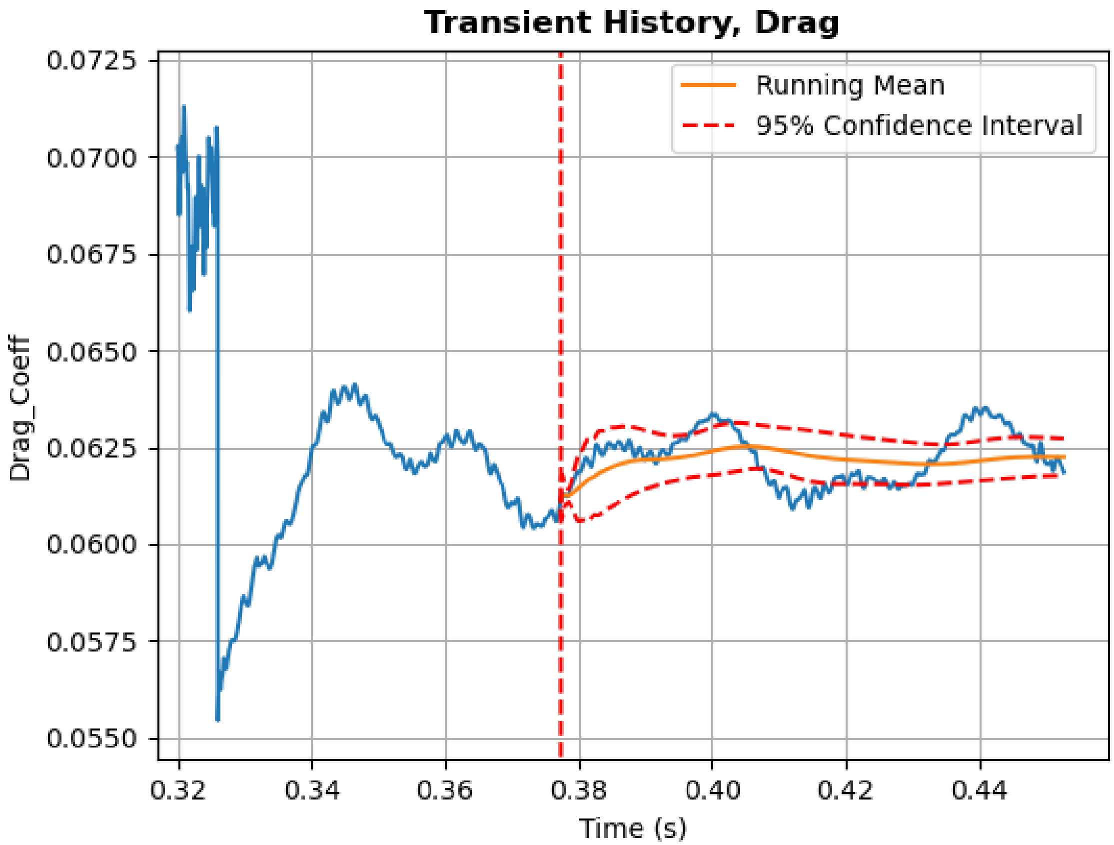
Wing-tip deflections reduced by about 1.5 - 2 mm if wing-root deformations are removed

HRLES Forces - Lift



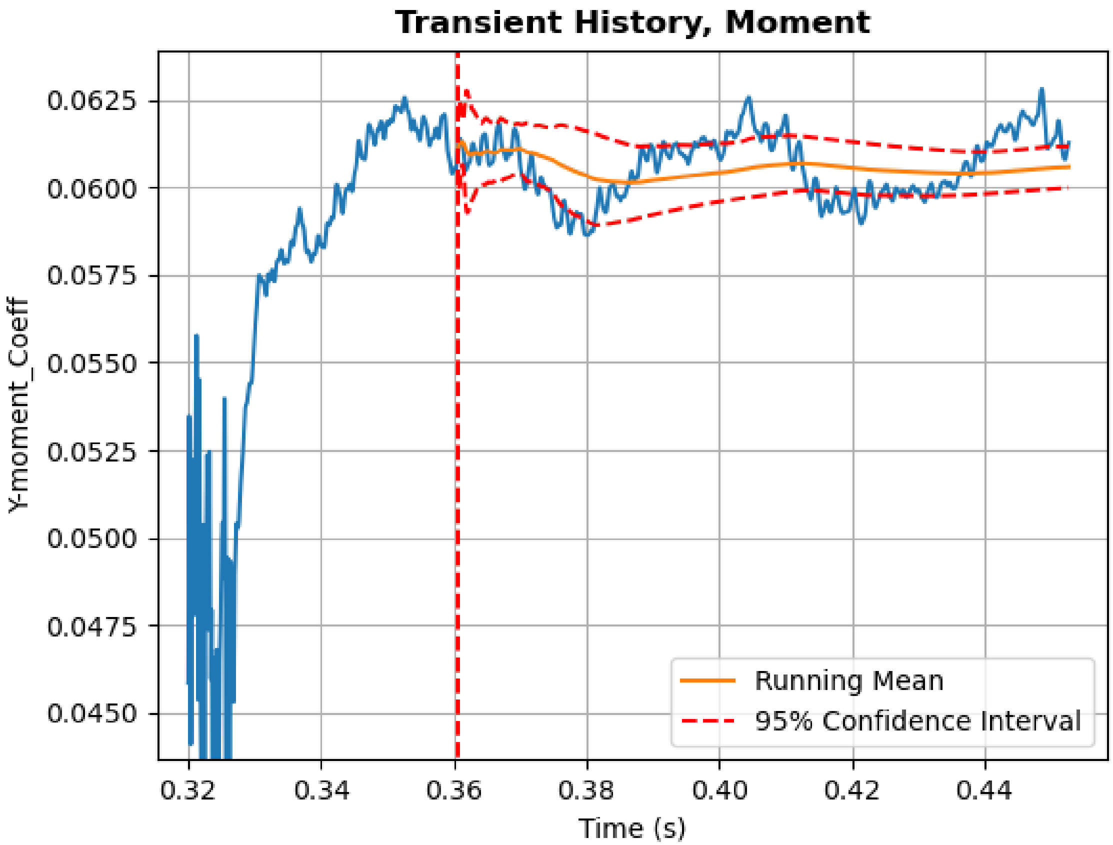
Mean C_L = 0.6421 (Exp. = 0.65408)

HRLES Forces - Drag



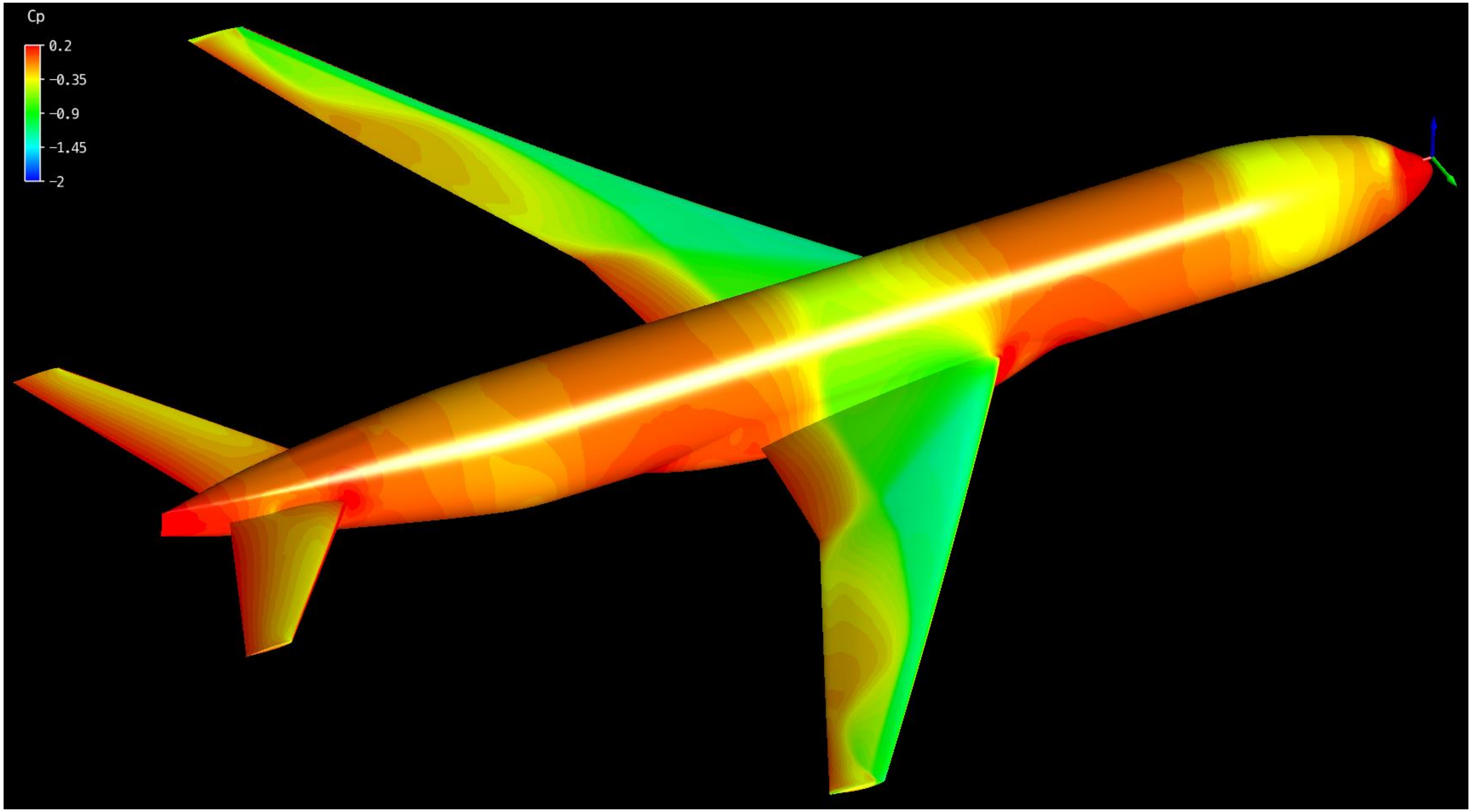
Mean C_D = 0.0622 (Exp. = N/A)

HRLES Forces - Moment



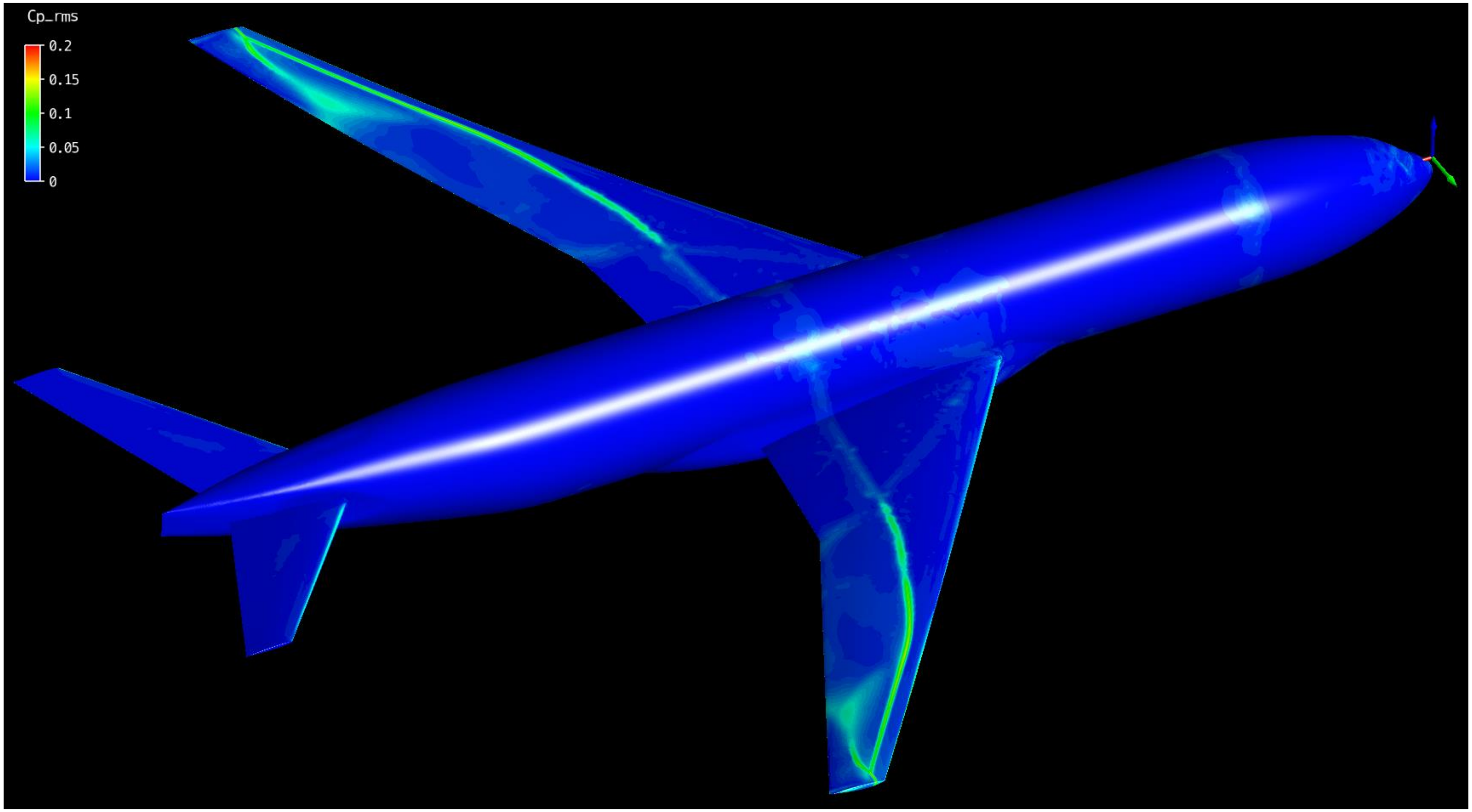
Mean C_M = 0.0604 (Exp. = 0.02 - this cause of this discrepancy is not yet fully understood)

HRLES Solution



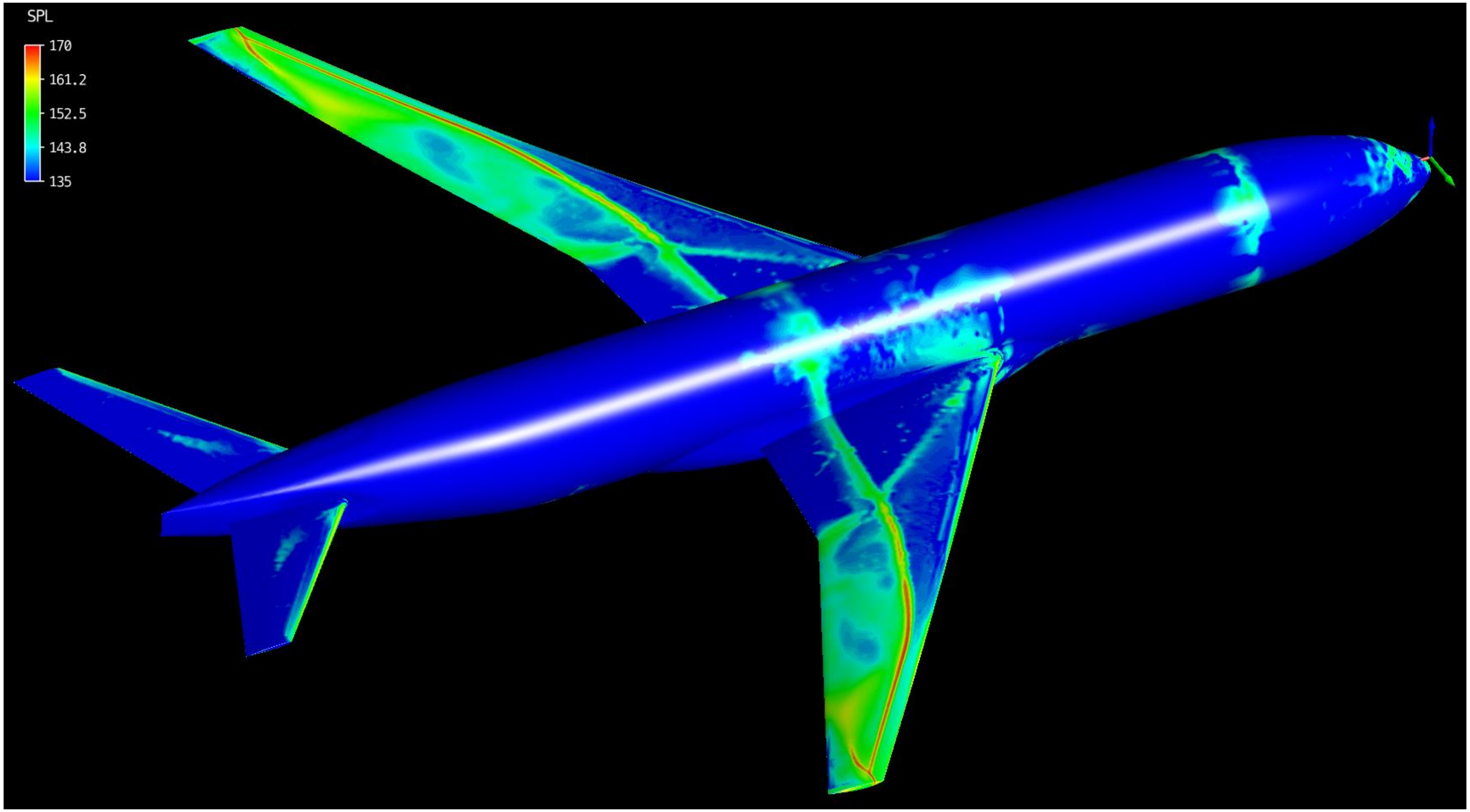
Mean Cp (Cadence L2 mesh, solution mapped to original jig geometry)

HRLES Solution



Cp_rms (Cadence L2 mesh, solution mapped to original jig geometry)

HRLES Solution

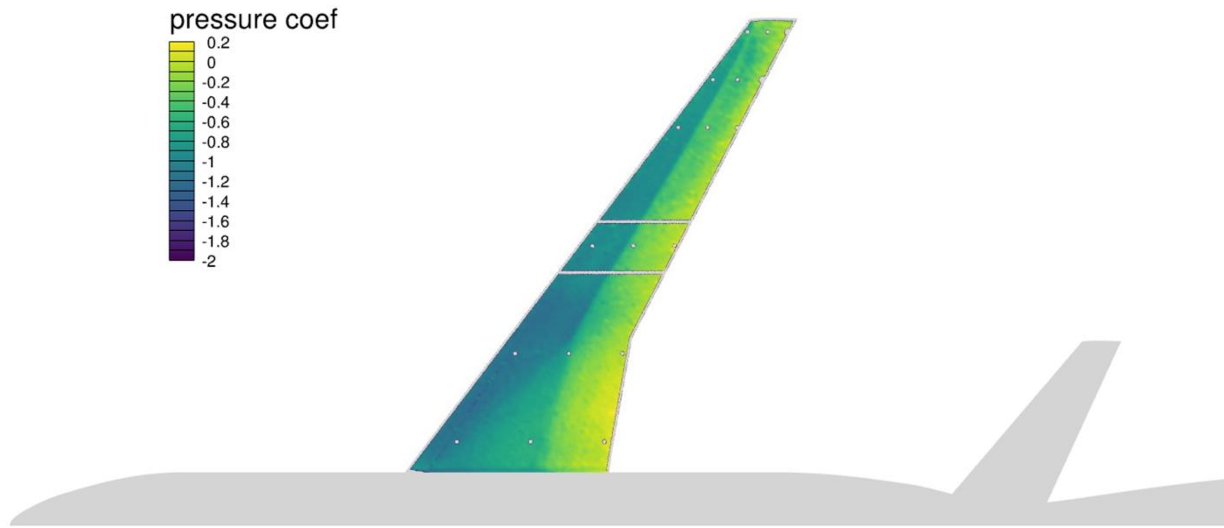


Surface SPL (dB) (Cadence L2 mesh, solution mapped to original jig geometry)

HRLES Solution

Experimental data from UPSP seems to be plotted with viridis colormap…

Experiment mean Cp:

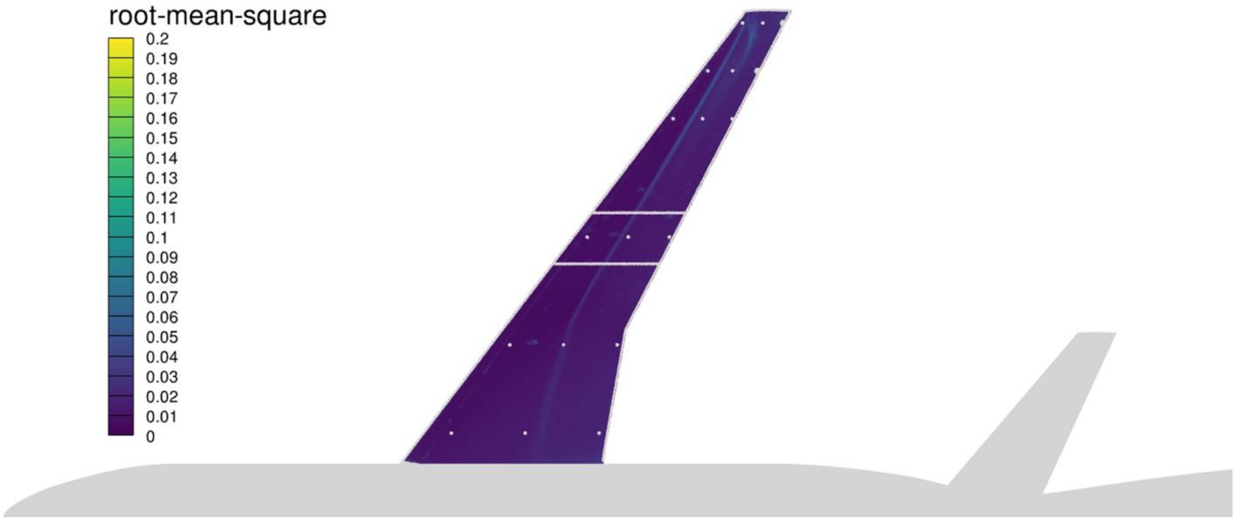


HRLES time-averaged Cp on same scale:

HRLES Solution

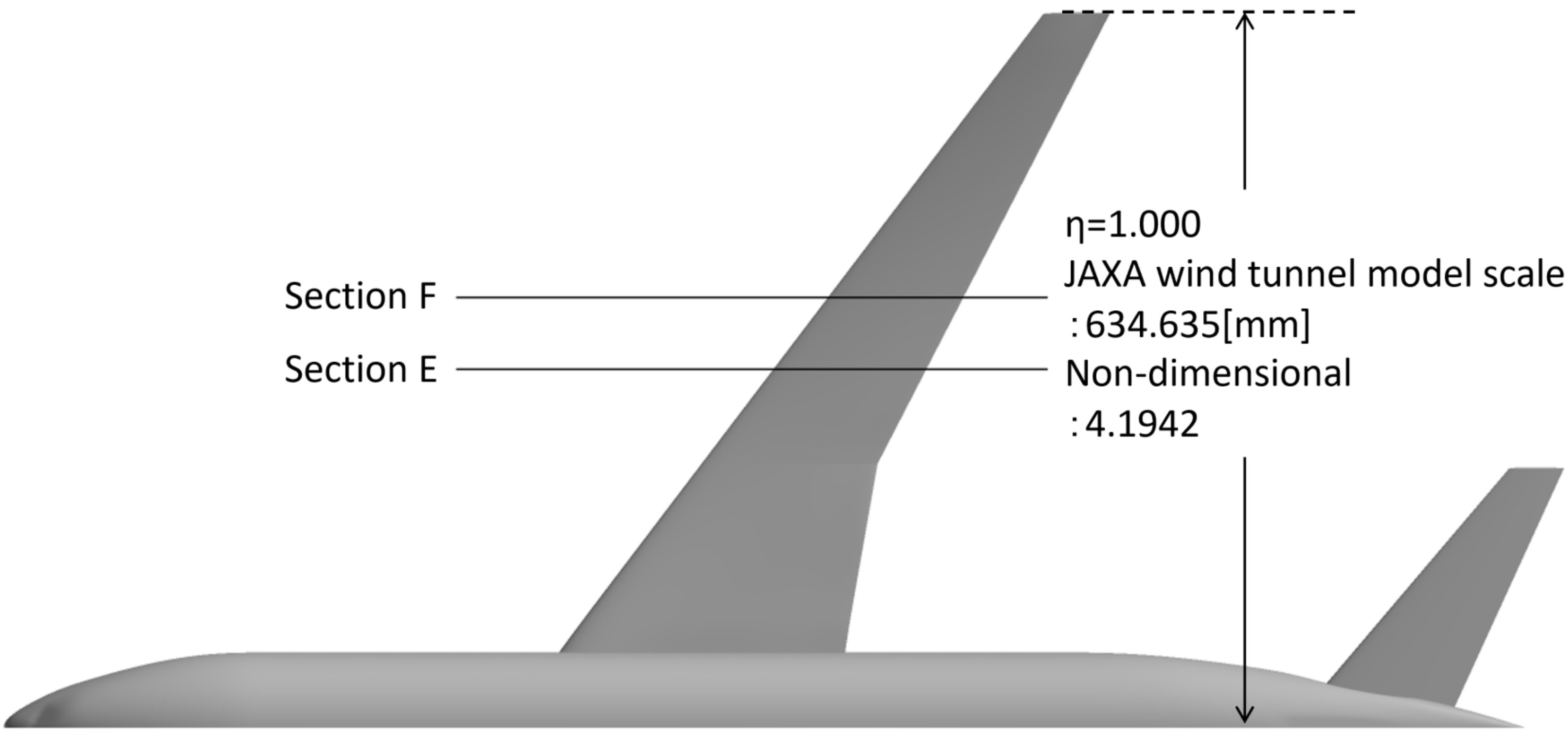
Experimental data from UPSP seems to be plotted with viridis colormap…

Experiment Cp_rms:



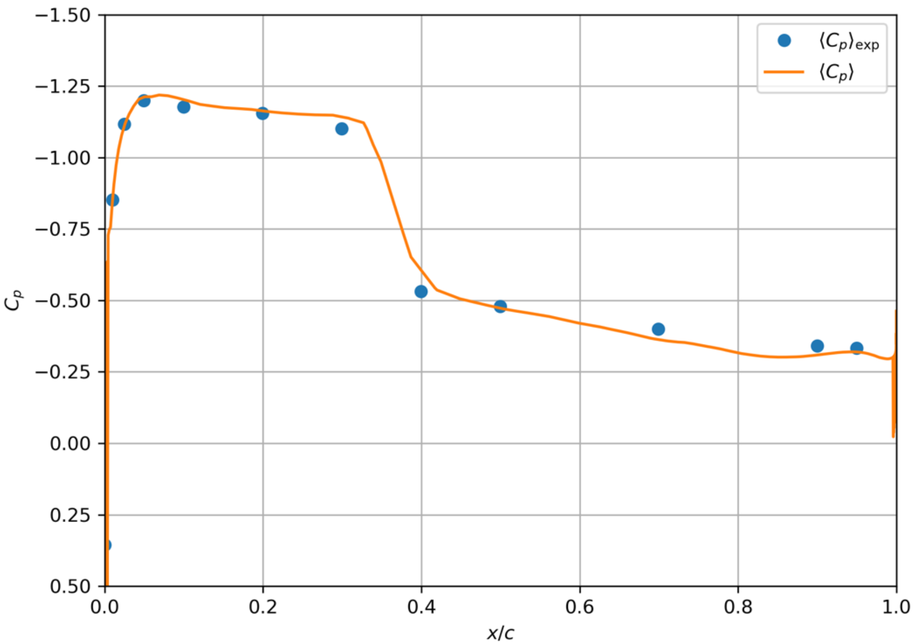
HRLES Cp_rms on the same scale:

Reference Cut Locations

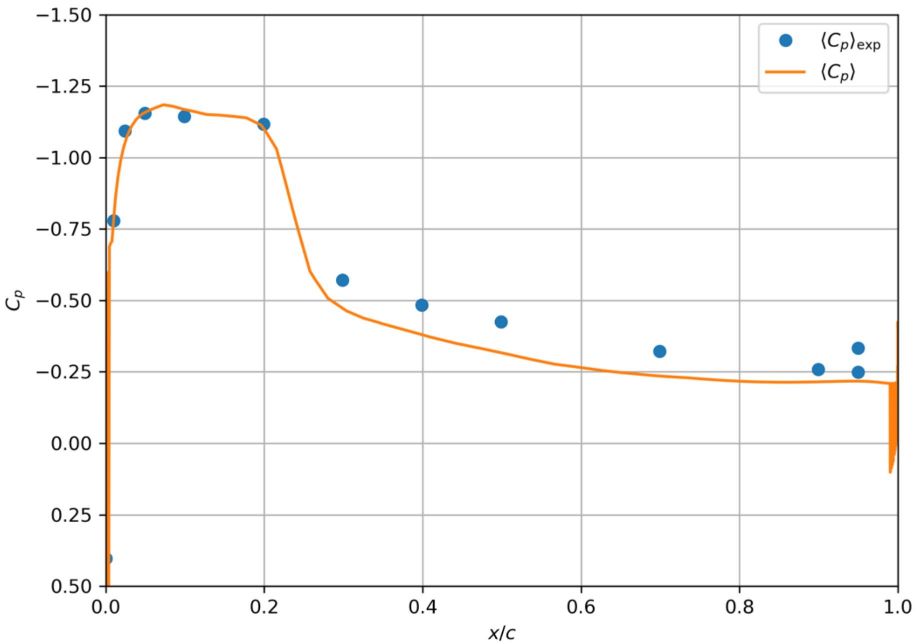


Obtained from JAXA: https://cfdws.chofu.jaxa.jp/apc/dpw/upsp.html

HRLES Reference Cut Comparisons: <Cp>

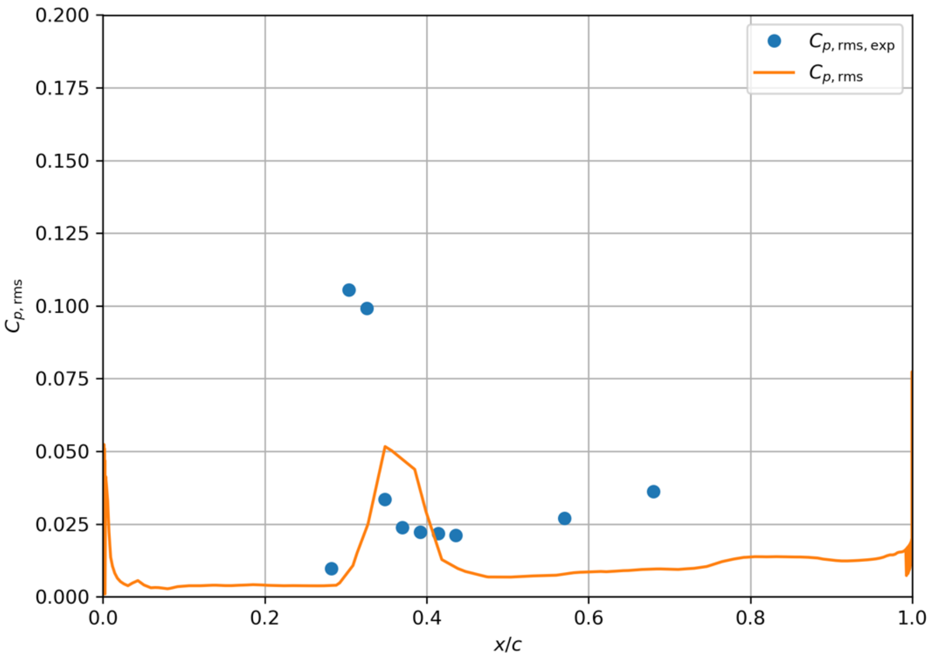


Section E ($\eta = 0.5021$)

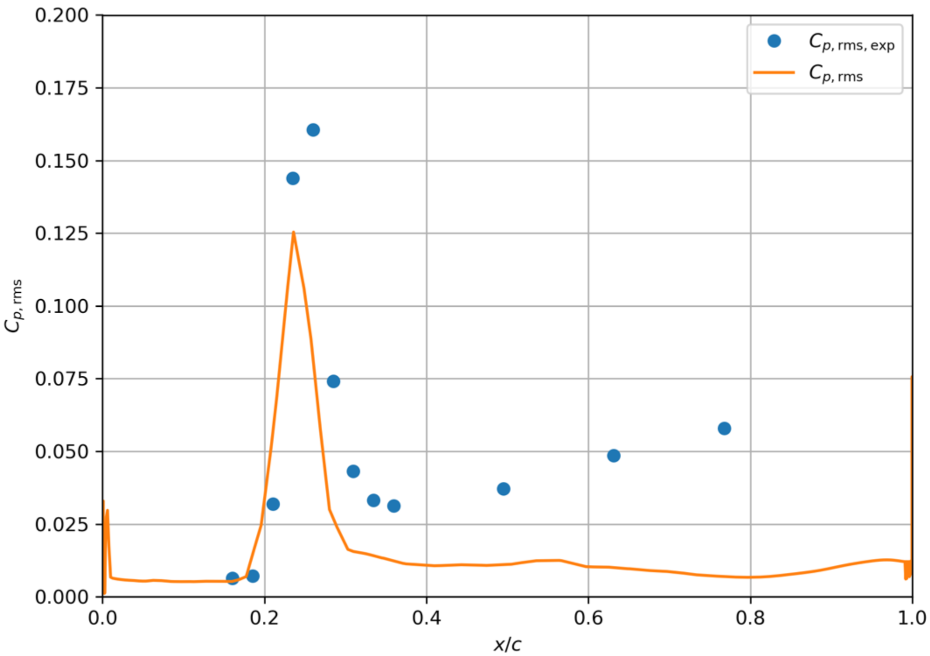


Section F ($\eta = 0.6028$)

HRLES Reference Cut Comparisons: Cp_rms

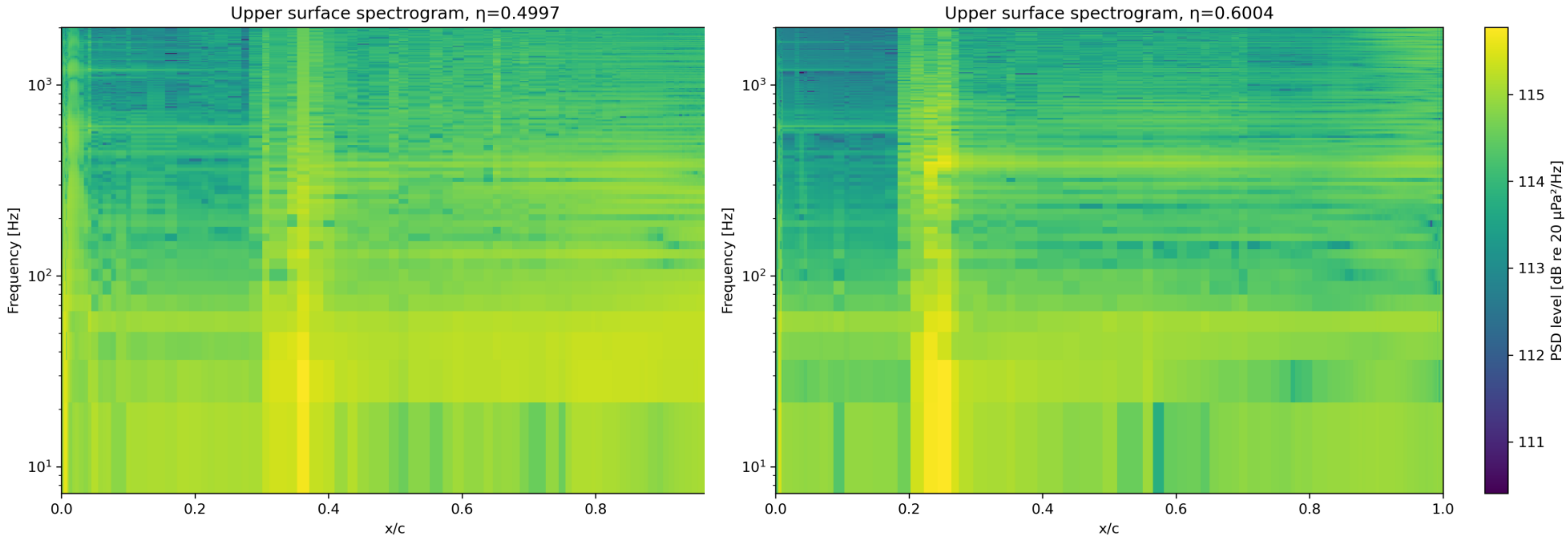


Section E ($\eta = 0.4997$)



Section F ($\eta = 0.6004$)

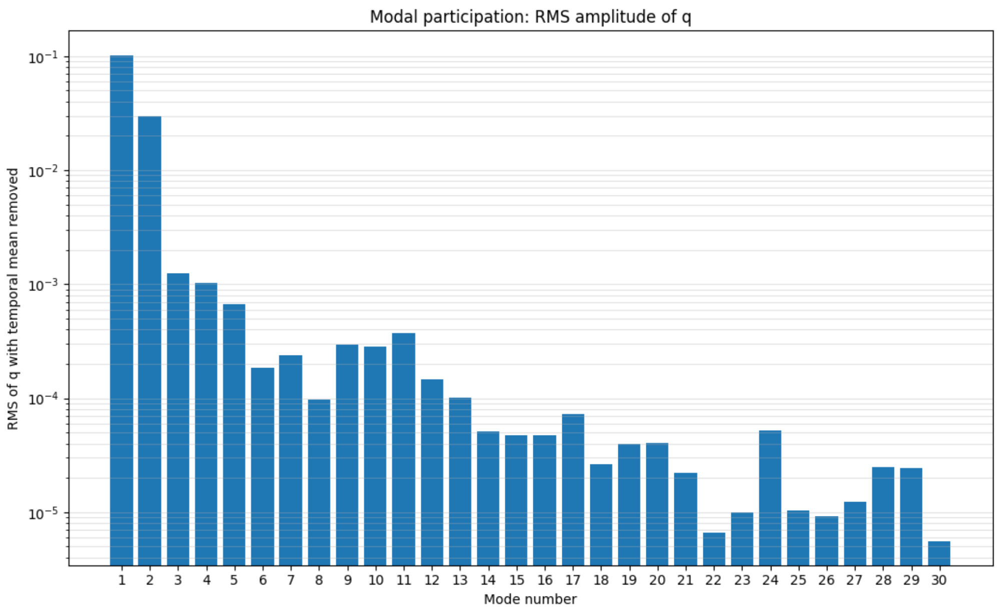
HRLES Spectrograms at Reference Cut Locations

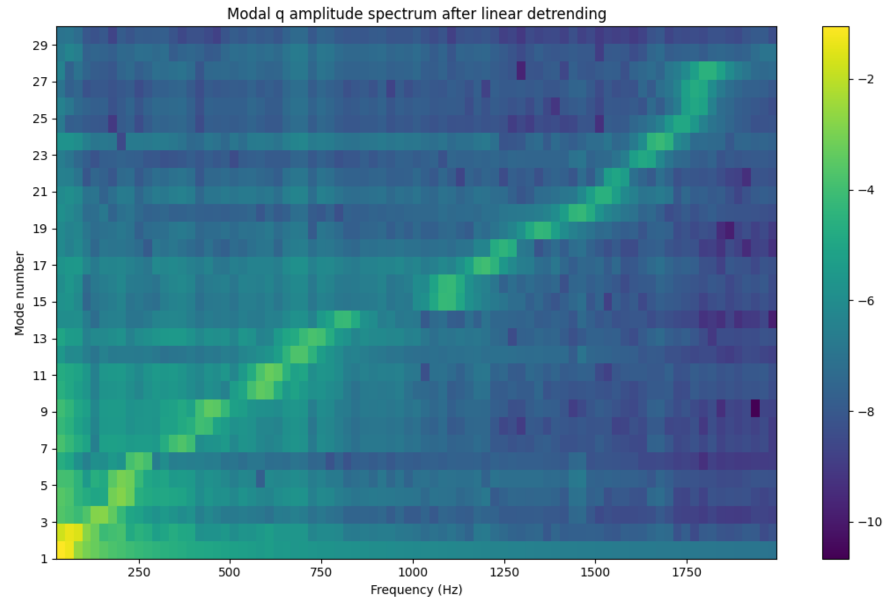


Section E

Section F

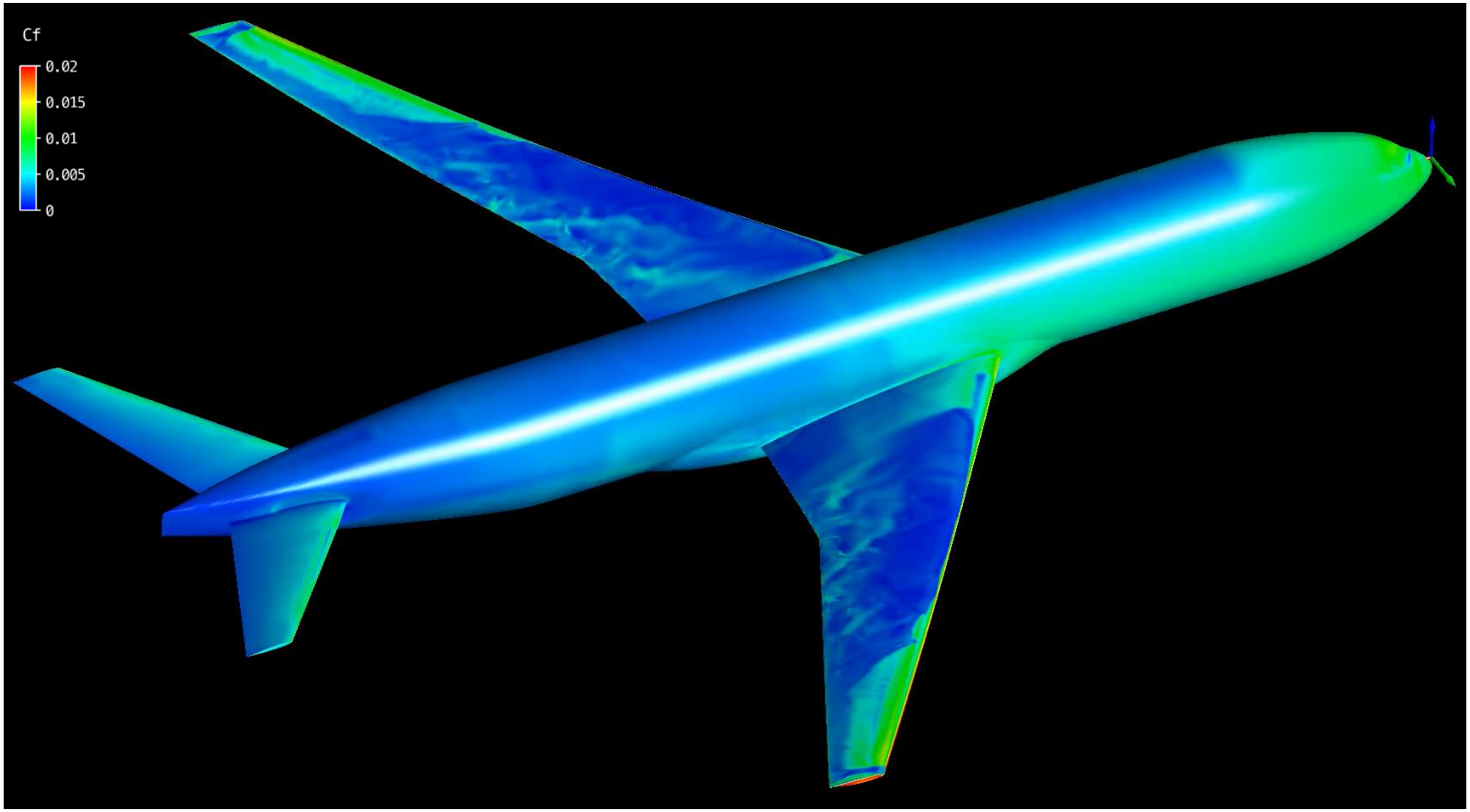
HRLES Modal Participation Factors



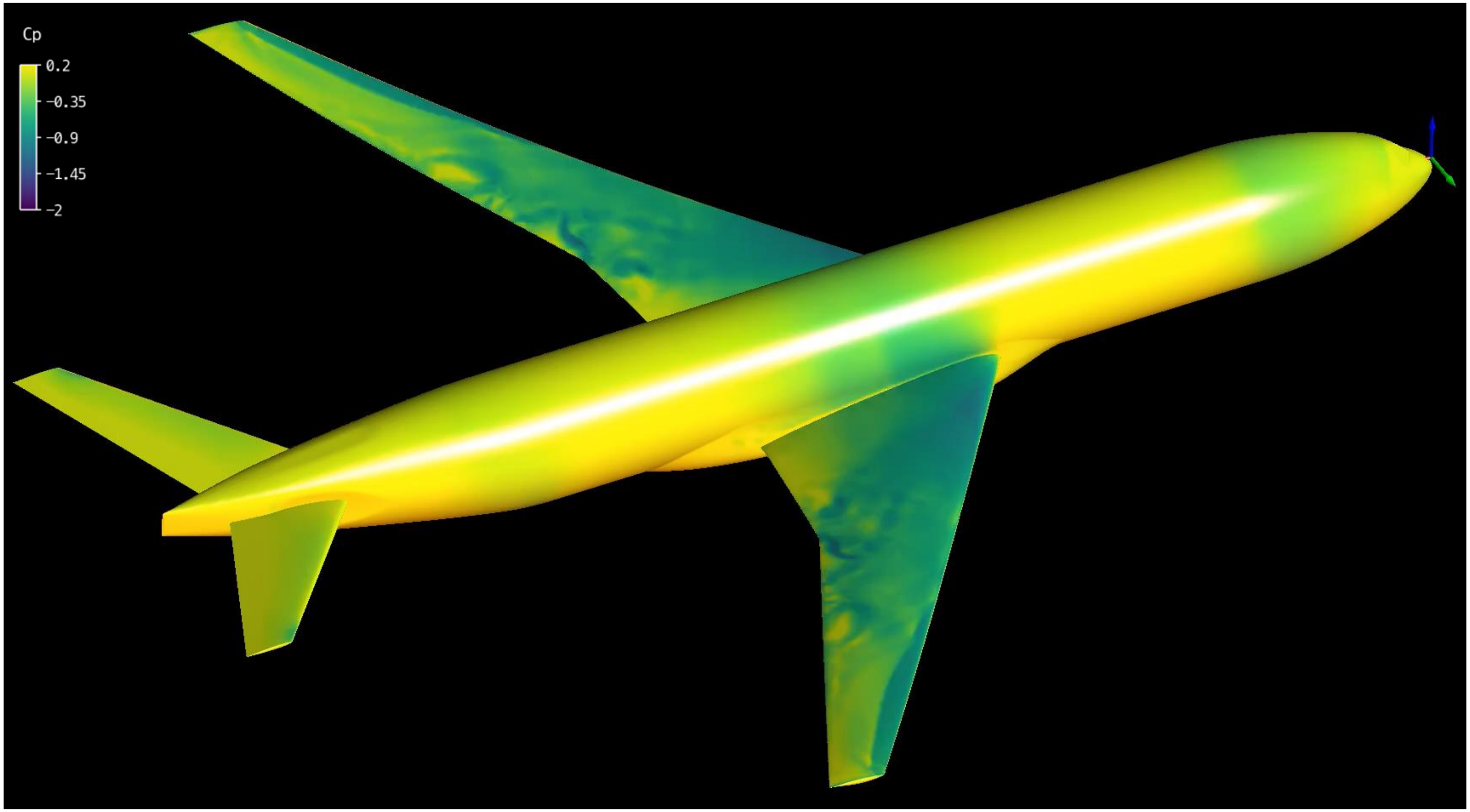


- First two modes dominate (~24 Hz and ~48 Hz)
- Higher modes are present, but with modal-coordinate amplitudes 2–3 orders of magnitude smaller (N.B. modal amplitudes normalized by mass matrix)
- Fuselage motion appears to be dominated by the first structural mode, with a frequency of around 25 Hz, while the wing-tip deflection appears to have a strong contribution from the second structural mode

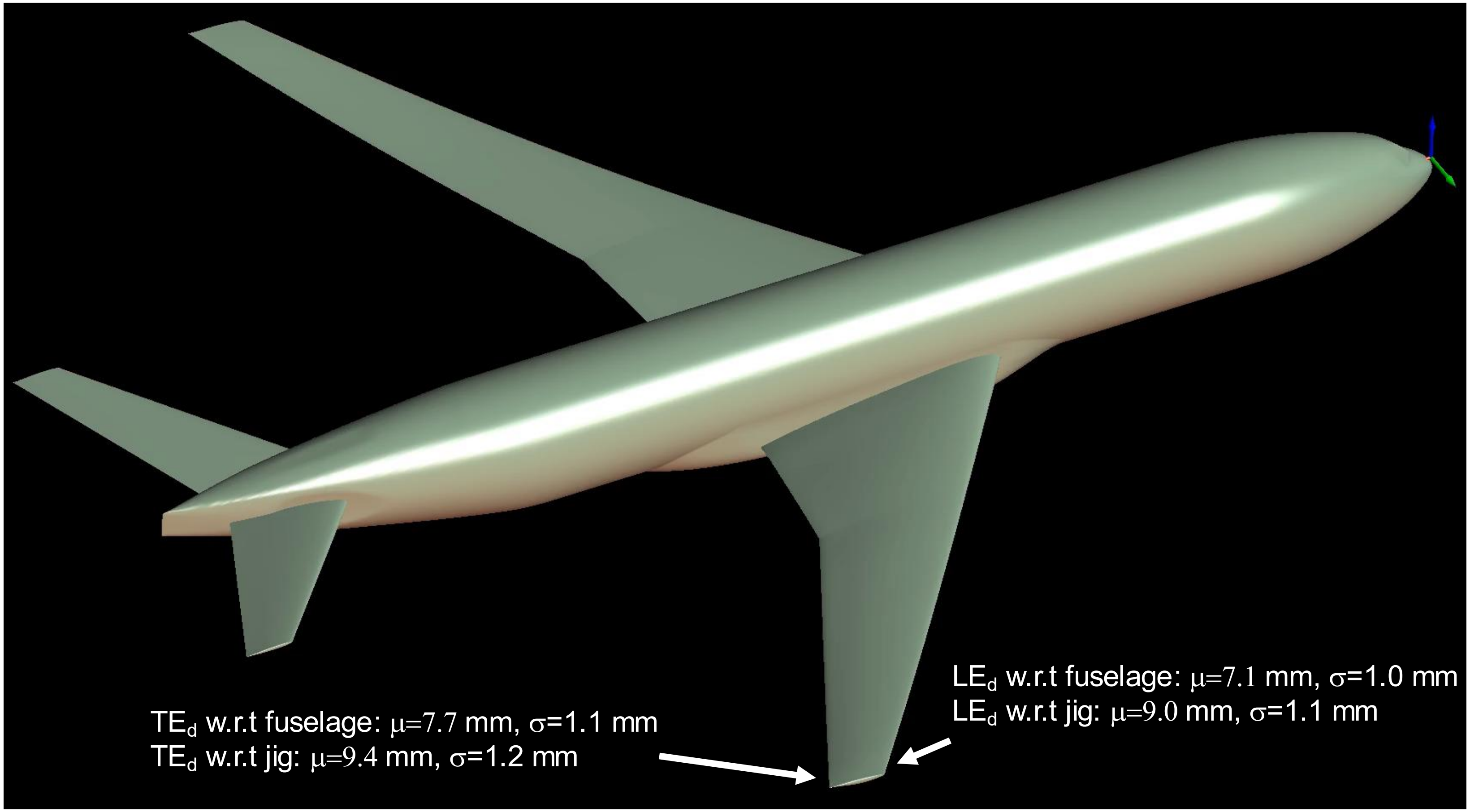
Time-Dependent Cf



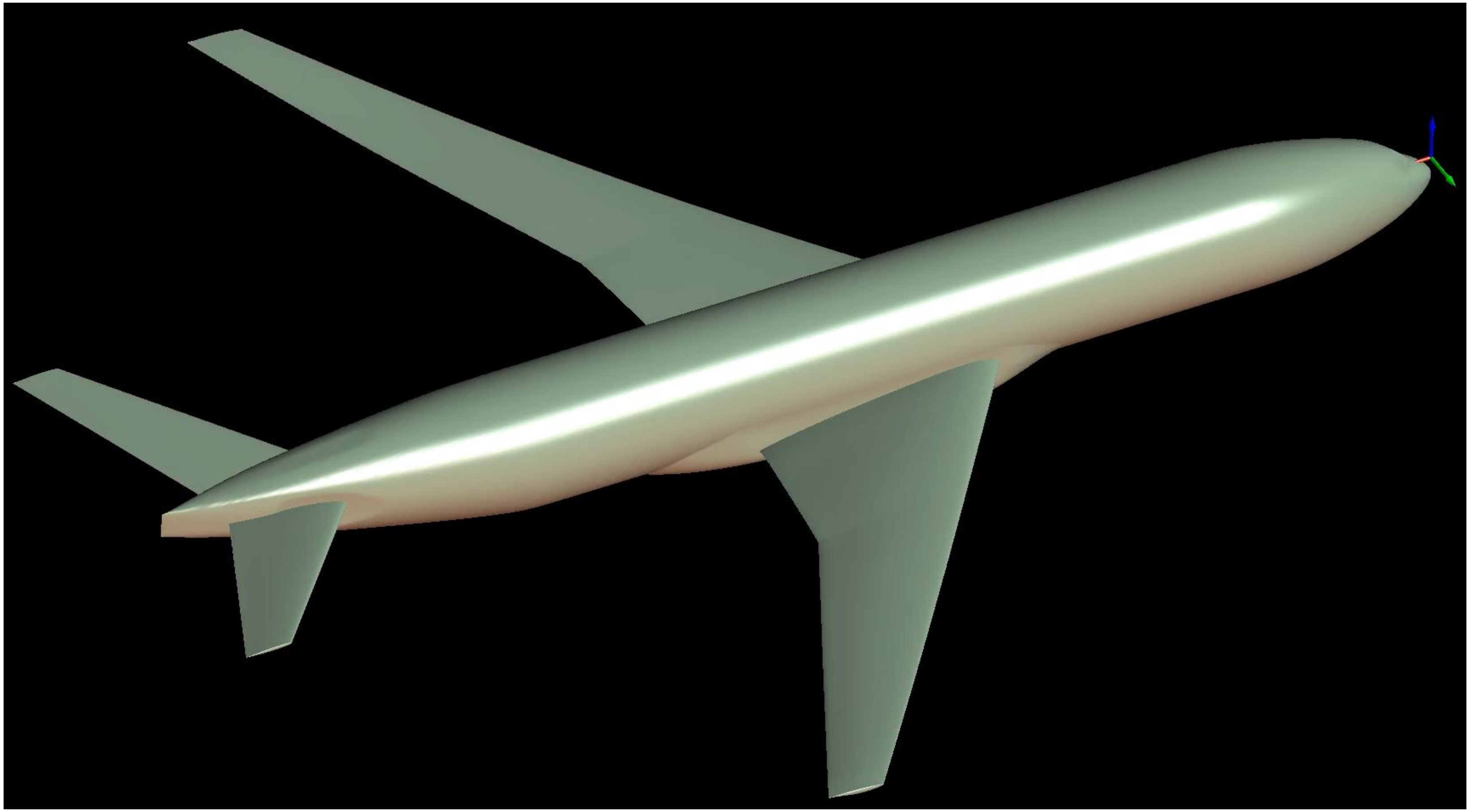
Time-Dependent Cp



HRLES Deformations



HRLES Deformations x10



Summary

- Initial attempt at DPW8 Case 3 has demonstrated the process of coupled CFD/FSI
- These cases are expensive, but large Δt HRLES can reduce the cost while giving more reliable results than URANS
- Mean HRLES results are in reasonable agreement with experiment, but pitching moment is too large
- Cp_rms slightly underpredicted at sectional/reference cuts; slightly overpredicted on outboard wing compared against JAXA's USPS contour map

Further Work Required…

- Mesh sensitivity and other AoAs (e.g., buffet onset) not yet studied

Thank You!

Special thanks to ONERA, JAXA, Cadence, workshop organizers and HRLES/WMLES TFG leads and members