

Predicting High-Lift Aerodynamics on NASA Common Research Model - Part II: Delayed Detached Eddy Simulations

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Computational Aerosciences Branch

NASA Ames Research Center

Advanced Modeling & Simulation (AMS) Seminar Series

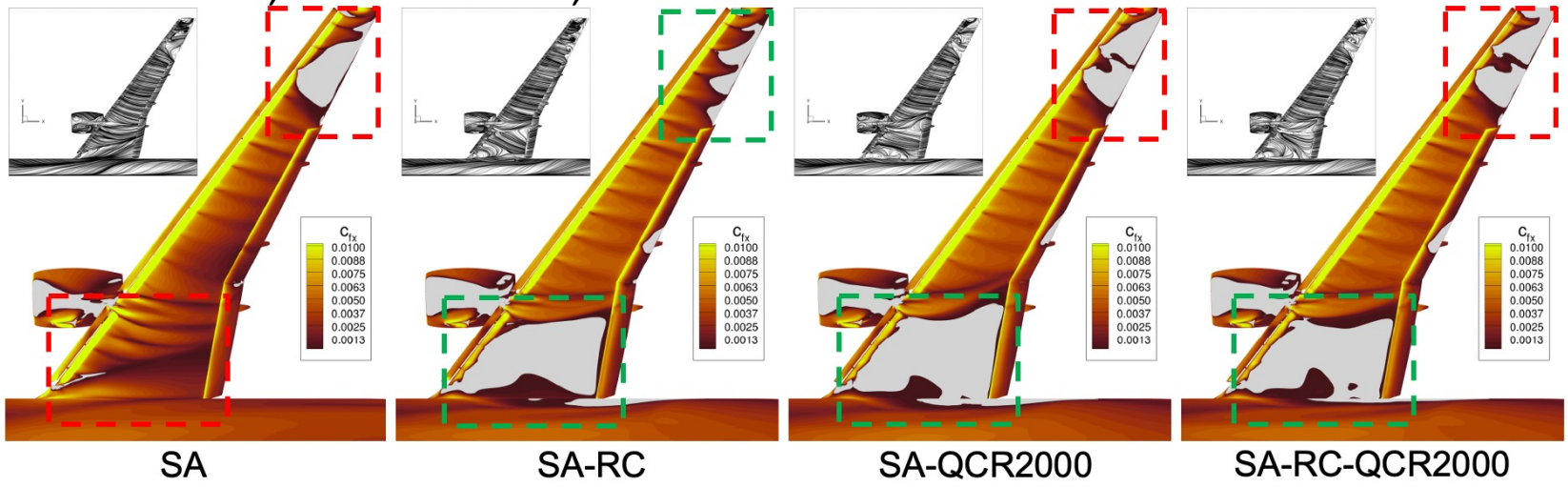
NASA Ames Research Center

June 2nd, 2022

Recap of Part I: RANS

J. Duensing *et al.* https://www.nas.nasa.gov/pubs/ams/2022/05-26-22.html

- Wind tunnel modeling provides better qualitative consistency with experiment (i.e., pitching moment break is captured), but other erroneous flow features still persist
- While all experimental flow phenomena could be predicted qualitatively using at least one method, no one RANS methodology can capture all flow topologies across entire α-range with exceptional accuracy (expected finding)
- If flow separation has a length scale on par with the MAC, the solution is very sensitive to mesh resolution, initial condition, and turbulence model choice

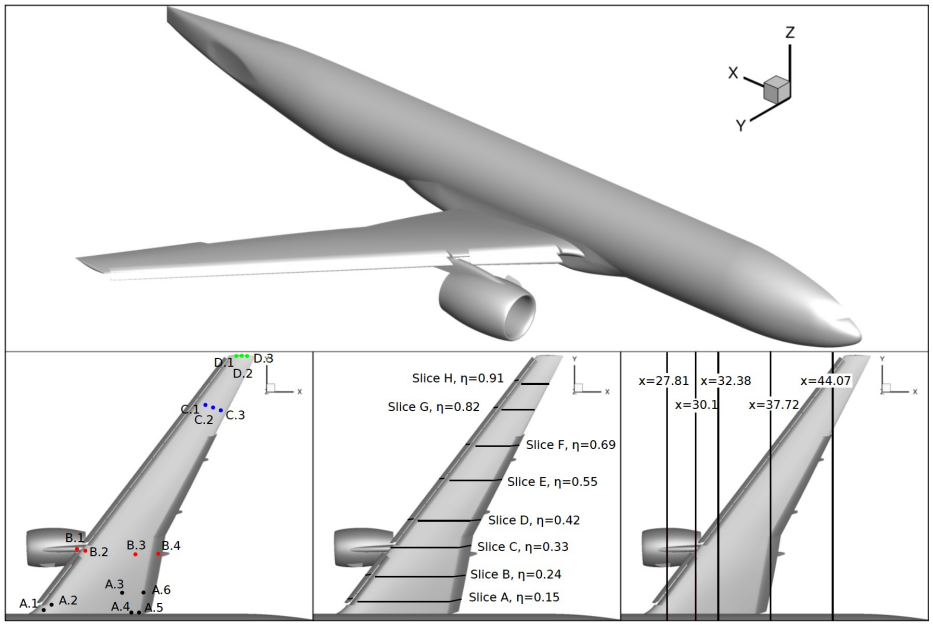


High Lift Prediction Workshop 4 (HLPW4)

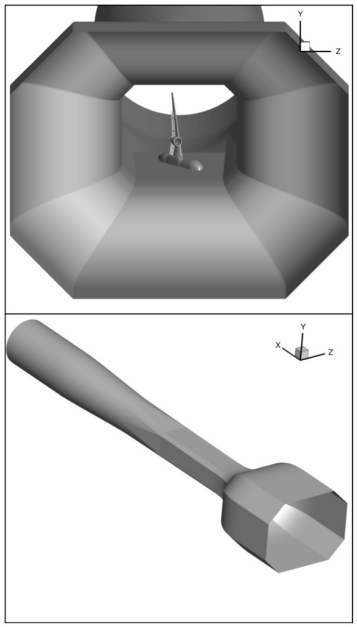
https://hiliftpw.larc.nasa.gov/

NASA Ames LAVA group participated in the RANS, HRLES and WMLES Technical Focus Groups (TFGs) and submitted data for each to the workshop in December 2021.

NASA semispan High-lift Common Research Model (CRM-HL) – Case 2a and 2b for HLPW4



(a) Free Air (Case 2a)



(b) Wind Tunnel (Case 2b)

LAVA HRLES Papers from HLPW4:

AIAA SciTech Forum2022:

- *Kiris, C. C., Ghate, A. S., Duensing, J. C., Browne, O. M. F., Housman, J. A., Stich, G.-D., Kenway, G., Dos Santos Fernandes, L. M., and Machado, L. M., "High-Lift Common Research Model: RANS, HRLES, and WMLES perspectives for CLmax prediction using LAVA," AIAA SciTech 2022 Forum, AIAA Paper 2022-1554, 2022. doi:10.2514/6.2022-1554*

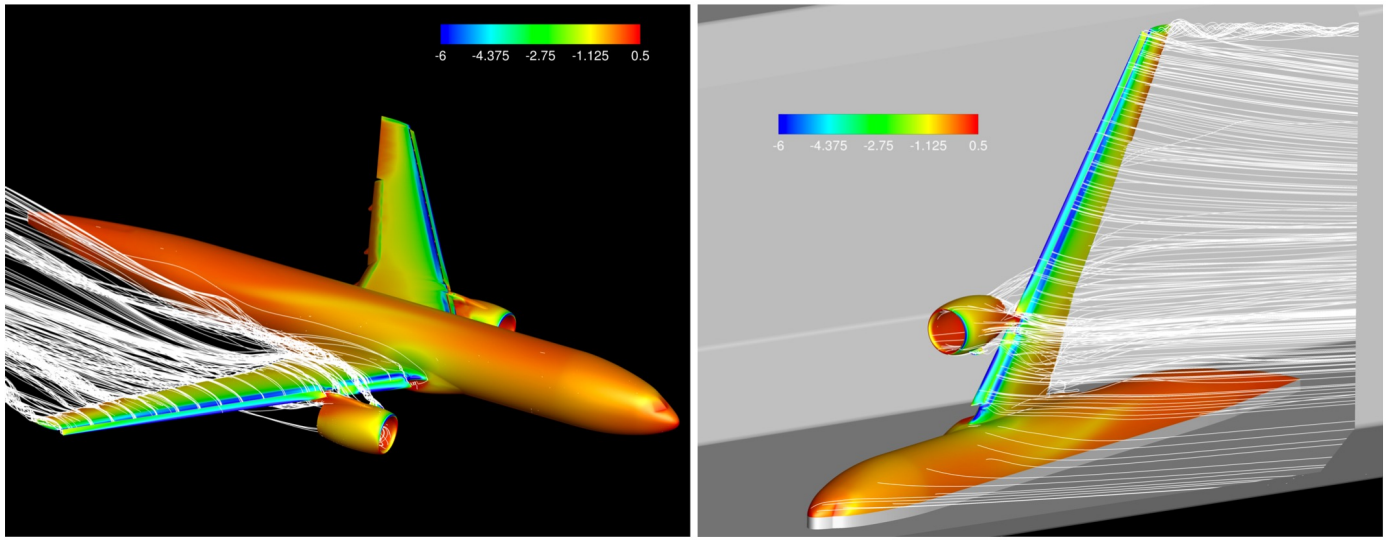
AIAA Aviation Forum 2022:

- *Browne, O., Housman, J., Kenway, G., Ghate, A., and Kiris, C., "A Hybrid RANS-LES Perspective for the High Lift Common Research Model Using LAVA," AIAA Aviation Paper to appear, 2022.*

NASA CRM-HL

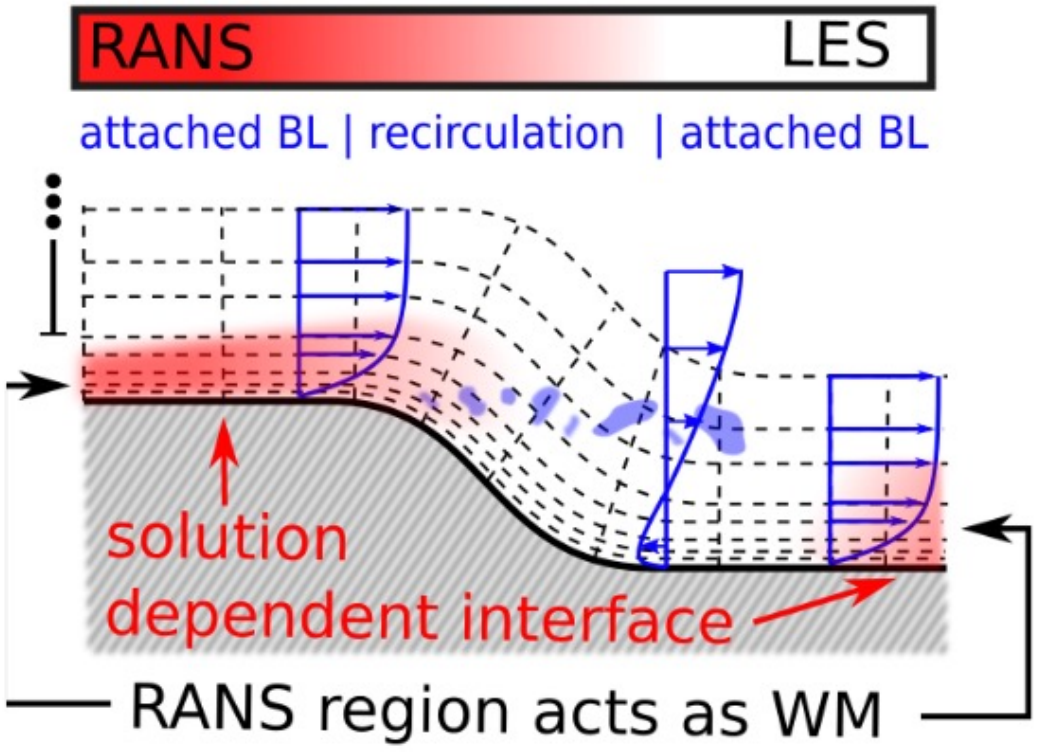
- CRM-HL developed as an open source geometry with high-lift devices at takeoff or landing configurations, representative geometry of a typical modern airliner.
- M=0.2, Re = 5.5e6, MAC = 7.00532m.
- Angle-of-Attack (AoA) sweep:
  - Free Air (corrected), α=[7.05, 11.29, 17.05, 19.57*, 20.55, 21.47],
  - WT (uncorrected), α=[5.98, 9.98, 15.48, 17.98*, 18.97, 19.98].

*near CLmax angle



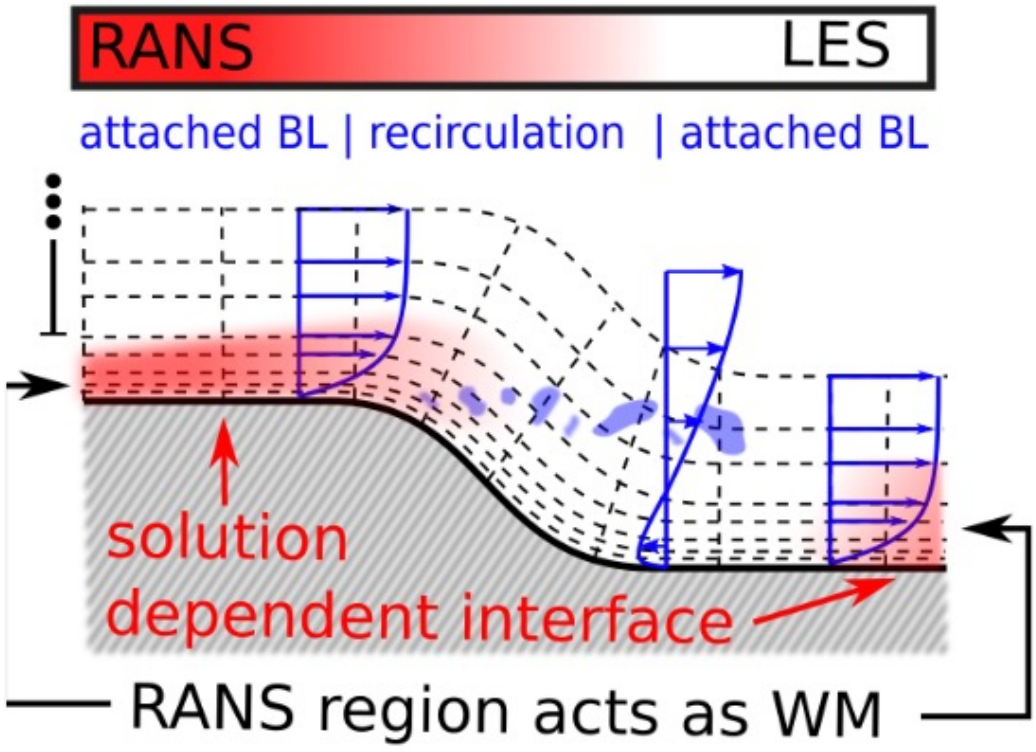
Hybrid RANS/LES: DDES

- Delayed Detached Eddy Simulations (DDES): attached boundary layers (RANS mode), separated boundary layer/wakes (LES mode)
- Automatic shielding functions are employed to determine if the flow locally should be in RANS mode or LES mode.
- First developed by Spalart et al. (1997) as DES97 with the following notable improvements:
  - DDES2006 (Spalart et al. 2006),
  - ZDES2012 mode 2 (Deck 2012)
  - ZDES2020 mode 2 Enhanced Protection (Deck & Renard 2020)

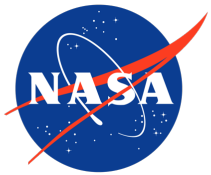


Hybrid RANS/LES: DDES (cont)

- Ease of implementation with existing underlying RANS model makes it popular choice for scale-resolving simulations.
- Model Stress Depletion (MSD) is a known issue of the method, can result in excessive separation due to under resolved mesh in LES mode - failure of the shielding function.
- Potential uncertainties of the method include appropriate choice of grid and timestep size, the underlying RANS model, the shielding function and grey zone, *etc*.



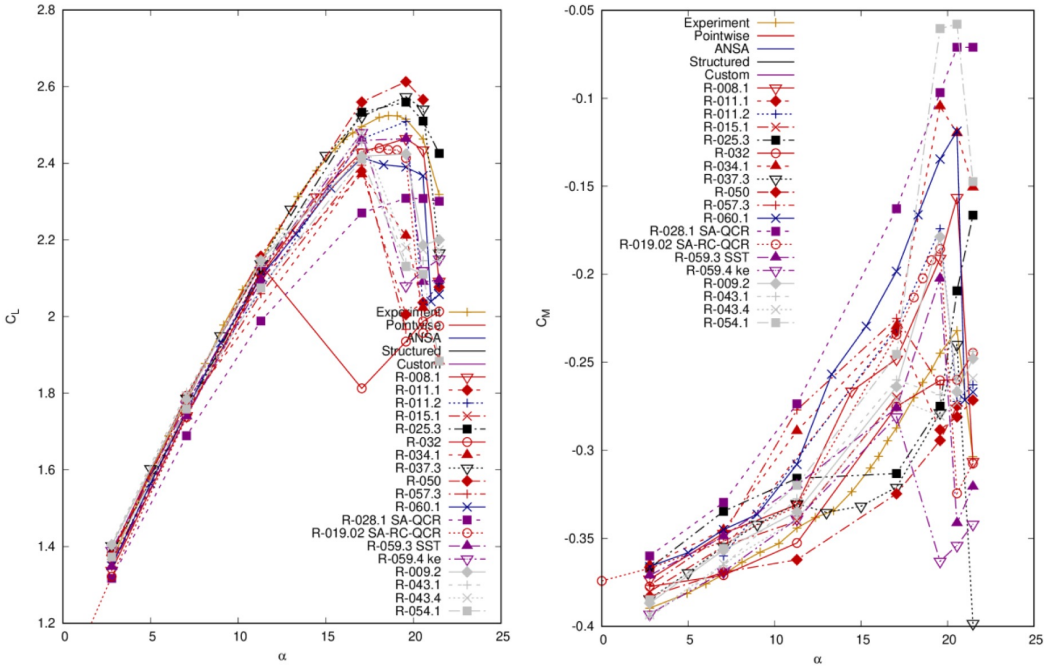
Outline



- Scope of this Work
- LAVA Framework and Meshing Approach
- NASA CRM-HL Results
  - Free air configuration
  - Wind tunnel configuration
- Summary

Scope of this Work

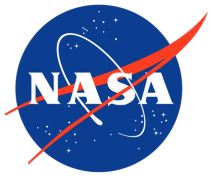
- Is HRLES a computationally feasible solution to overcome and address the failures seen in RANS?
- What are the best practices for HRLES scale resolving simulations for CLmax prediction?
- What are the sensitivities of HRLES solution to aspects such as underlying RANS closure and initial condition etc?



Lift and pitching moment coefficient predictions from the 4th AIAA High Lift Prediction Workshop best practice submissions for free air configuration (case 2a) presented at HLPW4 at Scitech 2022.[1]

[1]Ollivier-Gooch, C. & Coder, J. "Fixed-Grid RANS TFG,", 2022. URL https://hiliftpw.larc.nasa.gov/Workshop4/WorkshopPresentations/03_GMGW3_HLPW4_RANS.pdf, accessed: 2022-05-08.

Launch, Ascent, and Vehicle Aerodynamics (LAVA)



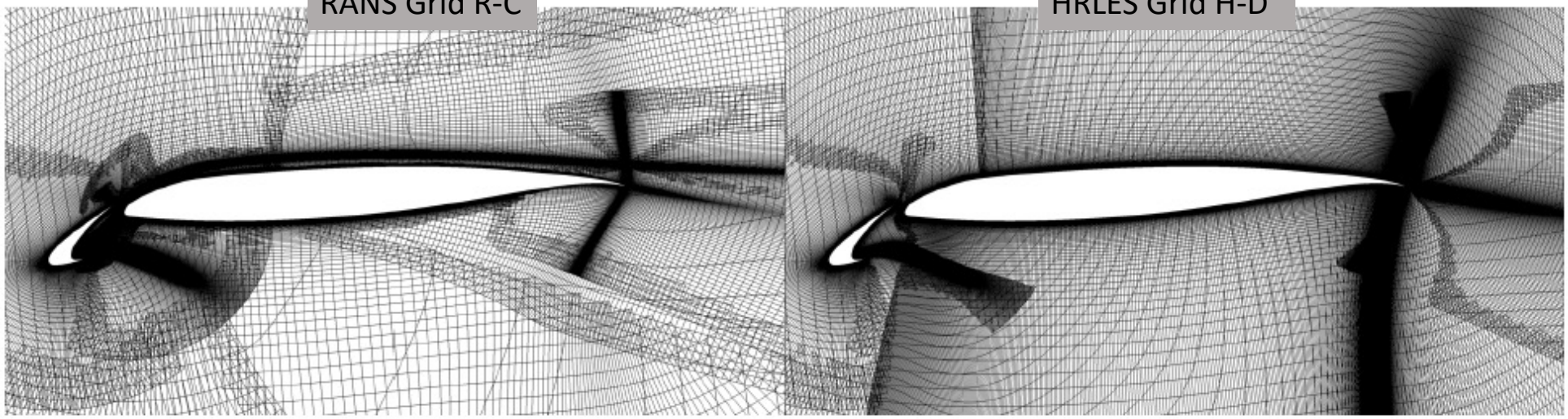
- Compressible Reynolds Averaged Navier-Stokes (RANS) equations with Favre averaging.
- Curvilinear Structured Overset Mesh Topology.
- Convective Scheme – blended third upwind/fourth-order centered accurate scheme (best practice); third-order WCNS (was deemed too dissipative); modified Roe (Riemann solver).
- Time Integration – implicit BDF2 time-stepping, 3 orders of residual convergence at each time-step.
- Underlying Turbulence Model – SA-neg (defined as SA for rest of presentation) and where noted with corrections (LRe - low Reynolds number, RC - Rotation Curvature, QCR2000 - Quadratic Constitutive Relation).
- Shielding Function – ZDES2020 Mode 2 Enhanced Protection (Deck & Renard 2020), maximum cell edge length use as local length scale in LES SGS closure.

Curvilinear Overset Grid System

Typical community practice: RANS grids are utilized for HRLES scale-resolving simulations is a common mistake, no universal best practices exist?

RANS Grid R-C

HRLES Grid H-D



(a) Outboard wing (y = 24 m.)

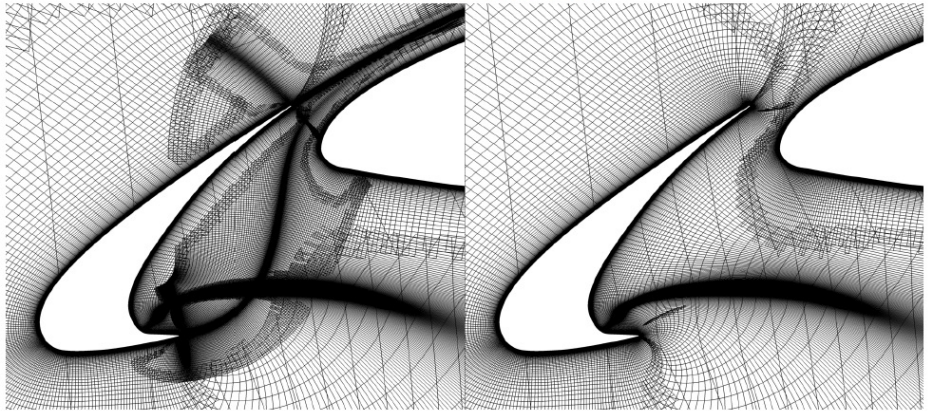
Main modifications to RANS Grids for HRLES (systematic and focused grid refinement):

- To prevent excessive outboard separation, the outboard region of the wing was significantly refined for HLRES Grid H-D – 8x streamwise and 16x spanwise when compared to Grid R-C.

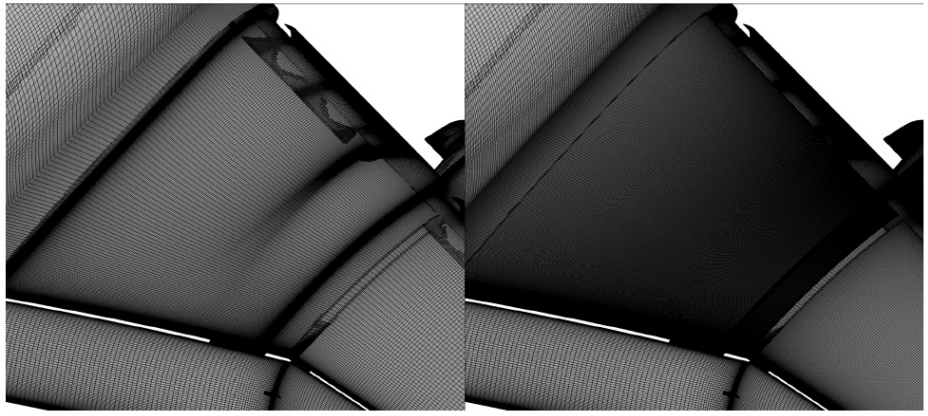
Curvilinear Overset Grid System (cont.)

RANS Grid R-C

HRLES Grid H-D



(b) Slat element (y = 15 m.)



(c) Inboard wing upper surface

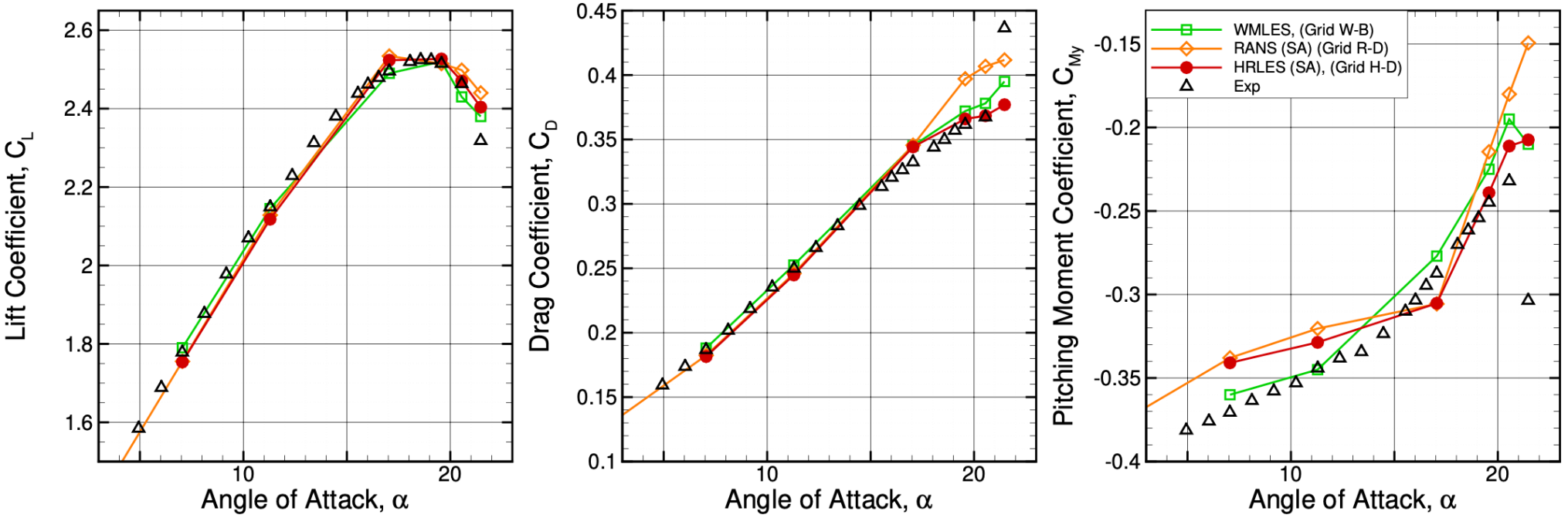
HRLES Grid System, best practice grid is Grid H-D and Δt = 2e-4s

- The grid points in the slat wake were redistributed to ensure lower aspect ratio cells were in the slat wake which are more appropriate for resolving the fluctuations in the slat wake.
- The inboard section on the wing was also refined in Grid H-D 4x in stream and span and the grid points were redistributed in the spanwise direction to reduce the clustering at the wing-collar juncture and the wake of the chine vortex.

Name	Solve Points	Target y^+	Max Stretching Ratio	Comments
Grid R-C	224M	1.0	1.10	
Grid H-A	365M	1.0	1.10	inboard + outboard refinement
Grid H-B	325M	1.0	1.10	modified slat wake grid + outboard refinement
Grid H-C	421M	1.0	1.10	outboard refinement
Grid H-D	571M	1.0	1.10	inboard + midboard + nacelle refinement

Integrated Loads – Free Air

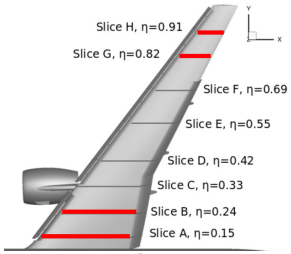
Aerodynamic loads comparison between LAVA RANS[1], HRLES and WMLES[2] with corrected experimental results.



[1]*Duensing, J. C., Housman, J. A., Dos Santos Fernandes, L. M., Machado, L. M., and Kiris, C., "A Reynolds-Averaged Navier-Stokes Perspective for the High Lift-Common Research Model Using the LAVA Framework," AIAA Aviation Paper to appear, 2022.*

[2]*Ghate, A., Stich, G.-D., Kenway, G., Housman, J., and Kiris, C., "A Wall-Modeled LES Perspective for the High Lift Common Research Model Using LAVA," AIAA Aviation Paper to appear, 2022.*

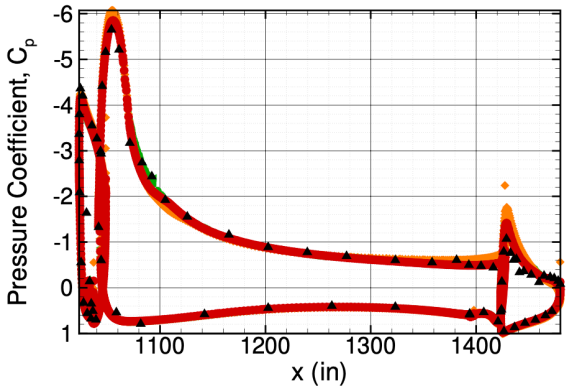
Surface Pressure, Cp – Free Air



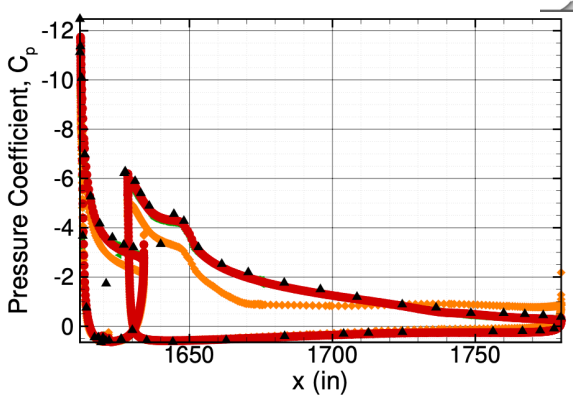
α=19.57

RANS
HRLES
WMLES

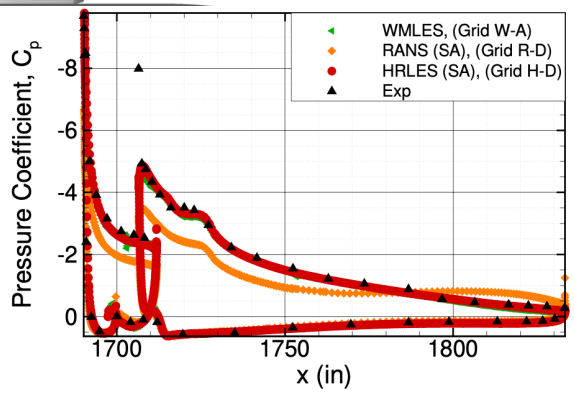
α=21.47



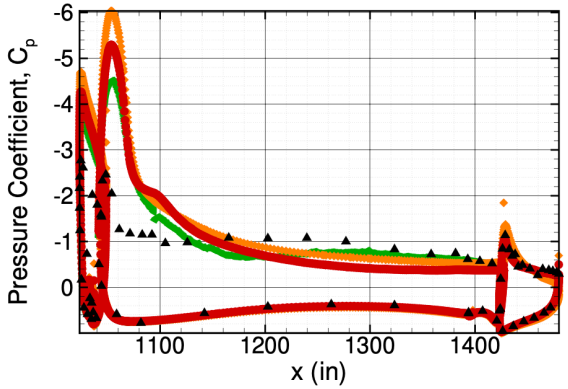
(a) Slice A, $\eta = 0.15$



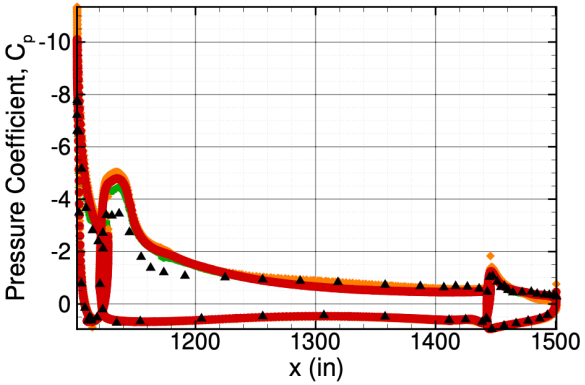
(b) Slice G, $\eta = 0.82$



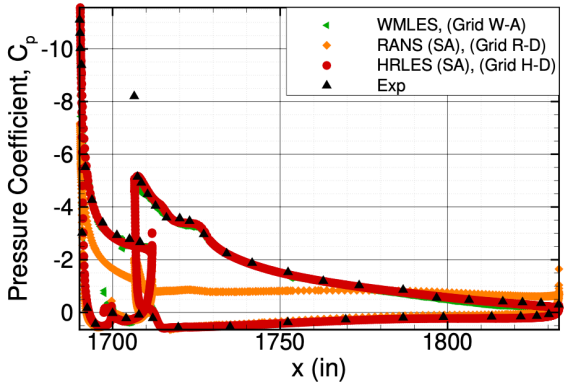
(c) Slice H, $\eta = 0.91$



(a) Slice A, $\eta = 0.15$



(b) Slice B, $\eta = 0.24$



(c) Slice H, $\eta = 0.91$

Surface Cf Streamlines – Free Air

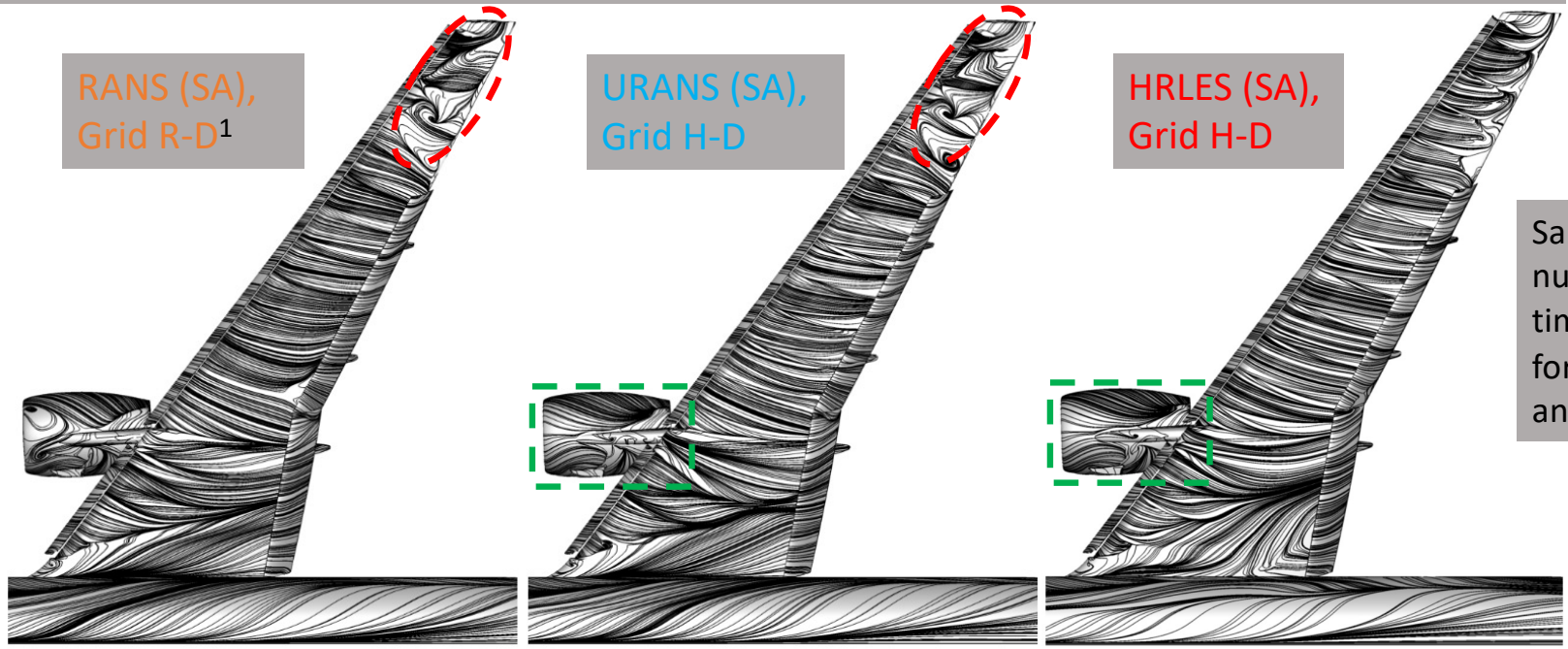
- Comparison of flow topology for RANS, URANS and HRLES with SA model at highest AoA.
- Similar flow topologies seen between RANS and URANS except on nacelle (could be initial condition sensitivity).
- "Apples to Apples" comparison between URANS and HRLES shows direct benefit of utilizing a HRLES closure.

α=21.47

RANS (SA), Grid R-D[1]

URANS (SA), Grid H-D

HRLES (SA), Grid H-D

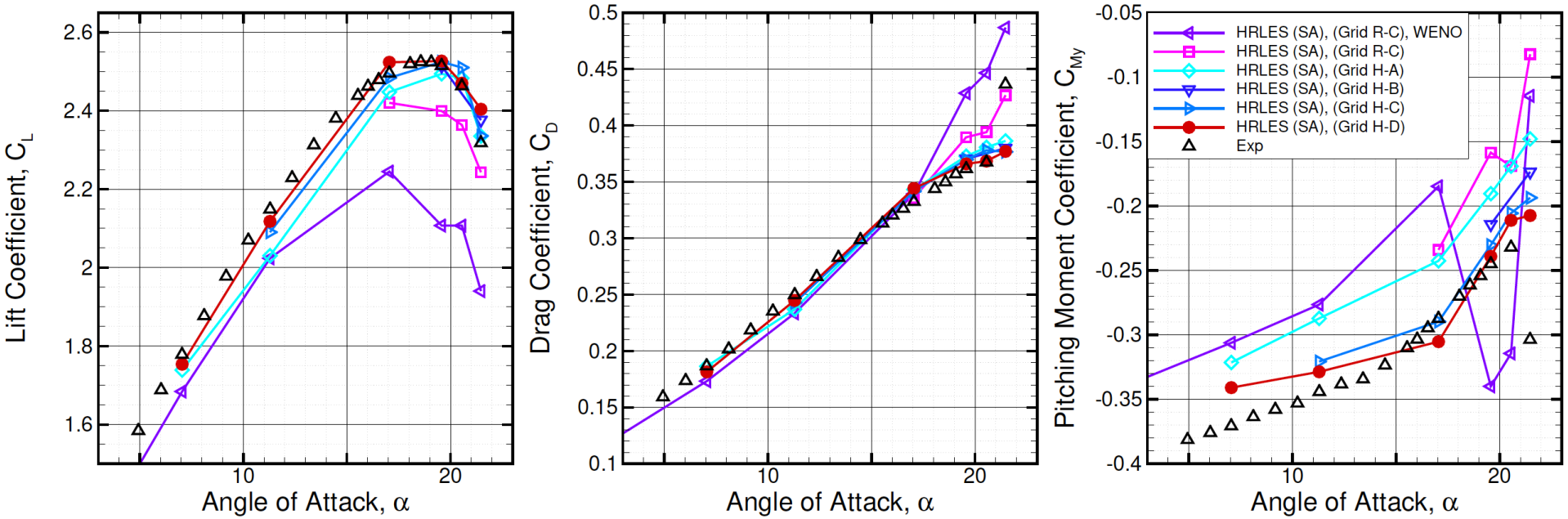


Same grid, numerics and timestep size for URANS and HRLES

[1]*Duensing, J. C., Housman, J. A., Dos Santos Fernandes, L. M., Machado, L. M., and Kiris, C., "A Reynolds-Averaged Navier-Stokes Perspective for the High Lift-Common Research Model Using the LAVA Framework," AIAA Aviation Paper to appear, 2022.*

Integrated Loads – Free Air (Grid Resolution Study)

Aerodynamic loads for various grid levels and numerics computed with HRLES compared with corrected experimental results. Best practice HRLES is shown in red.



Note: pitch break not guaranteed in free air case

Surface Cf Streamlines – Free Air

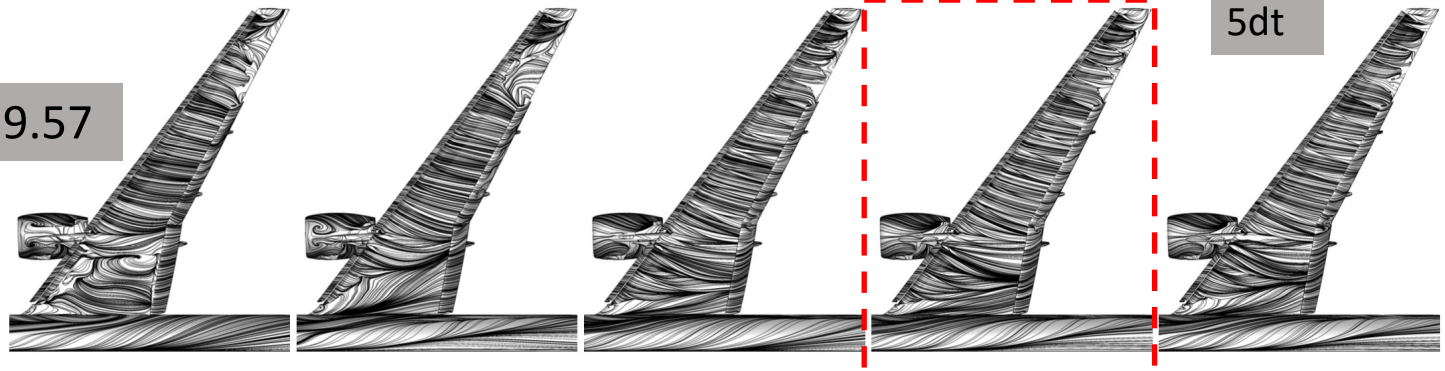
Reducing numerical dissipation

Increasing spatial resolution

Reducing timestep size

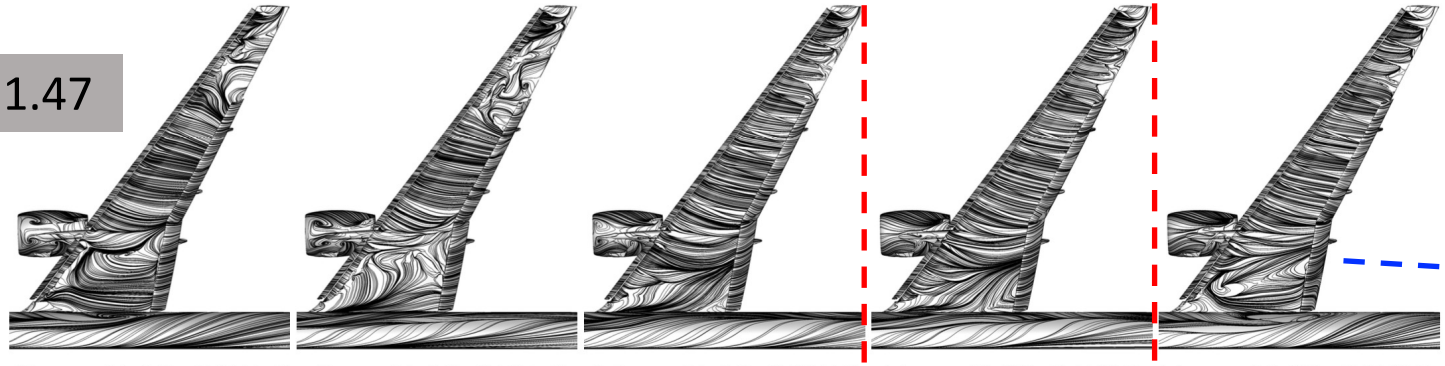
5dt

α=19.57



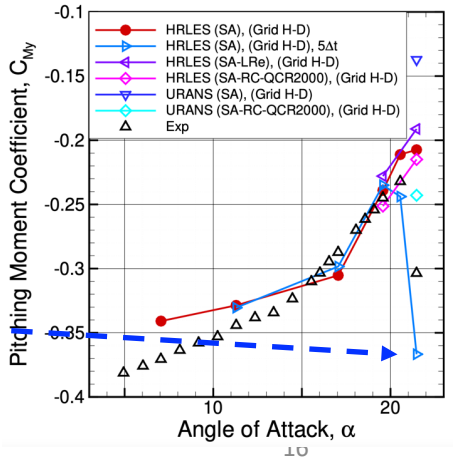
(f) α = 19.57°, Grid R-C, WENO (g) α = 19.57°, Grid R-C (h) α = 19.57°, Grid H-C (i) α = 19.57°, Grid H-D (j) α = 19.57°, Grid H-D, $5\Delta t$

α=21.47



(k) α = 21.47°, Grid R-C, WENO (l) α = 21.47°, Grid R-C (m) α = 21.47°, Grid H-C (n) α = 21.47°, Grid H-D (o) α = 21.47°, Grid H-D, $5\Delta t$

Surface skin friction Cf coefficient for CLmax and post-stall for various grid level, numerics and time-step size. Best practice shown in red.



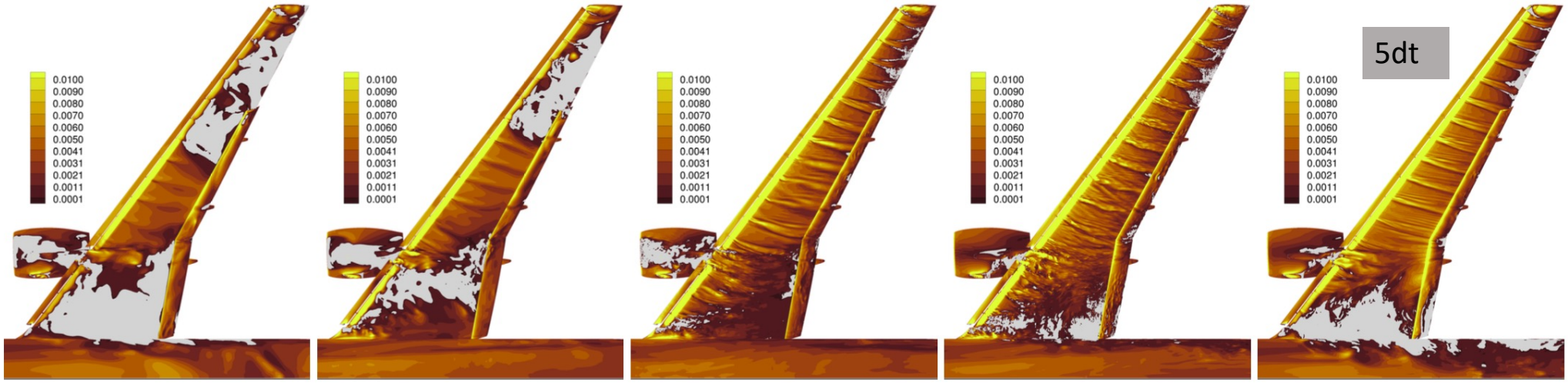
Surface Cfx Contour – Free Air

α=21.47

Reducing numerical dissipation

Increasing spatial resolution

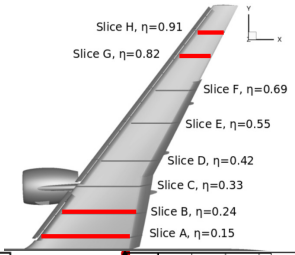
Reducing timestep size



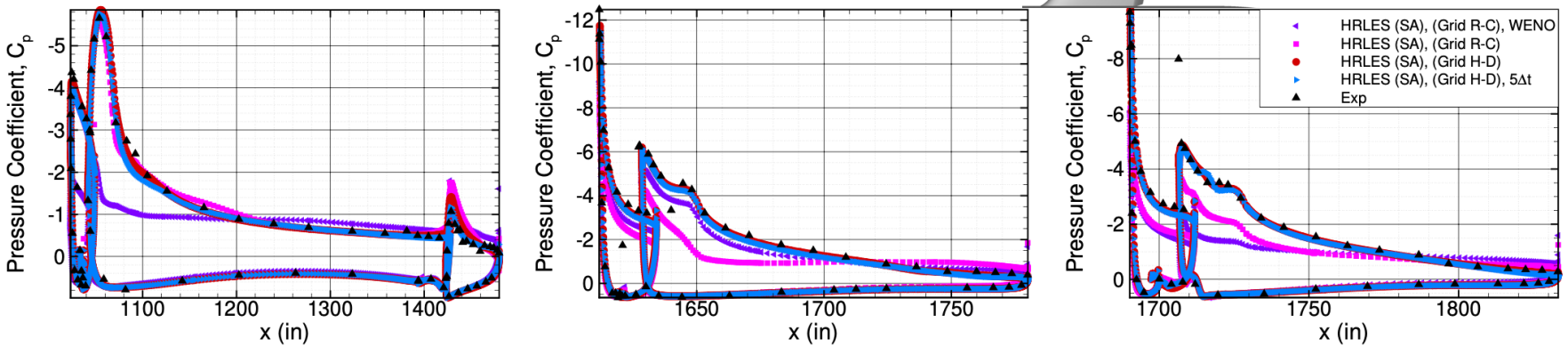
(a) $\alpha = 21.47°$, Grid R-C, WENO (b) $\alpha = 21.47°$, Grid R-C (c) $\alpha = 21.47°$, Grid H-C (d) $\alpha = 21.47°$, Grid H-D (e) $\alpha = 21.47°$, Grid H-D, $5\Delta t$

Contours clipped for Cfx<0 to highlight separated flow

Surface Pressure, Cp – Free Air

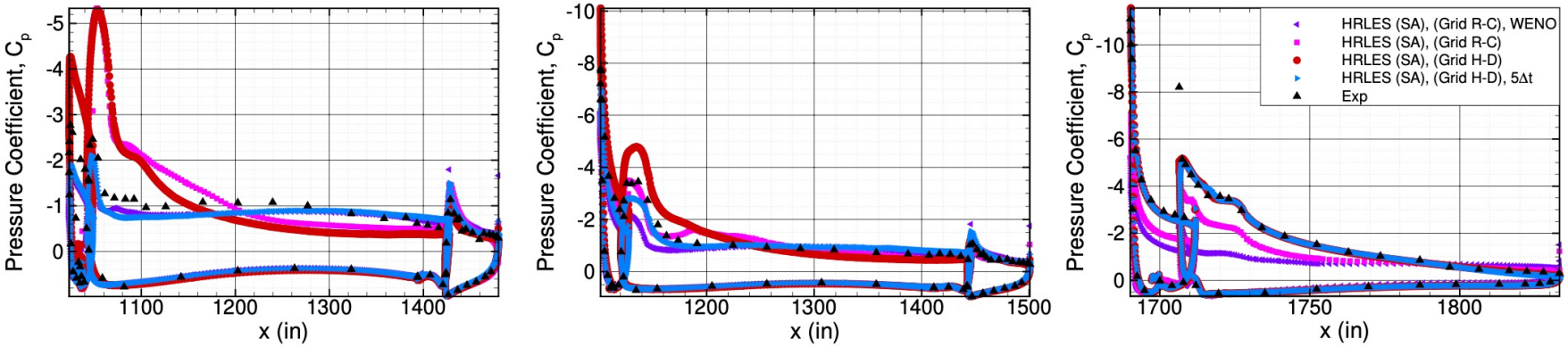


α=19.57



(a) Slice A, $\eta = 0.15$ (b) Slice G, $\eta = 0.82$ (c) Slice H, $\eta = 0.91$

α=21.47



(a) Slice A, $\eta = 0.15$ (b) Slice B, $\eta = 0.24$ (c) Slice H, $\eta = 0.91$

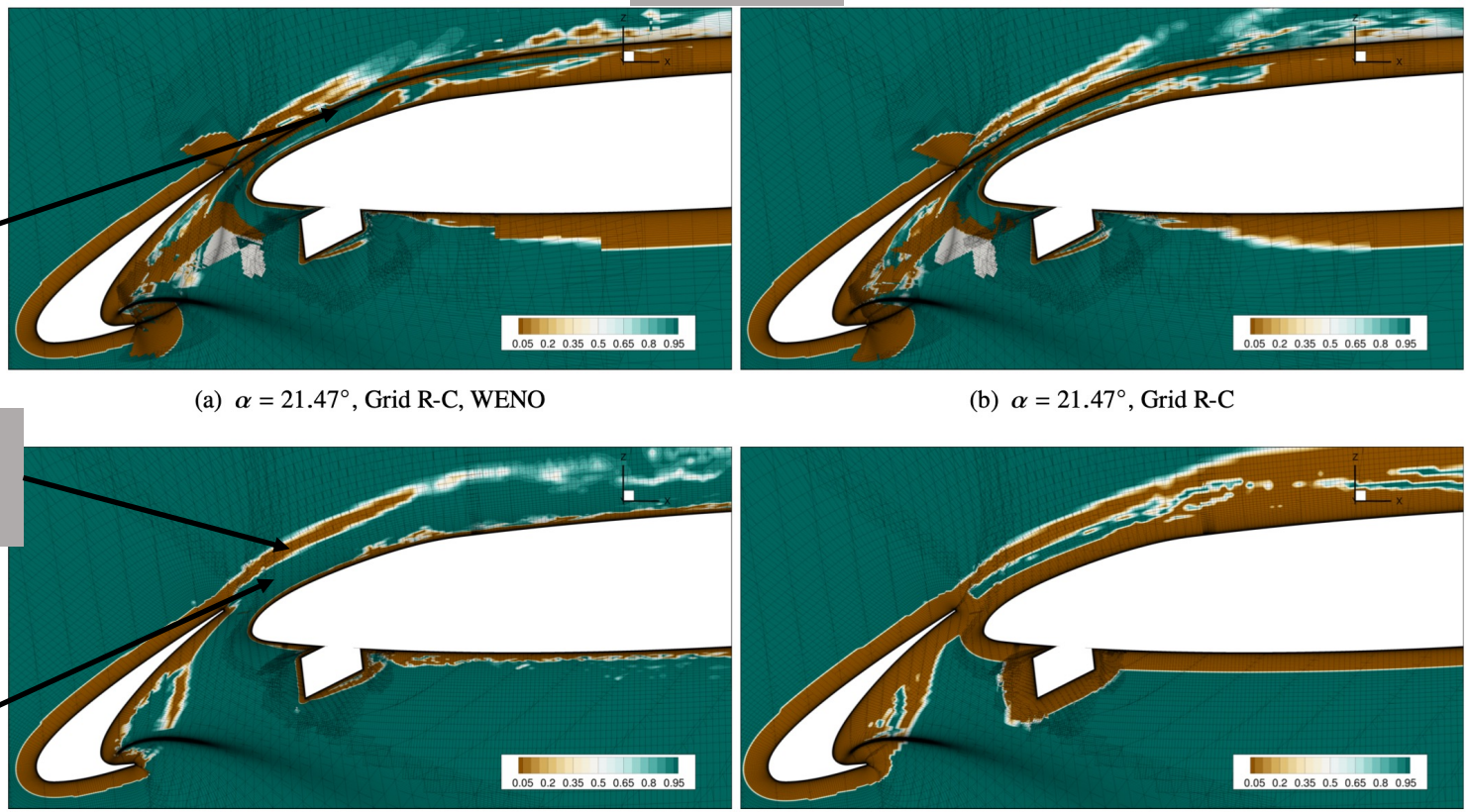
Shielding Function, fd – Free Air

α=21.47

Slat wake grid

RANS mode, fd=0

LES mode, fd=1



(a) $\alpha = 21.47°$, Grid R-C, WENO

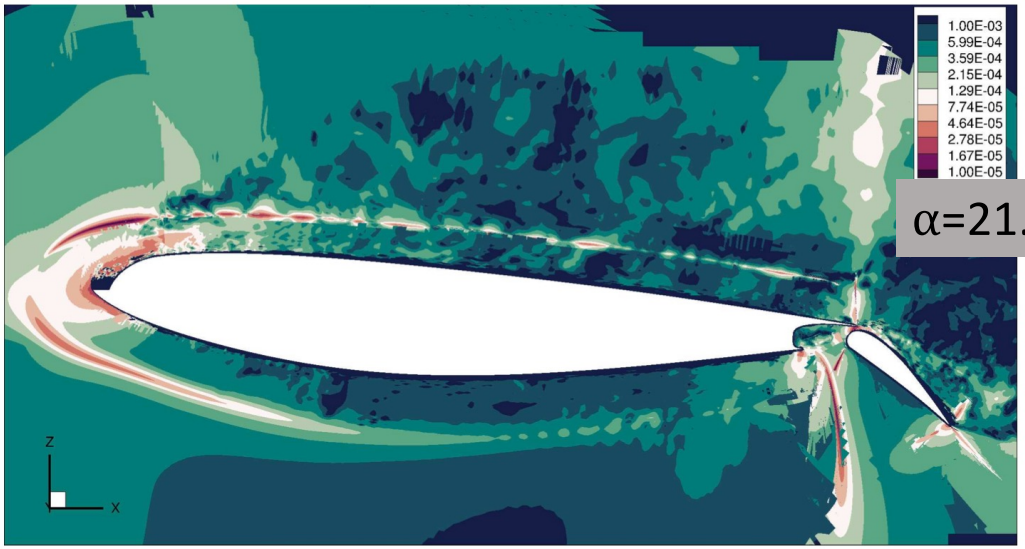
(b) $\alpha = 21.47°$, Grid R-C

(c) $\alpha = 21.47°$, Grid H-D

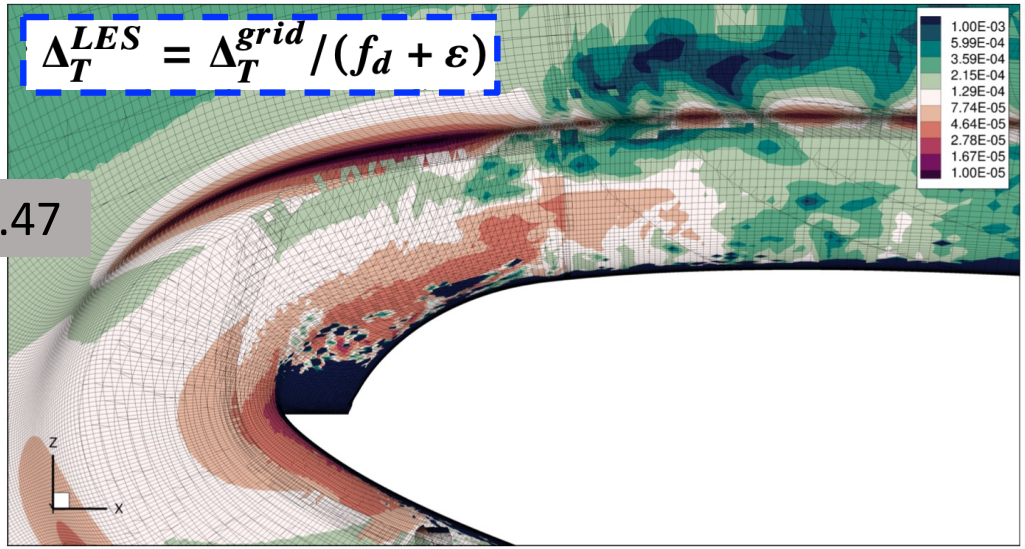
(d) $\alpha = 21.47°$, Grid H-D, $5\Delta t$

Shielding Function, Δt^{LES} – Free Air

- Contour map shows Δt^{LES}:
  - the green regions highlight areas where the choice of time step respects the *resolvable* time scales while the red regions highlight areas where the local grid length scales permit existence of finer time-scale motions which are ultimately *filtered* by the BDF2 temporal discretization.
  - It is evident that the majority of the resolvable LES motions are in-fact preserved by the time-step size, except near a small region near the leading edge close to the slat cutout.

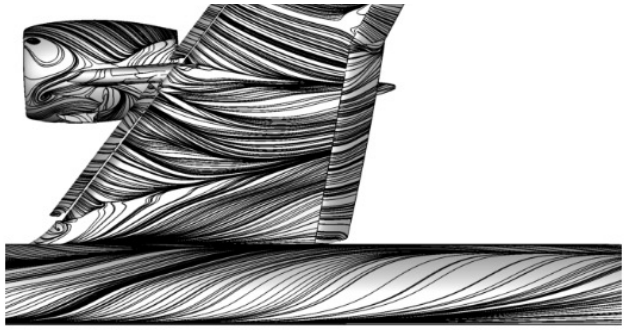


(a) $y = 4.0$m slice

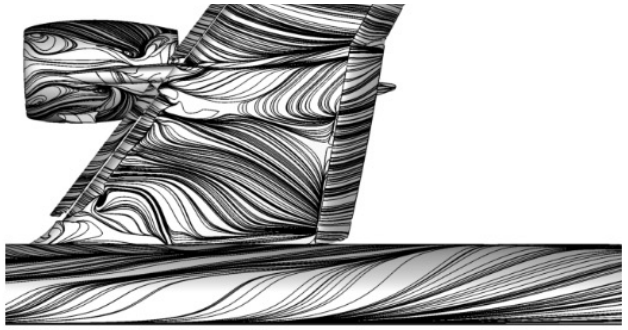


(b) $y = 4.0$m slice (zoomed in view)

Surface Cf Streamlines – Free Air

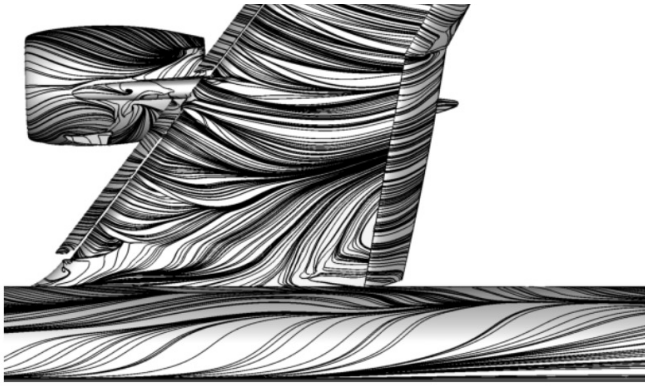


(a) RANS (SA), Grid R-D

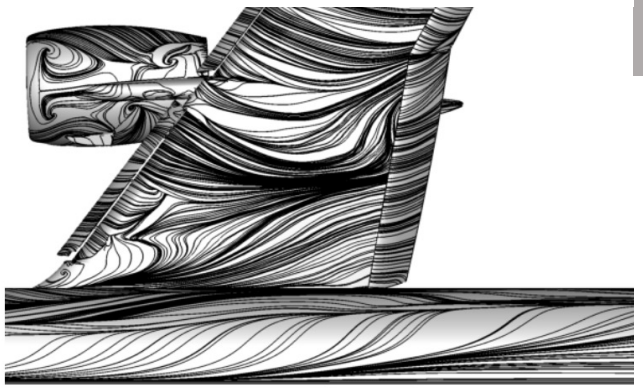


RANS (SA-RC-QCR2000), Grid R-D

α=21.47



(d) HRLES (SA)

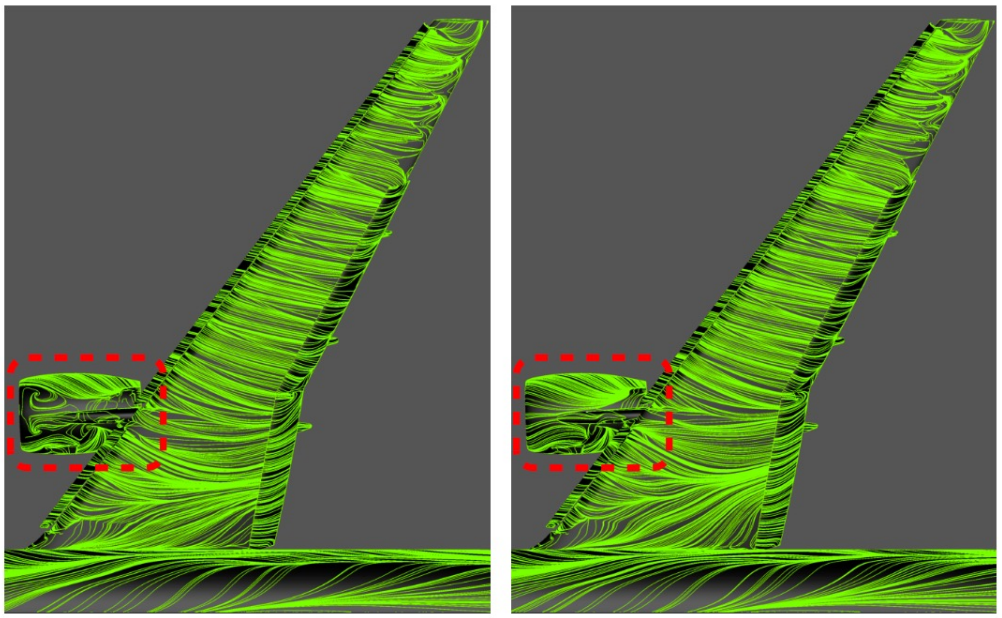


HRLES (SA-RC-QCR2000)

Comparison of the flow topology between RANS/HRLES (SA) and RANS/HRLES (SA-RC-QCR2000).

Wind Tunnel (WT) Initialization

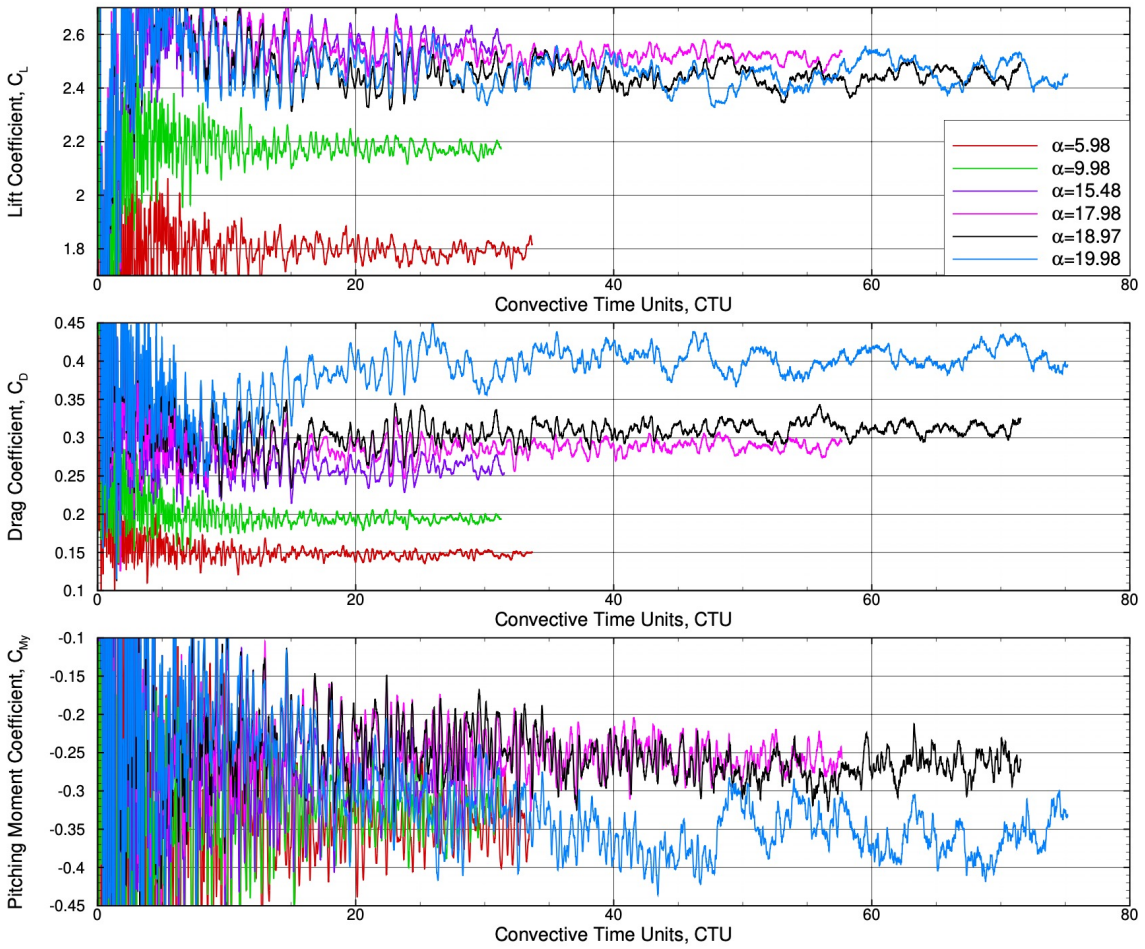
Comparison of tunnel initialization procedure with a “pseudo-cold-start” (from freesteam conditions) and from a steady state RANS solution.



(a) Initial condition - RANS (b) Initial condition - freestream

Load Histories - WT

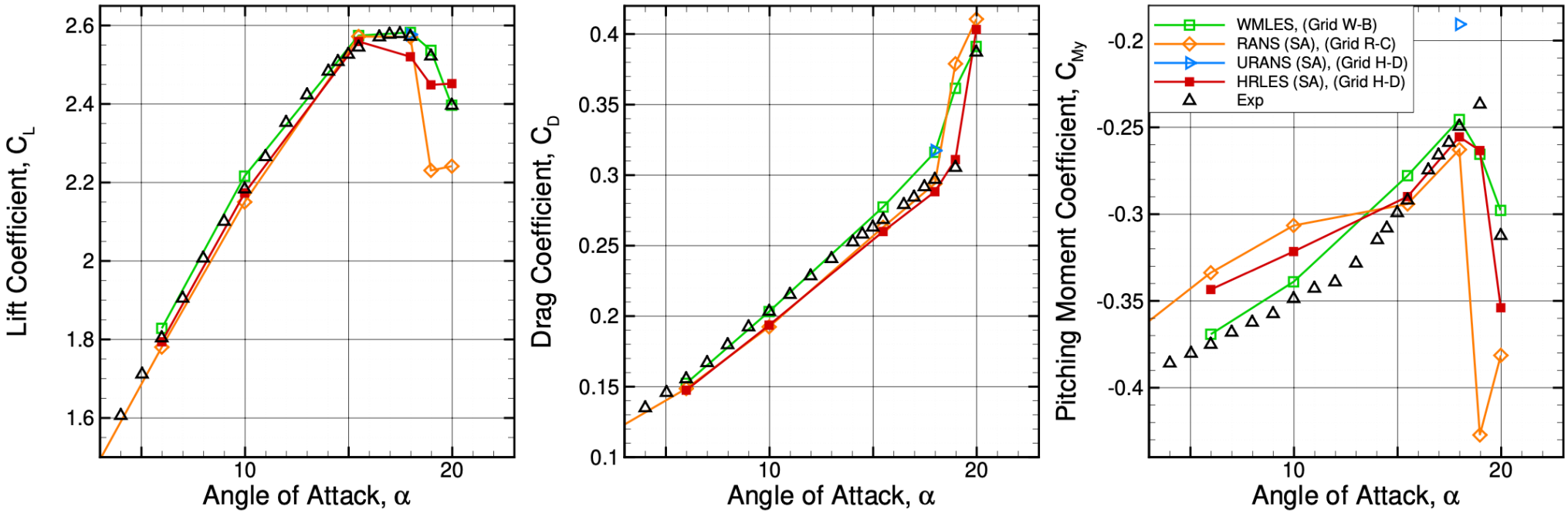
α=5.98
α=9.98
α=15.48
α=17.98
α=18.97
α=19.98



It was noted that lower three angles-of-attack that approximately $30CTU$ was needed while $50 - 70CTU$ were required for the three higher angles-of-attack

Integrated Loads – WT

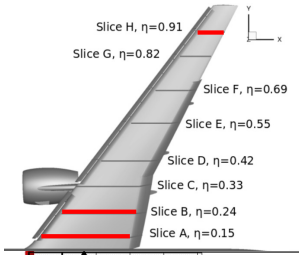
Aerodynamic loads comparison between LAVA RANS[1]/URANS, HRLES and WMLES[2] with uncorrected experimental results.

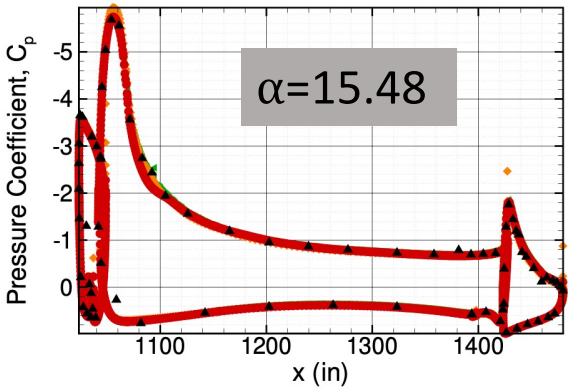


[1]*Duensing, J. C., Housman, J. A., Dos Santos Fernandes, L. M., Machado, L. M., and Kiris, C., "A Reynolds-Averaged Navier-Stokes Perspective for the High Lift-Common Research Model Using the LAVA Framework," AIAA Aviation Paper to appear, 2022.*

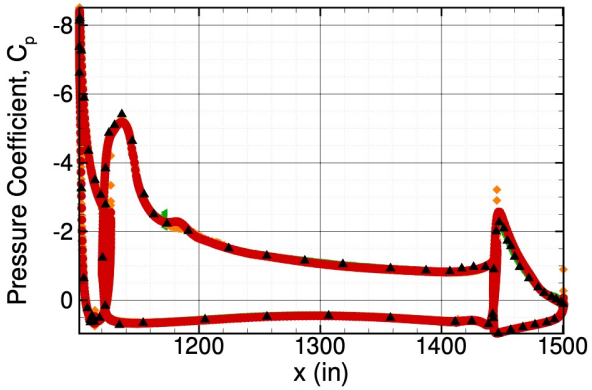
[2]*Ghate, A., Stich, G.-D., Kenway, G., Housman, J., and Kiris, C., "A Wall-Modeled LES Perspective for the High Lift Common Research Model Using LAVA," AIAA Aviation Paper to appear, 2022.*

Surface Pressure, Cp – WT

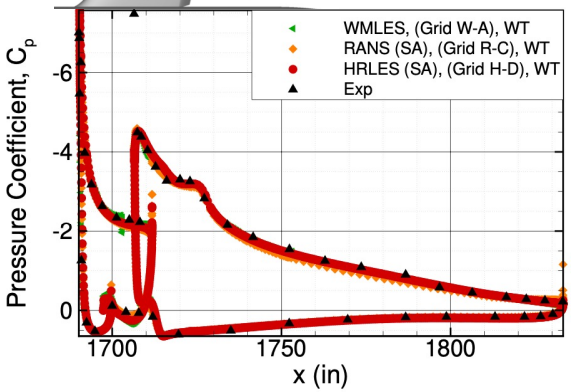




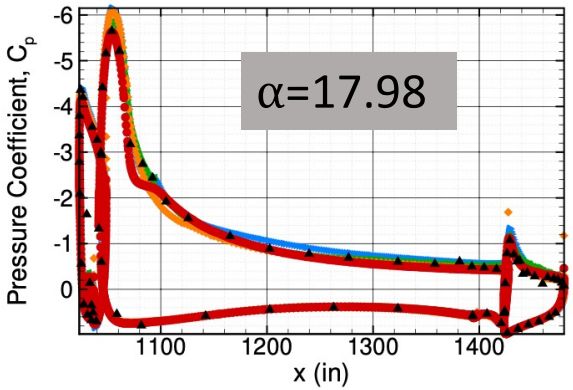
(a) Slice A, $\eta = 0.15$



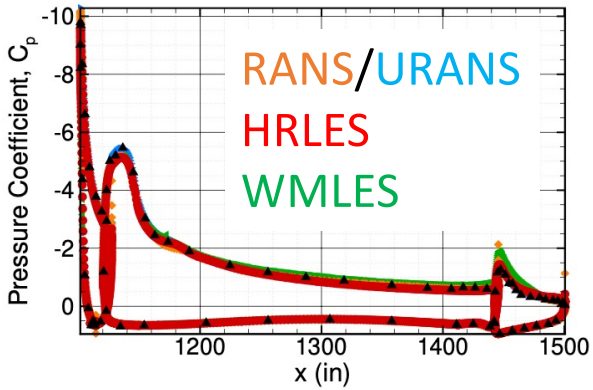
(b) Slice B, $\eta = 0.24$



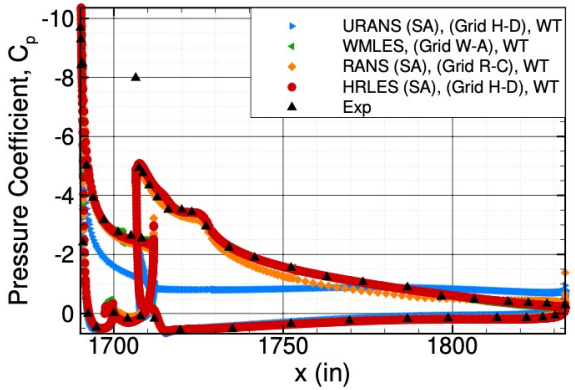
(c) Slice H, $\eta = 0.91$



(a) Slice A, $\eta = 0.15$

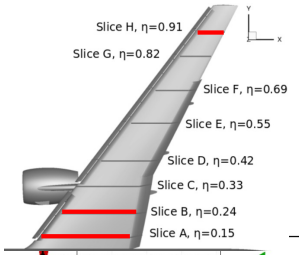


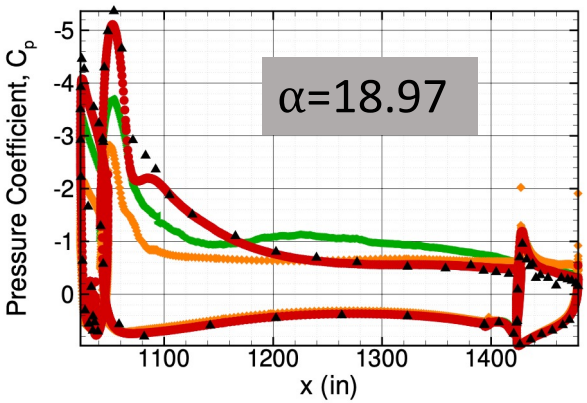
(b) Slice B, $\eta = 0.24$



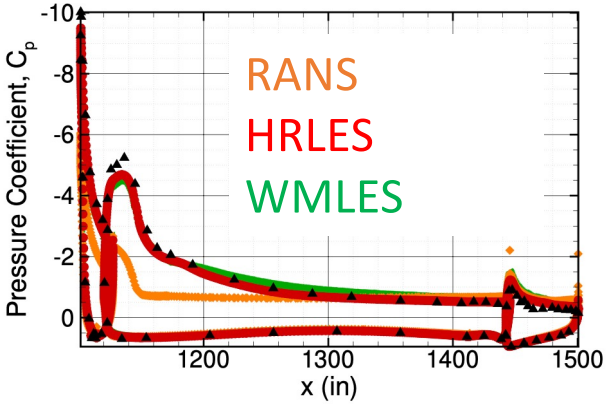
(c) Slice H, $\eta = 0.91$

Surface Pressure, Cp – WT

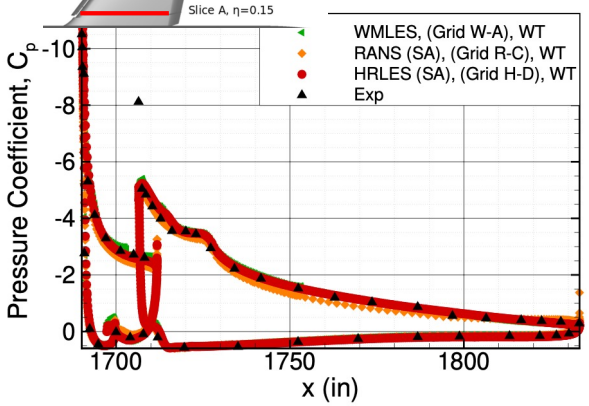




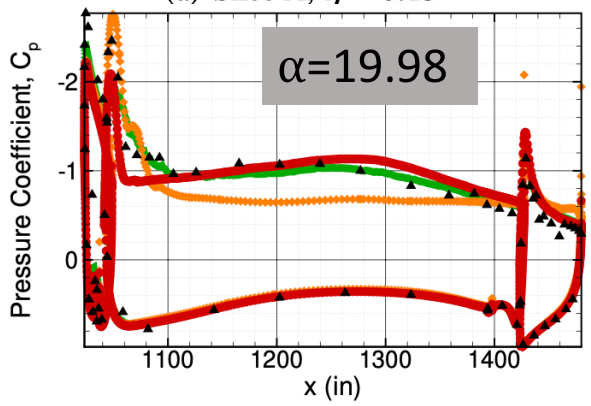
(a) Slice A, $\eta = 0.15$



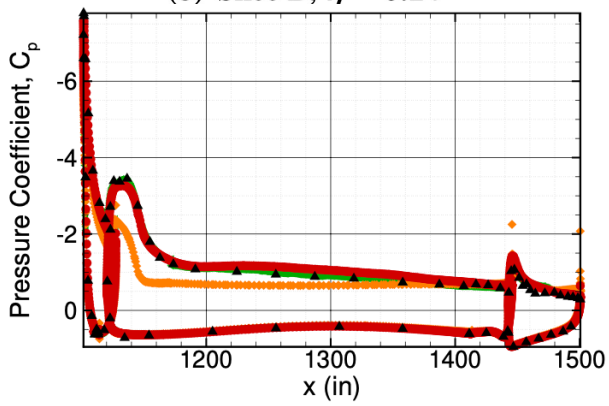
(b) Slice B, $\eta = 0.24$



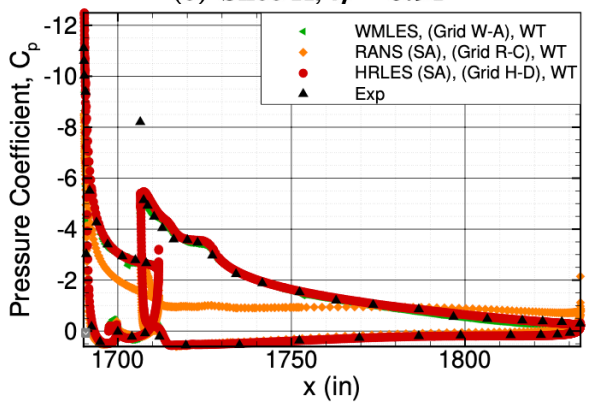
(c) Slice H, $\eta = 0.91$



(a) Slice A, $\eta = 0.15$

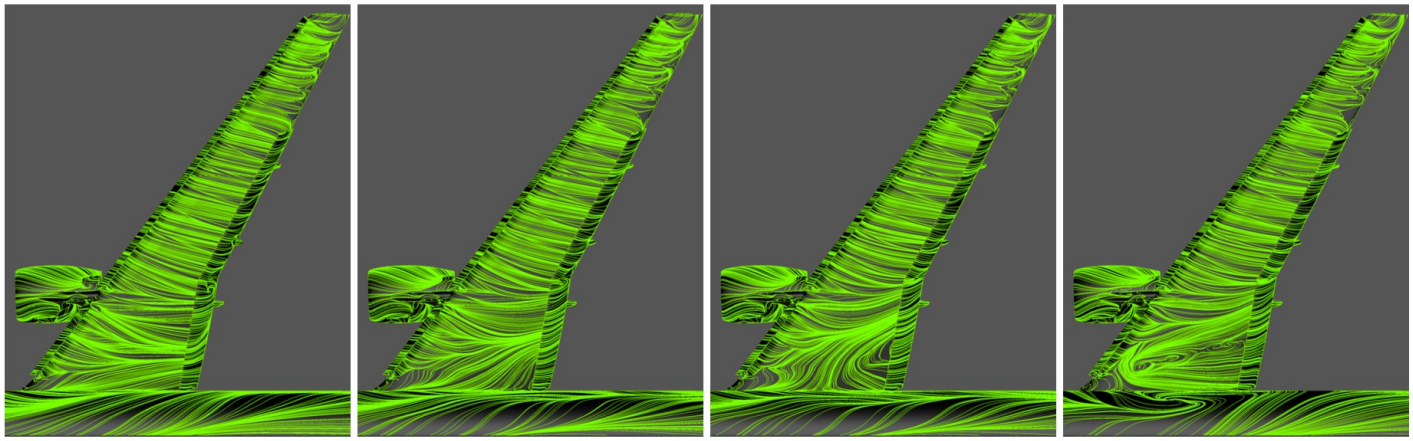


(b) Slice B, $\eta = 0.24$

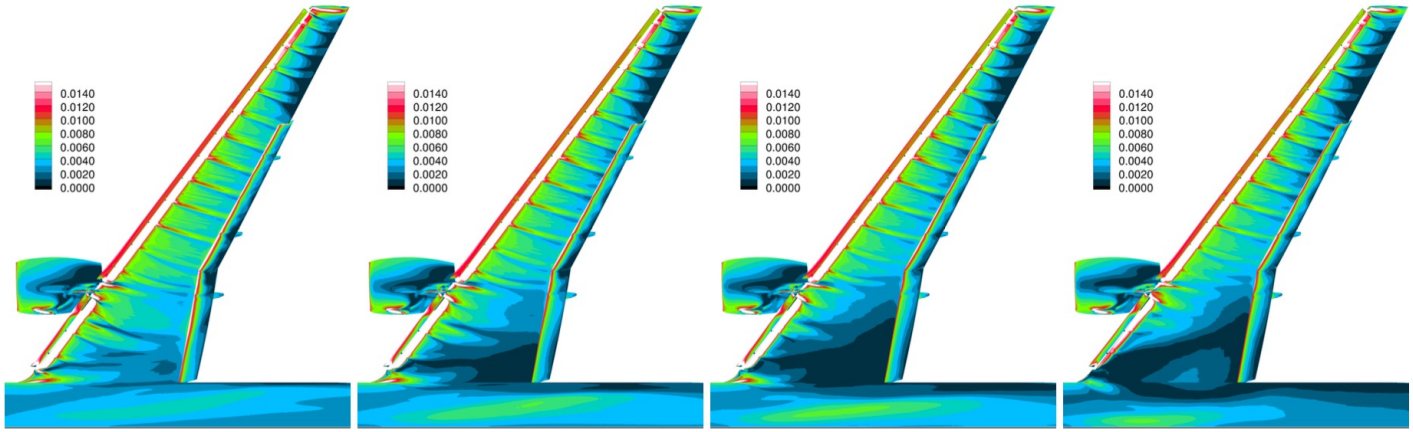


(c) Slice H, $\eta = 0.91$

Surface Cf Streamlines/Contour – WT



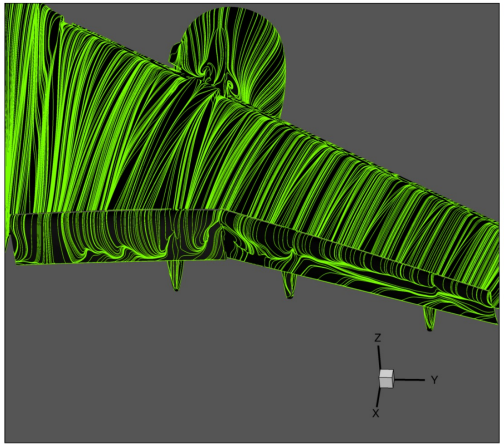
(a) $\alpha = 15.48°$ (b) $\alpha = 17.98°$ (c) $\alpha = 18.97°$ (d) $\alpha = 19.98°$



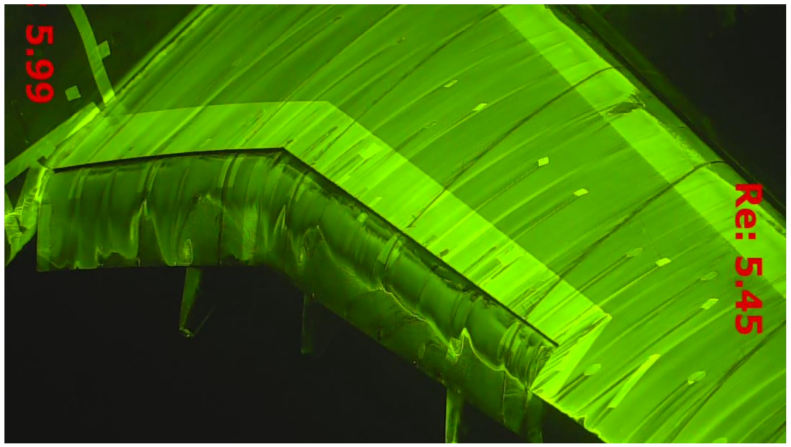
(e) $\alpha = 15.48°$ (f) $\alpha = 17.98°$ (g) $\alpha = 18.97°$ (h) $\alpha = 19.98°$

Streamline vs Oil-Flow Comparison – WT

α=5.98



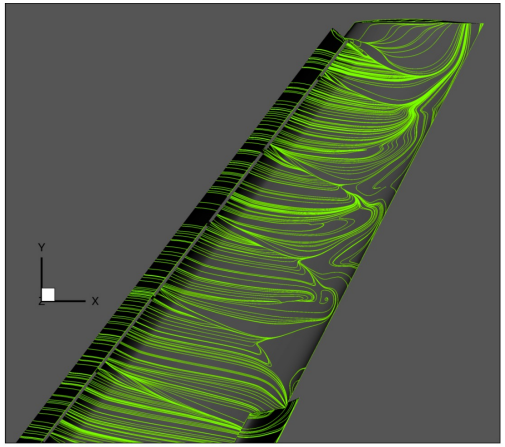
(a) HRLES



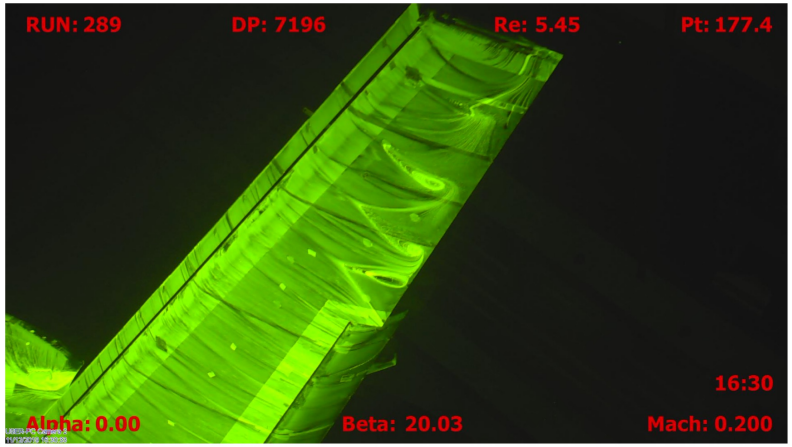
(b) Oil Flow

Comparison of inboard and outboard flaps

α=19.98



(a) HRLES



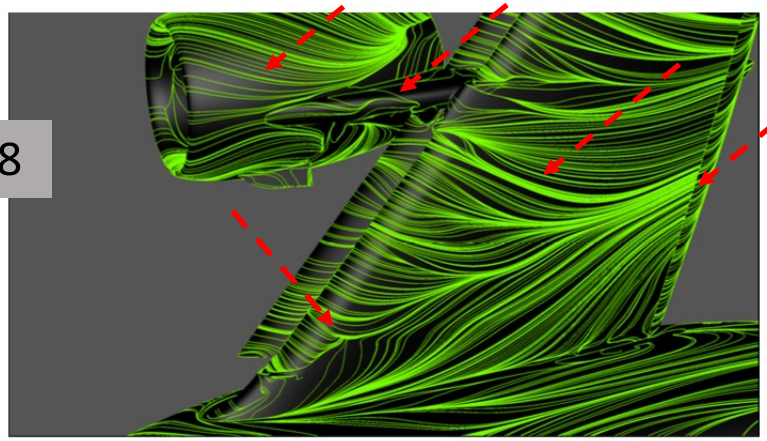
(b) Oil Flow

Comparison of outboard region of the wing

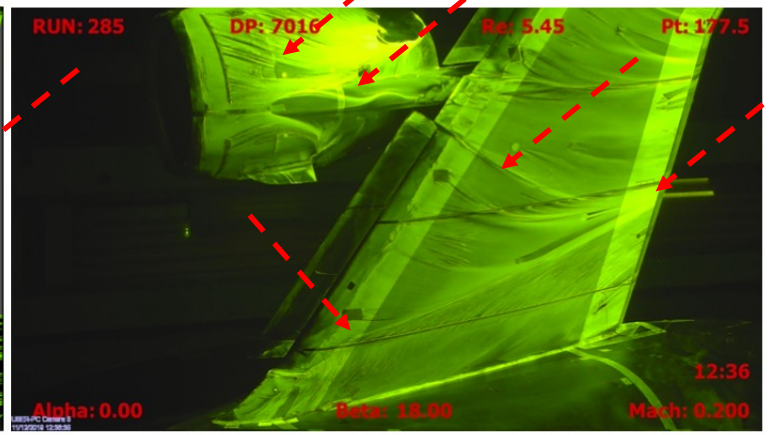
QinetiQ tunnel experiments
https://hiliftpw.larc.nasa.gov

Streamline vs Oil-Flow Comparison – WT

α=17.98

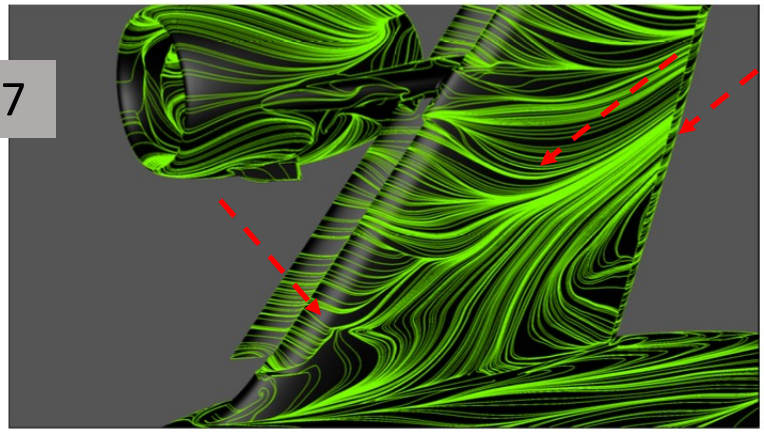


(a) HRLES

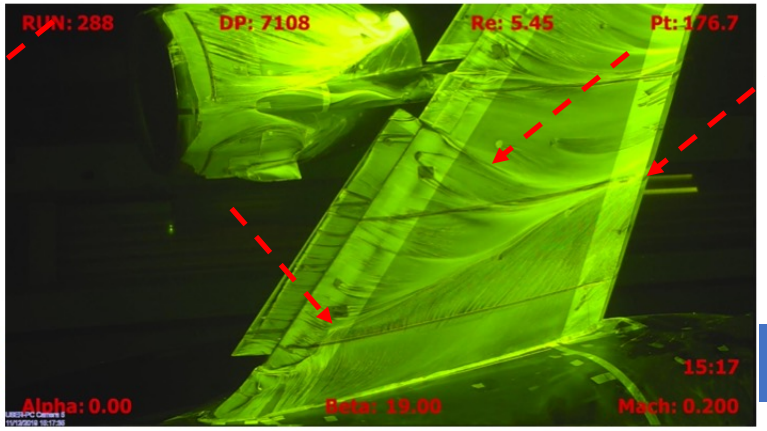


(b) Oil Flow

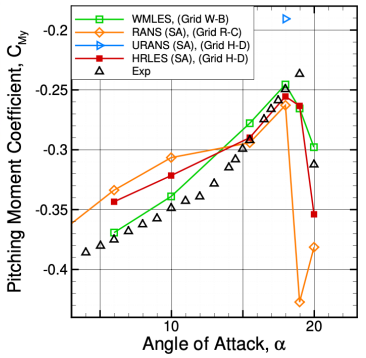
α=18.97



(a) HRLES



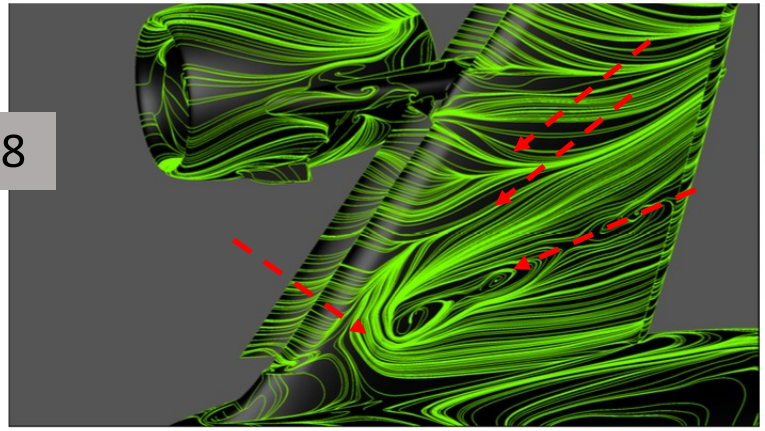
(b) Oil Flow



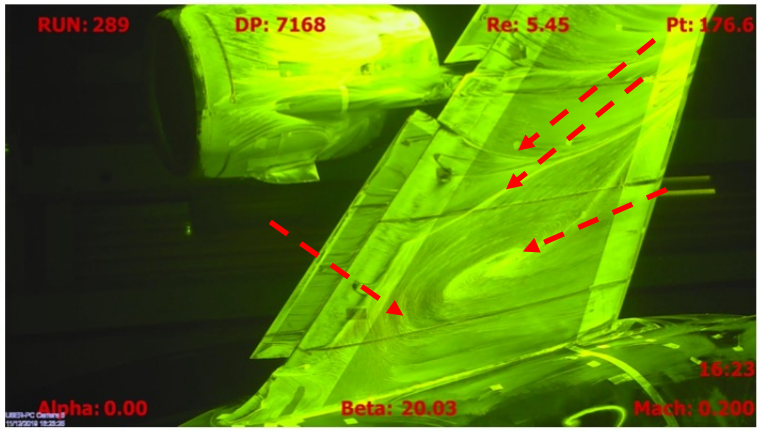
QinetiQ tunnel experiments
https://hiliftpw.larc.nasa.gov

Streamline vs Oil-Flow Comparison – WT

α=19.98

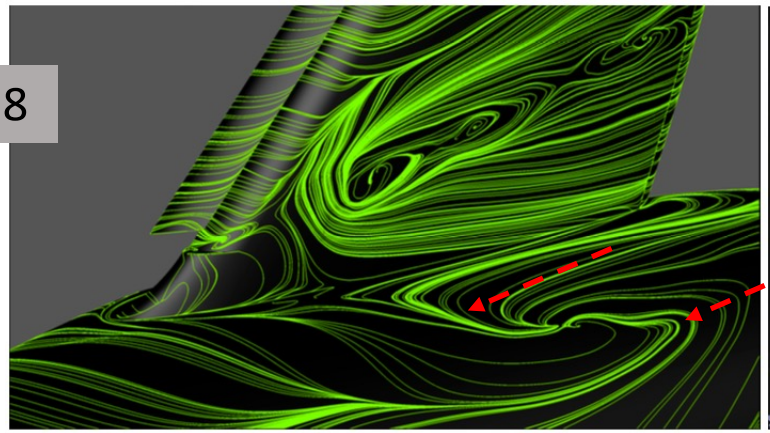


(a) HRLES

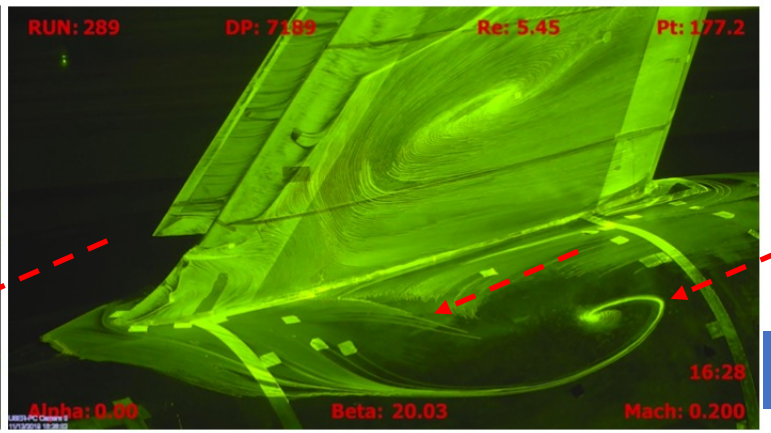


(b) Oil Flow

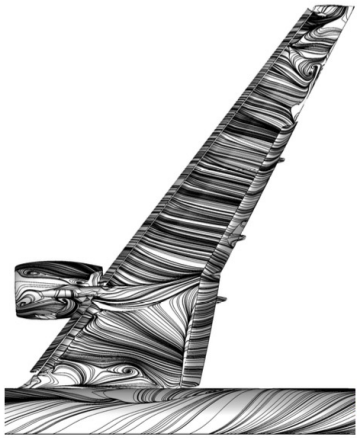
α=19.98



(a) HRLES



(b) Oil Flow

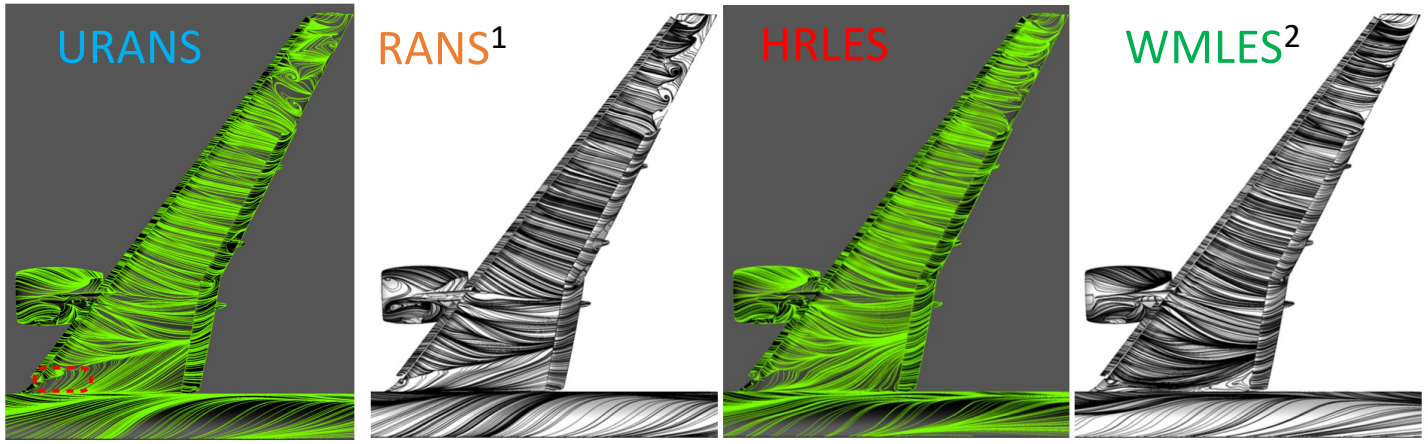


(d) RANS (SA), $\alpha = 19.98°$

QinetiQ tunnel experiments
https://hiliftpw.larc.nasa.gov

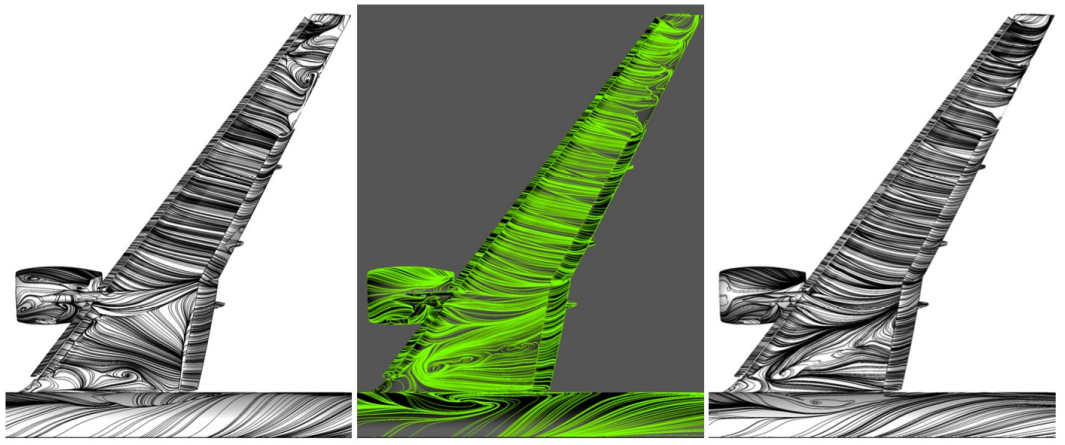
Surface Cf Streamline Comparison – WT

α=17.98



(a) URANS (SA) (a) RANS (SA), $\alpha = 17.98°$ (b) HRLES (SA), $\alpha = 17.98°$ (c) WMLES, $\alpha = 17.98°$

α=19.98



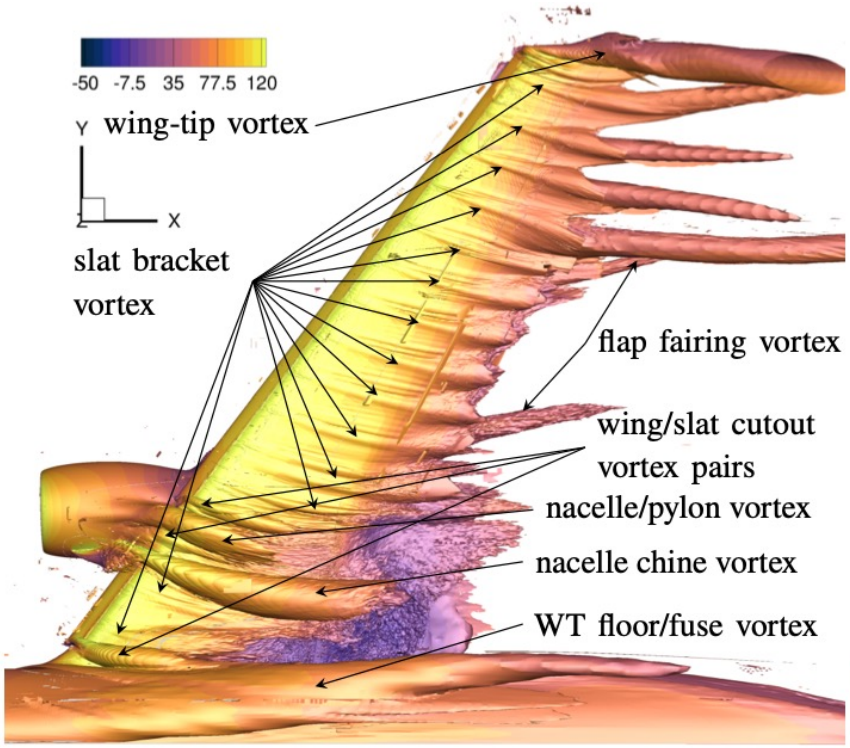
(d) RANS (SA), $\alpha = 19.98°$ (e) HRLES (SA), $\alpha = 19.98°$ (f) WMLES, $\alpha = 19.98°$

[1]*Duensing, J. C., Housman, J. A., Dos Santos Fernandes, L. M., Machado, L. M., and Kiris, C., "A Reynolds-Averaged Navier-Stokes Perspective for the High Lift-Common Research Model Using the LAVA Framework," AIAA Aviation Paper to appear, 2022.*

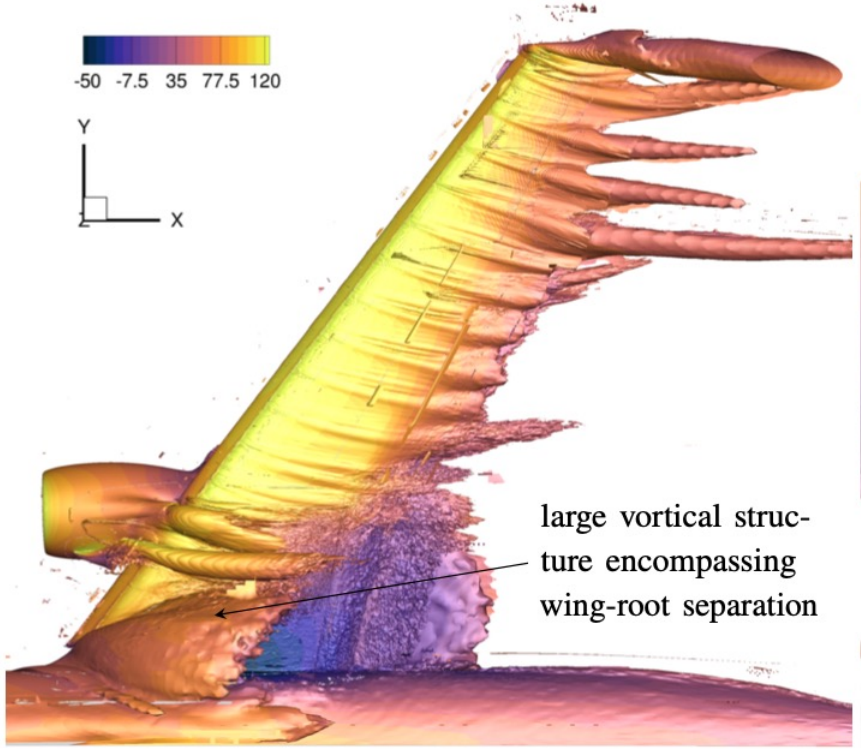
[2]*Ghate, A., Stich, G.-D., Kenway, G., Housman, J., and Kiris, C., "A Wall-Modeled LES Perspective for the High Lift Common Research Model Using LAVA," AIAA Aviation Paper to appear, 2022.*

Iso-Surface of Vorticity Magnitude - WT

HRLES (SA), α=17.98

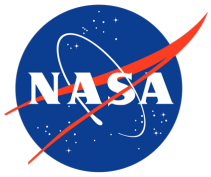


HRLES (SA), α=19.98



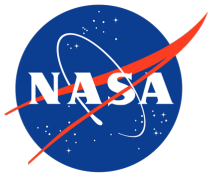
Vorticity magnitude computed from time averaged velocity field

Summary and Outlook



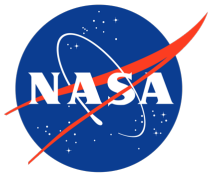
- A comprehensive assessment of the HRLES approach for CLmax and post-stall prediction of the NASA High-Lift Common Research Model (CRM-HL) was performed.
- An objective case has been made for HRLES as a viable approach for CLmax and post-stall prediction of high-lift aircraft geometries.
  - Roughly an order of magnitude more expensive in computational cost when compared with a steady-state RANS run.
- The HRLES method was evaluated for both the free air and wind tunnel configurations and its predictions were compared against experimental results from the QinetiQ tunnel and numerically against RANS and WMLES approaches.
- In addition HRLES addressed some of the shortcomings in RANS approaches and was competitive with WMLES in terms of solution accuracy.

Summary and Outlook (cont.)



- For the free air and the WT configurations, HRLES made modest improvements over RANS at the low angles-of-attack for pitching moment. More significant improvements for HRLES at CLmax and post-stall when compared to RANS.
- HRLES is able to address the sharp loss of lift predicted by RANS at the two highest angles-of-attack.
- Good agreement is shown across the board for HRLES and WMLES in the free air configuration. This holds largely true for the wind tunnel configuration as well.
- Excellent qualitative agreement was obtained when comparing the streamlines from the HRLES and the oil-flow from the QinetiQ experiment at CLmax and post-stall.
- Simply *"turning-on"* the HRLES model, with the RANS grid and employing numerics more suited to RANS produced predictions that were far inferior to RANS.

Summary and Outlook (cont.)

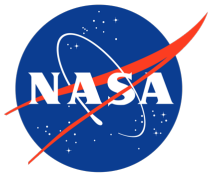


- Critical points for success with HRLES for CRM-HL:
  - It is important to refine (tangential spacing) the inboard/outboard regions of the wing to address the erroneous behavior of the RANS.
  - Remove anisotropic cells in the volume grid outside the boundary layer.
  - Sufficiently small time-step, and a low dissipation numerical scheme were all instrumental in achieving good agreement with the experimental data and WMLES.

Key Findings for Future Research Efforts:

- **Designing grids suitable for HRLES and meshing best practices** – once outside of boundary layer and in regions prone to separation as isotropic grid as is possible
- **Prudent choice of time-step size and use of low dissipation numerics**
- **Run out solutions for sufficiently long time interval**

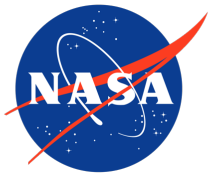
Summary and Outlook (cont.)



Outstanding Questions:

- **Large sensitivity persists due to the underlying RANS closure and choice of shielding function** – need to reduce "tuning" parameters to promote predictability
- **When is it cost effective to employ scale-resolving simulations (runtime, grid generation, etc)?**
- **Systematic uncertainties for this problem** – free air vs tunnel: tunnel boundary layer, stand-off, blockage effects, etc.

Acknowledgements



- This work was funded by NASA Aeronautics Research Mission Directorate's (ARMD) Transformational Tools and Technologies (TTT) project.
- Computer time has been provided by the NASA Advanced Supercomputing (NAS) facility at NASA Ames Research Center.
- Chris Rumsey's (NASA LaRC), Jeffrey Slotnick (Boeing)and Carolyn Woeber (Cadence) for the organization of HLPW4 and workshop participants for valuable discussions,
- Jared Duensing (NASA Ames), Leonardo Machado (NASA Ames), Luis Fernandes (NASA Ames), and Elisha Makarevich (formerly NASA Ames, Boeing) help with overset grid generation are gratefully acknowledged.
- The authors would also like to thank Gerrit-Daniel Stich (NASA Ames), Francois Cadieux (NASA Ames) and the rest of the LAVA group members for providing helpful feedback.