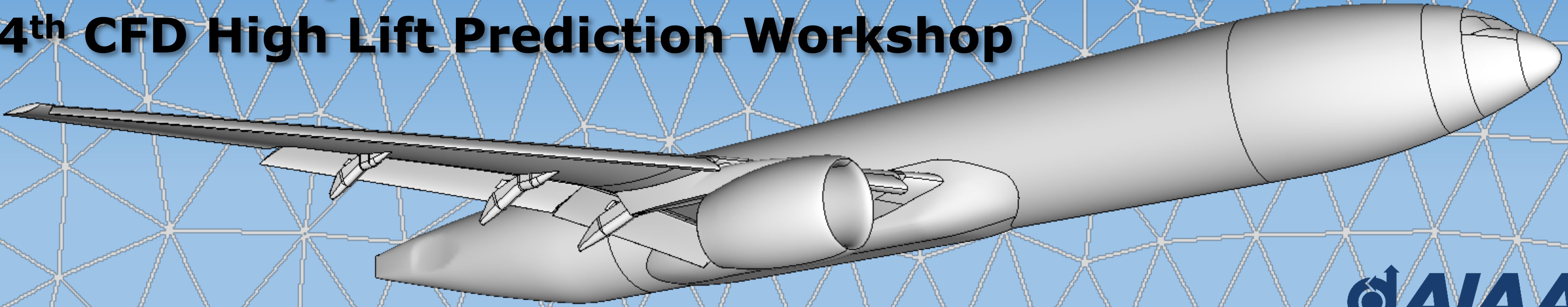
3rd Geometry and Mesh Generation Workshop
4th CFD High Lift Prediction Workshop



AIAA
SHAPING THE FUTURE OF AEROSPACE

Hybrid RANS/LES TFG

Neil Ashton (Amazon Web Services)
Paul Batten (Metacomp Technologies, Inc.)
Andrew Cary (Boeing)
Kevin Holst (University of Tennessee) + HRLES TFG members

Team Details

TFG ID/Name
G = Geometry
R = RANS
A = Adaptation
H = High-order
L = Hybrid RANS/LES
W = WMLES/LB

TFG Name	**HRLES**
Number of Active Participants	7 teams
Number of Observers	>20

		Test Cases				
Group ID	Tools Used (Geom/Grid/Solver), by name	1a	1b	2a	2b	3
L-001	ANSA/CFD++			x	x	
L-004	ANSA/FUN3D	x		x		
L-005	Committee D/Kestrel/KCFD v12	x				
L-016	LAVA/LAVA structured curvilinear			x		
L-038	ANSA/Tau V.2019.1.2 (modified, HLD2)			x		x
L-053	Pointwise C/Cflow, ver.5.10.1	x				
W-032	Powerflow/PowerFLOW 6	x	x	x	x	

Terminology

- DES – Detached-Eddy Simulation
- DDES – Delayed Detached-Eddy Simulation
- ZDES – Zonal Detached-Eddy Simulation
- “Grey-Area Problem” – The region between a fully modelled RANS zone (majority of turbulence is from the RANS model) to a fully resolved region where the only modeled turbulence is from the sub-grid scale model (LES) or the numerical scheme (ILES) or both (LES)
- “Shielding Function” – The component parts of a hybrid model that decide where to operate as LES and where to operate as RANS
- “SA(-RC)+(QCR)” Spalart-Allmaras RANS model with optional Rotation/Curvature correction and optional Quadratic Constitutive Relation
- “Hysteresis” – When the reaction of a system to change depends upon its prior state or reactions to change
- “Stationarity” – ‘Convergence’ for hybrid RANS/LES, i.e., mean, variance, autocorrelation are no longer changing with time

Key Questions for HRLES

#	Key Question
1	Do hybrid RANS-LES methods provide improved accuracy over RANS methods to predict CLmax for the right reason (pre and post Clmax - to understand separation process)?
2	What mesh resolution/type is required to achieve this accuracy and what is the sensitivity?
3	What is the HPC cost compared to steady RANS?
4	What Best-Practices are recommended to achieve alpha sweeps for hybrid RANS-LES (i.e., address hysteresis and bifurcation)?
5	What Best-Practices are recommended to achieve statistical convergence for Hybrid RANS-LES simulations (e.g., total time-averaging period and averaging-window start time, t_0)?
6	What is the influence of the wind-tunnel on the simulation accuracy?

Note – this is not a thorough overview of every group's submissions but only those that help us to answer the key questions. Therefore some submissions will not be discussed in this presentation. AIAA Aviation will have papers from each group as well as a summary paper that will cover all.

Note – other than KQ1, due to limited data, only case 2a/2b will be discussed

Key Findings / Lessons Learned

KQ 1	Do hybrid RANS-LES methods provide improved accuracy over RANS methods to predict CLmax for the right reason (pre and post CLmax to understand separation process)?

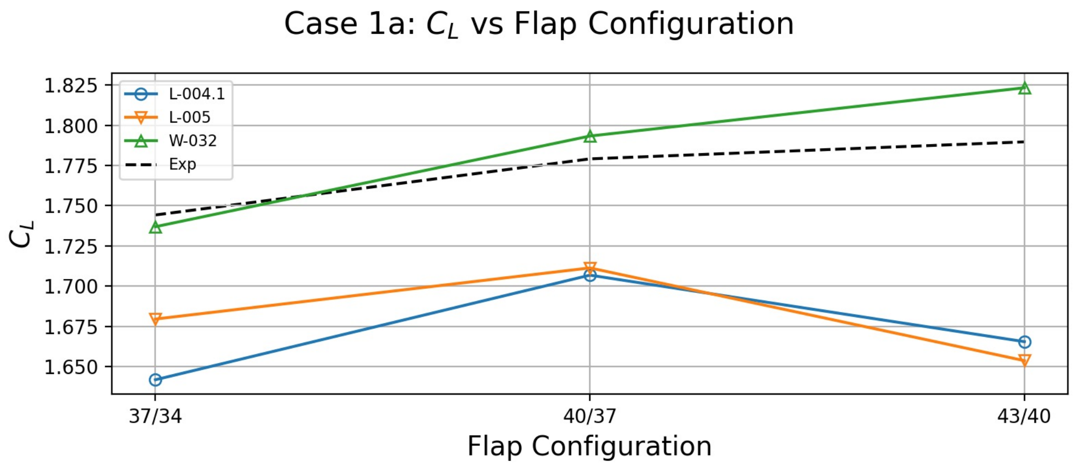
Key Findings / Lessons Learned
• In general, for case2a/2b, HRLES methods offer improved accuracy over RANS, mainly due to less outboard separation at the highest AoA which results in improved lift, drag and moment prediction. Not enough data to conclude on case 1a but limited data suggests HRLES find it challenging.
• Near and beyond Cl_Max this improvement is consistent across a range of flow solvers, mesh topologies and by multiple independent participants
• Improvement is consistent for case2a (free-air) and case2b (wind-tunnel)
• The 'why' has still not been fully addressed i.e., whether the failure of RANS models is the underprediction of the turbulent shear-stress or some failure to capture larger-scale unsteady effects – further work is needed to answer this important question
• Still need to be careful with correlation to exp. – future full-span exp. tests will help but for now we need some caution, particularly for case 2a (free-air).

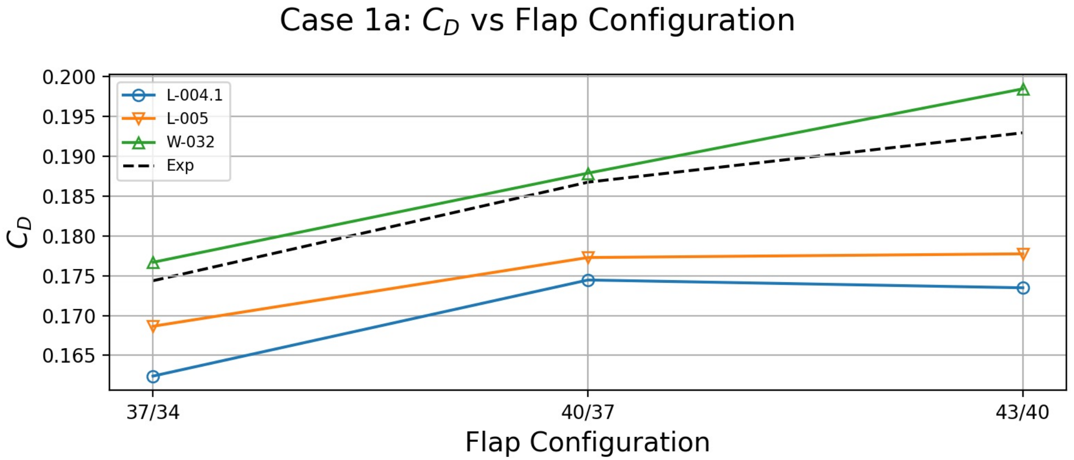
Supporting Evidence

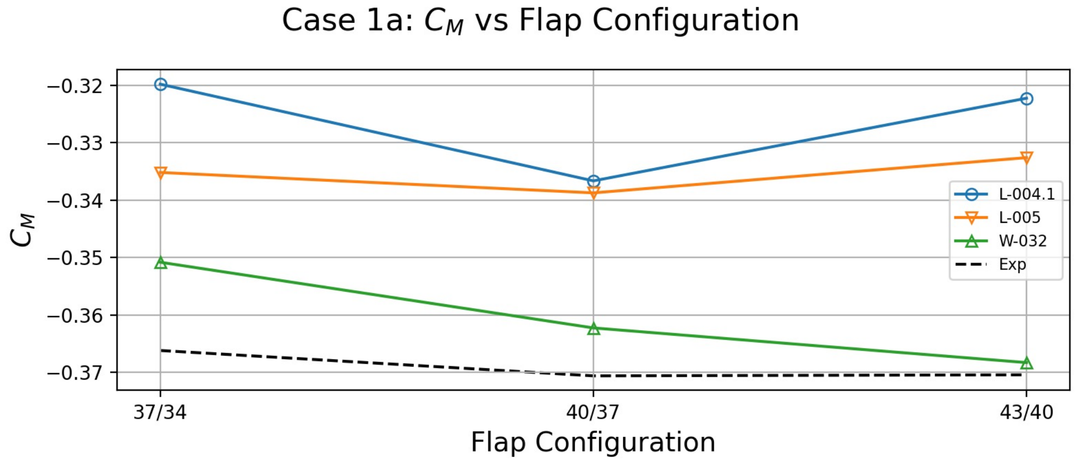
Case 1a

Supporting Evidence

KQ 1	Do hybrid RANS-LES methods provide improved accuracy over RANS methods to predict CLmax for the right reason (pre and post CLmax to understand separation process)?







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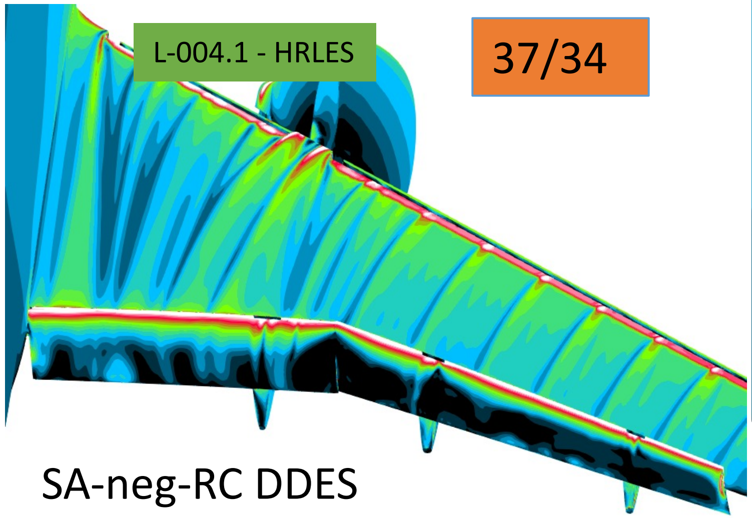

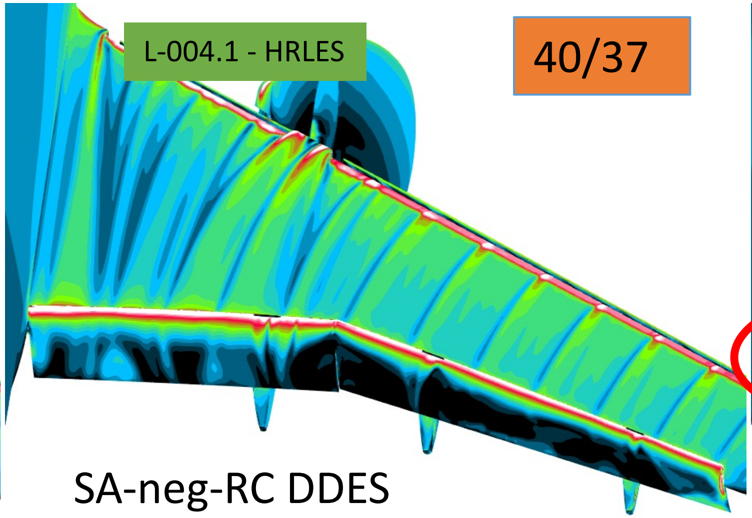

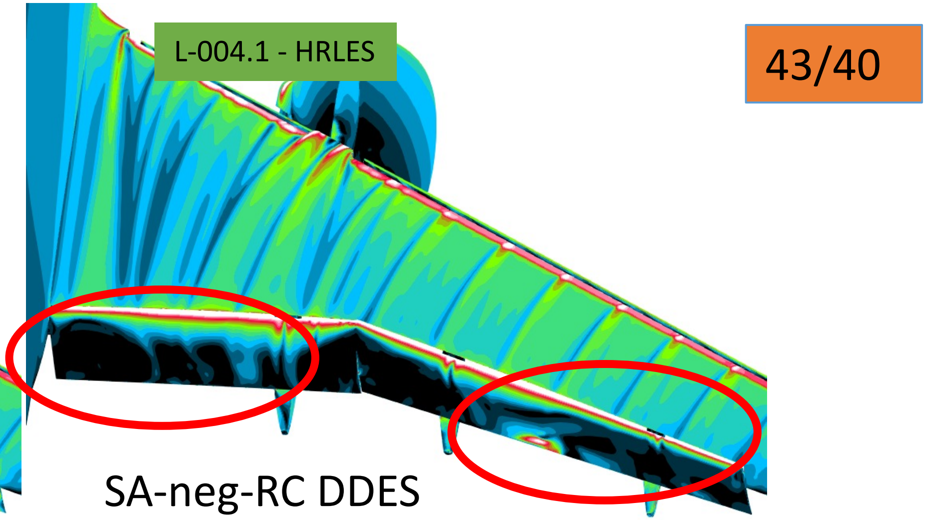

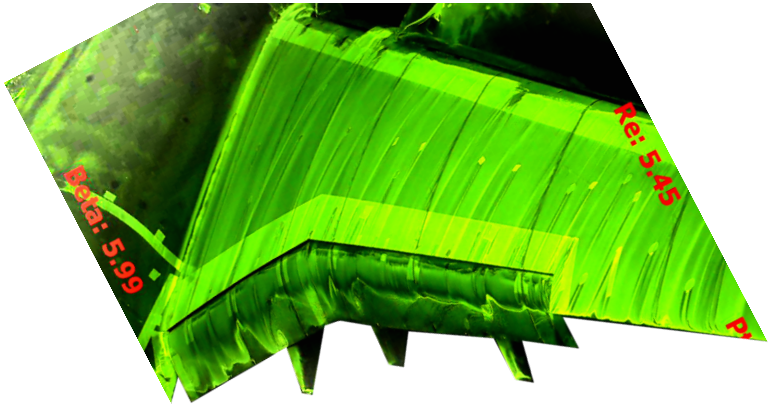

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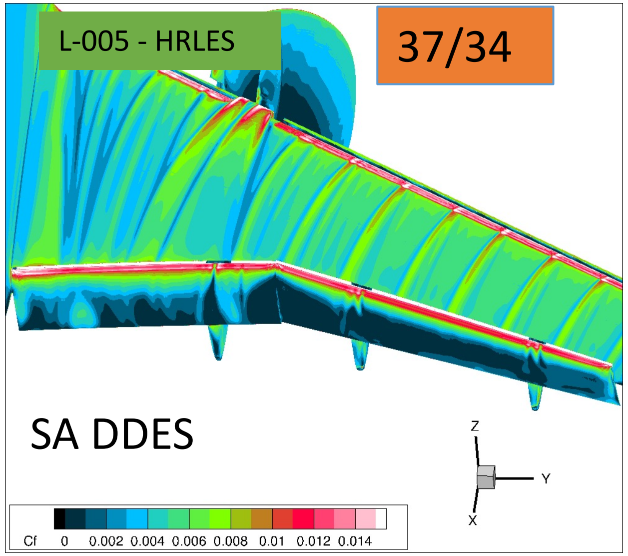

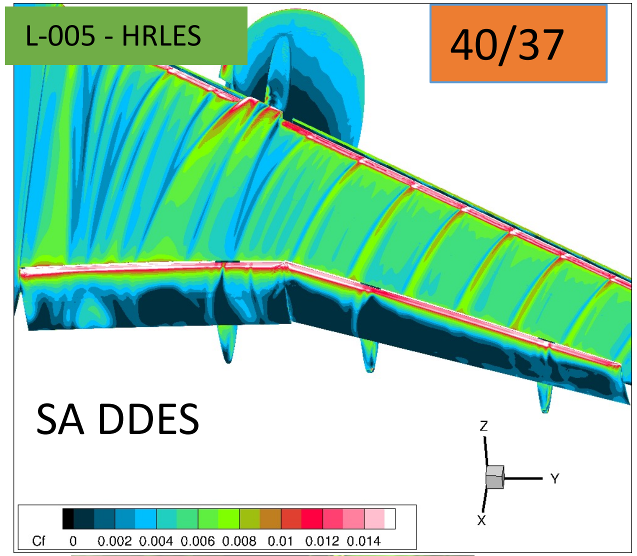

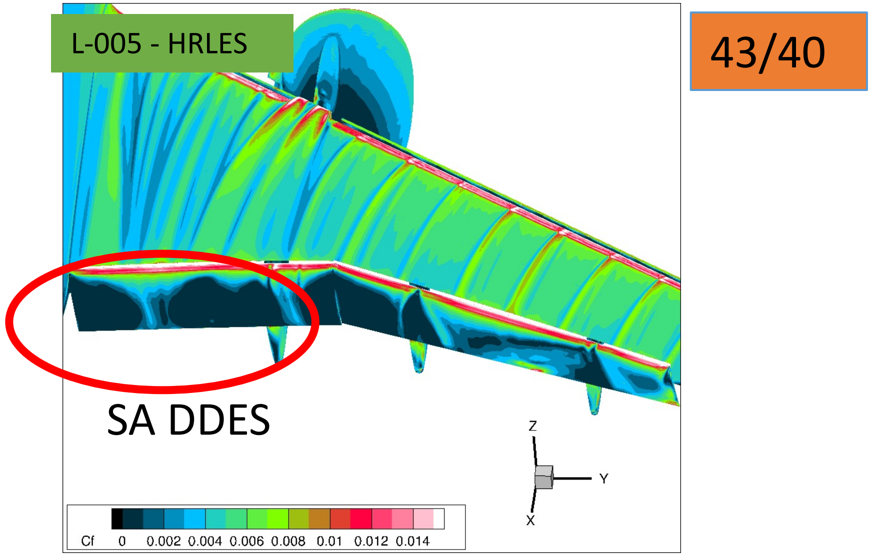

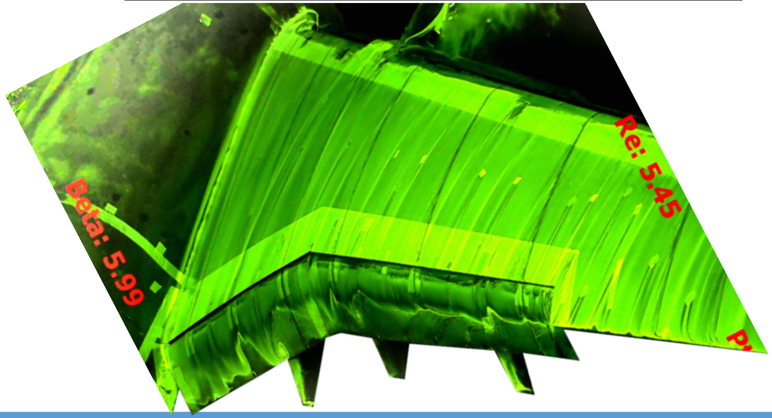

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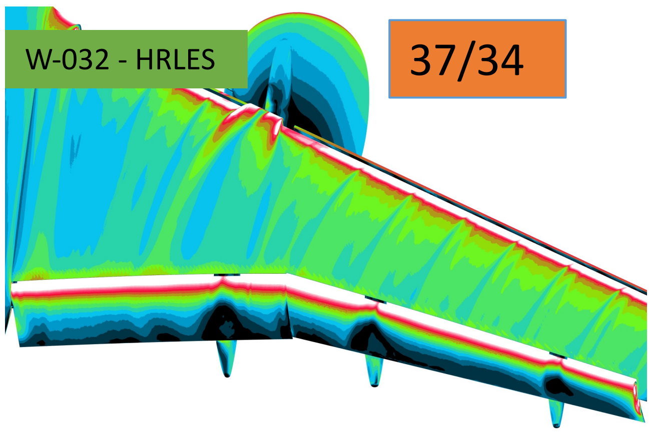
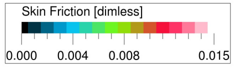
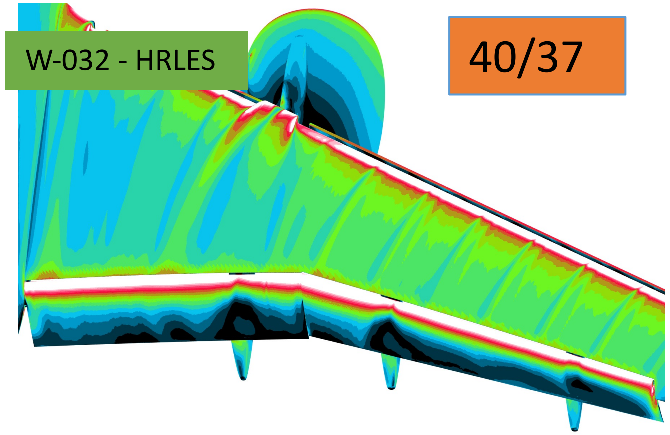


K-ε VLES LBM





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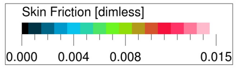

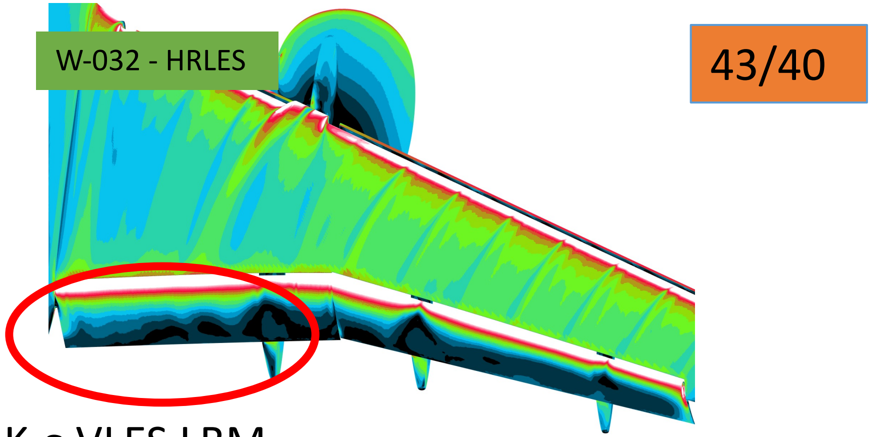

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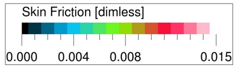

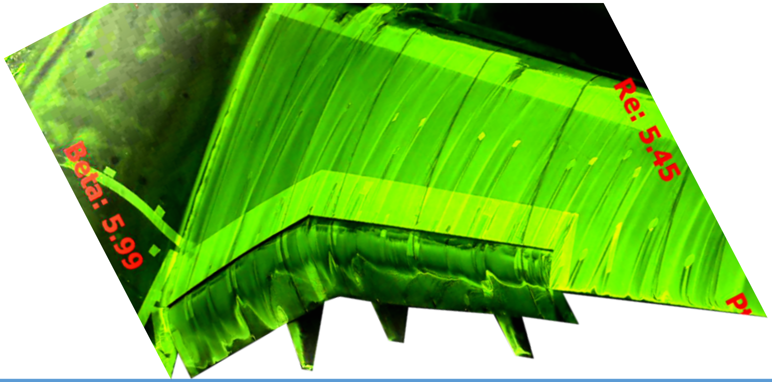

Supporting Evidence

Case 2a/b

Supporting Evidence

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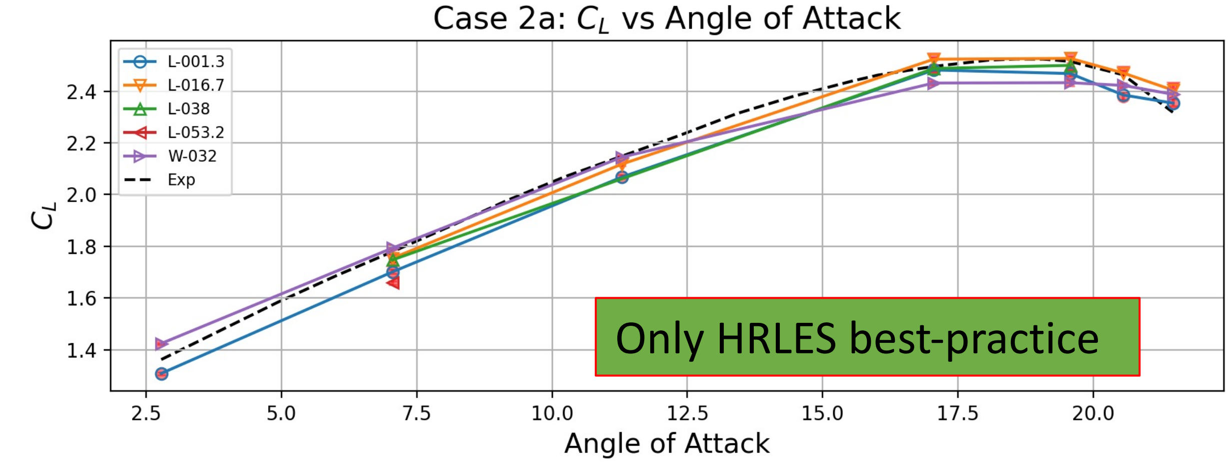

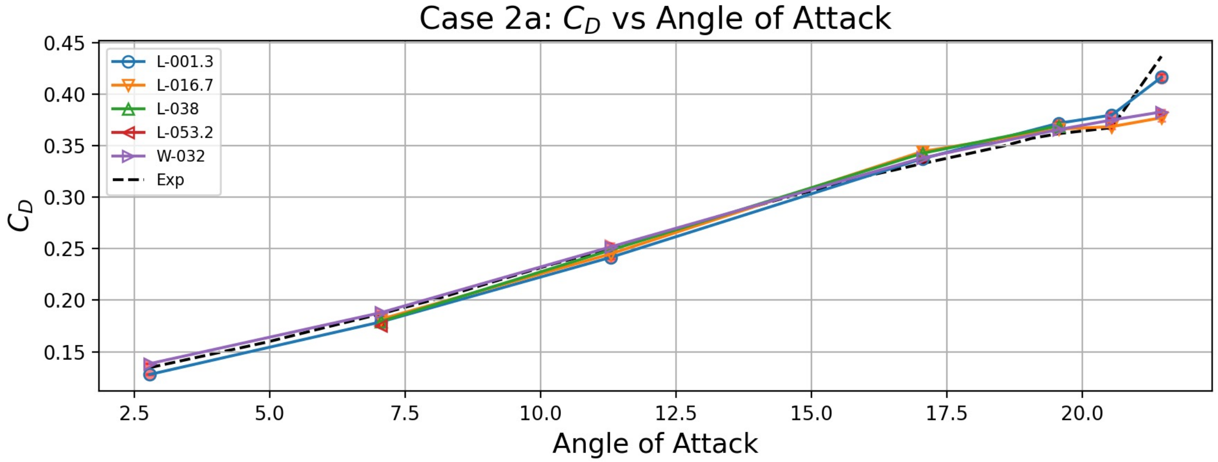

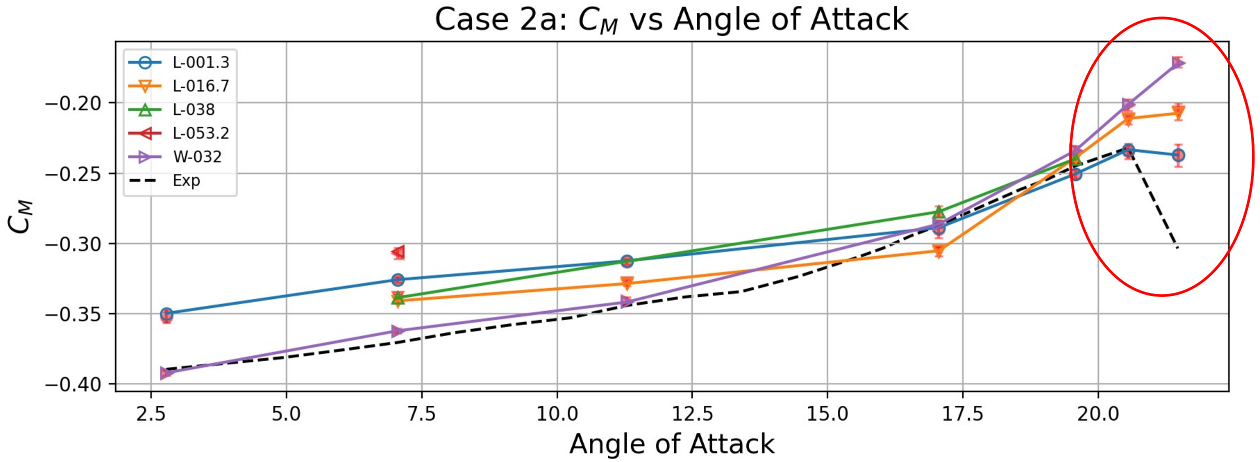

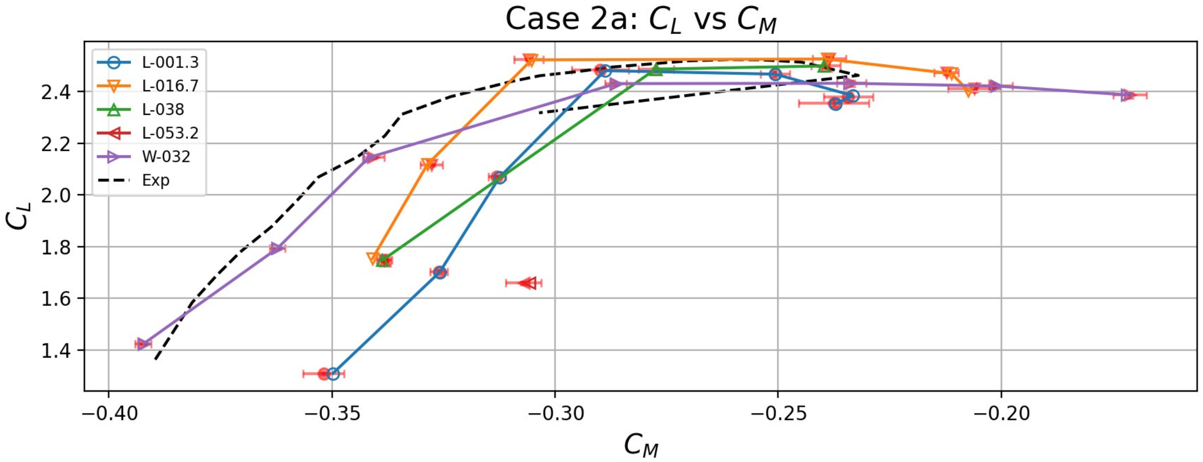

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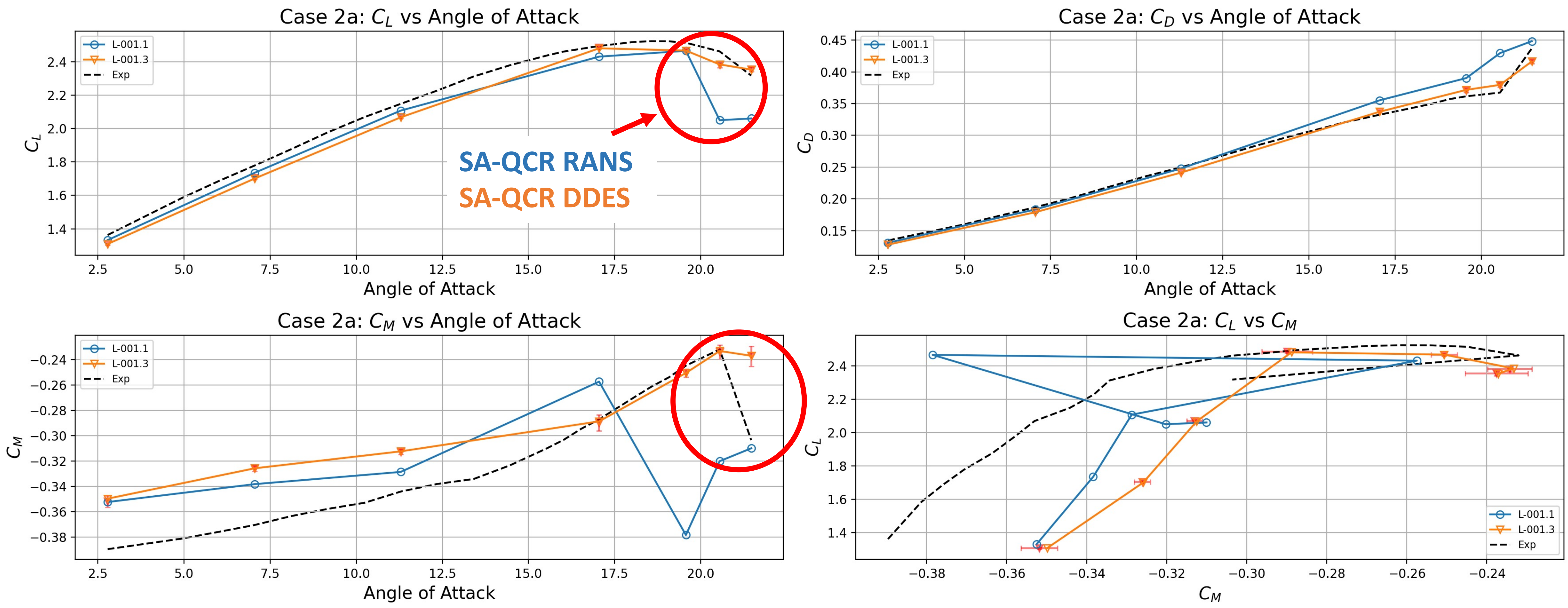


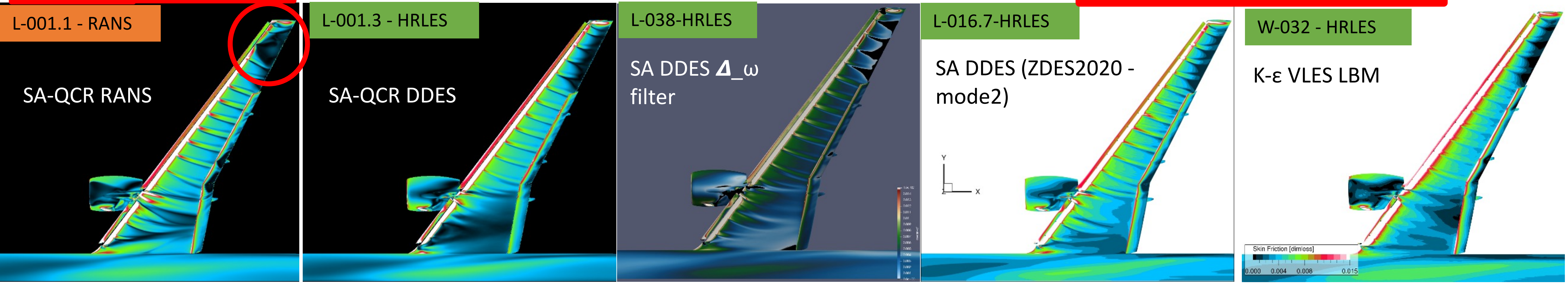
Supporting Evidence

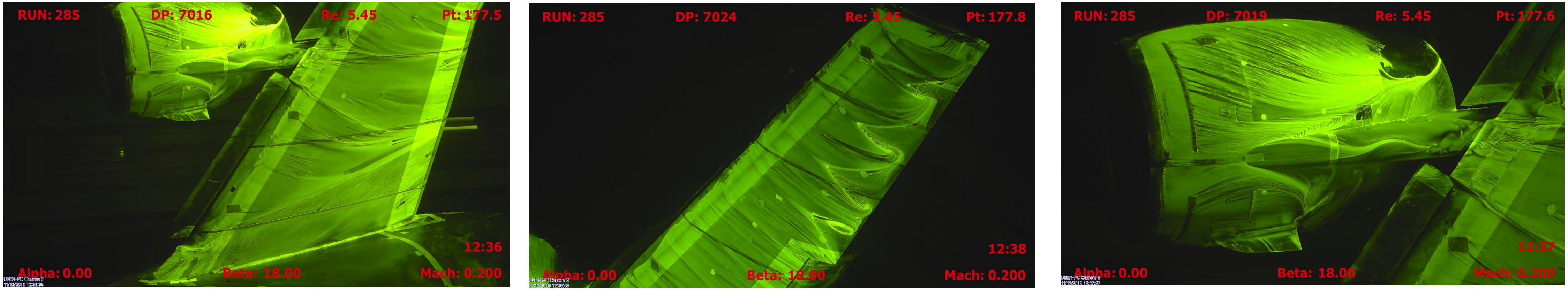
SHAPING THE FUTURE OF AEROSPACE

KQ 1	Do hybrid RANS-LES methods provide improved accuracy over RANS methods to predict CLmax for the right reason (pre and post CLmax to understand separation process)?

Case2a | 19.57 AoA

Only showing best-practice





Supporting Evidence

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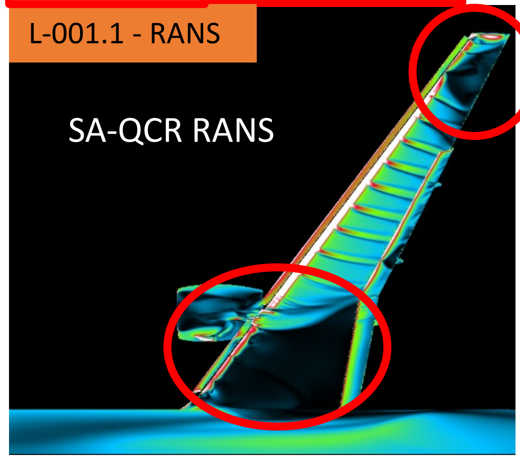
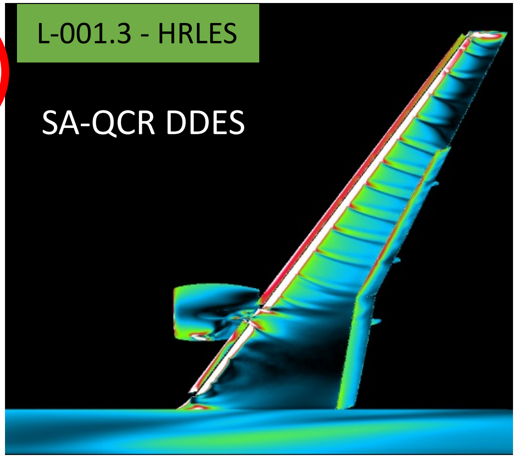
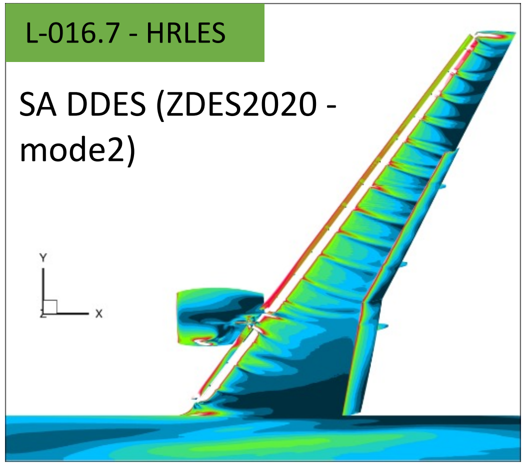
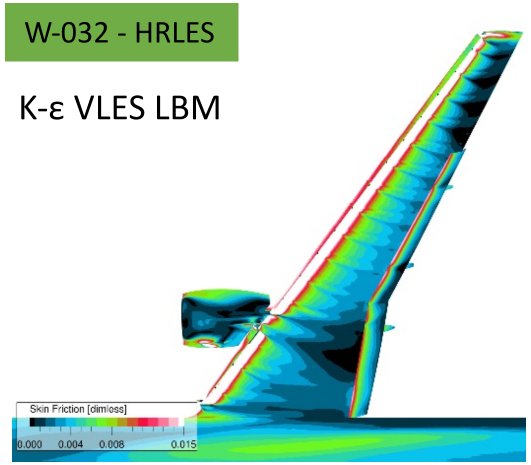
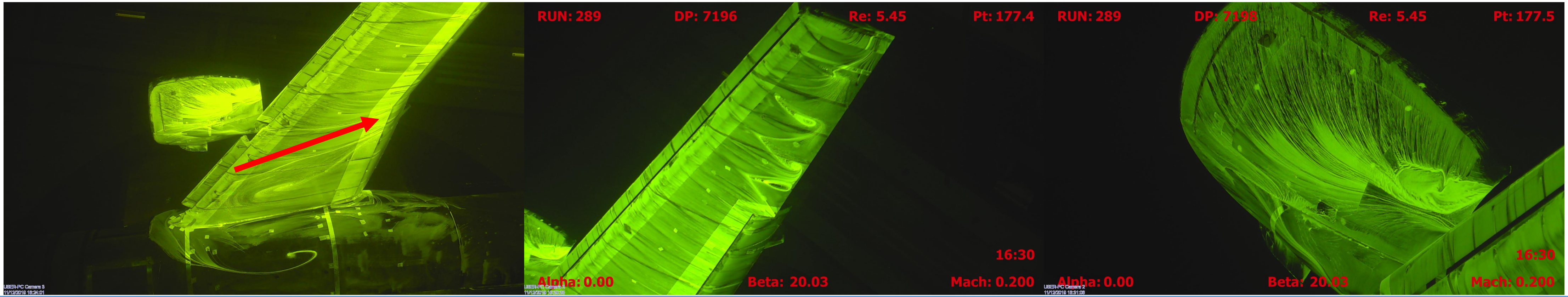
Case2a | 21.47 AoA











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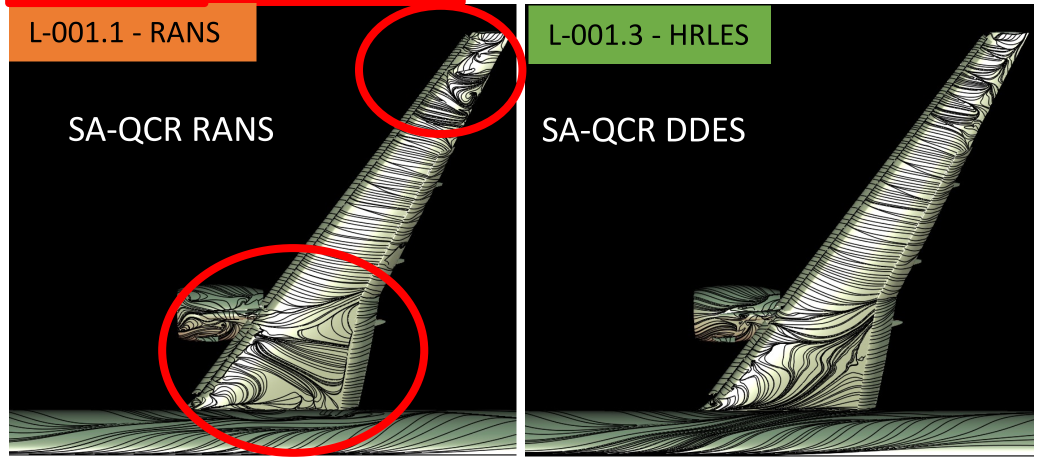
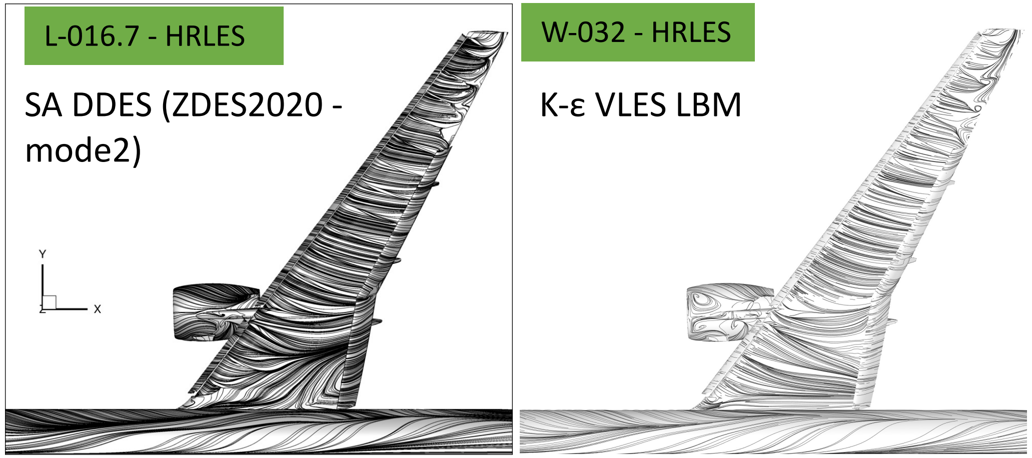
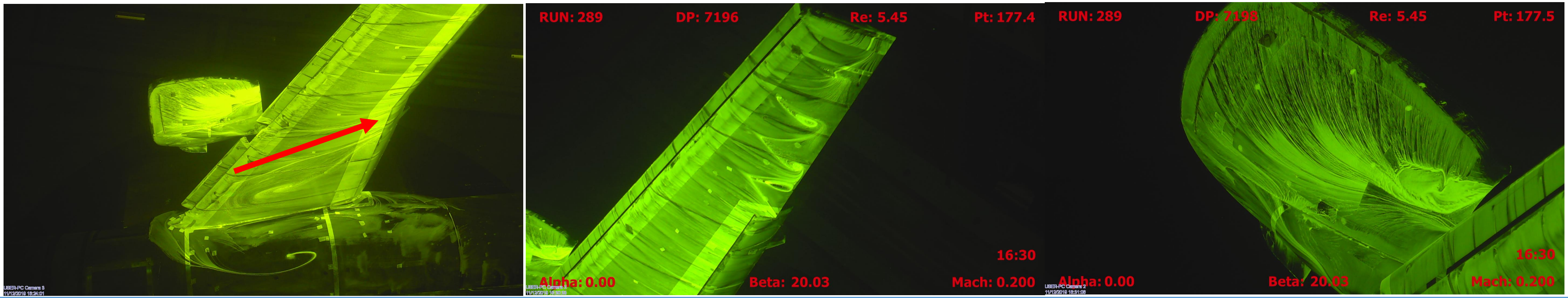
Case2a | 21.47 AoA

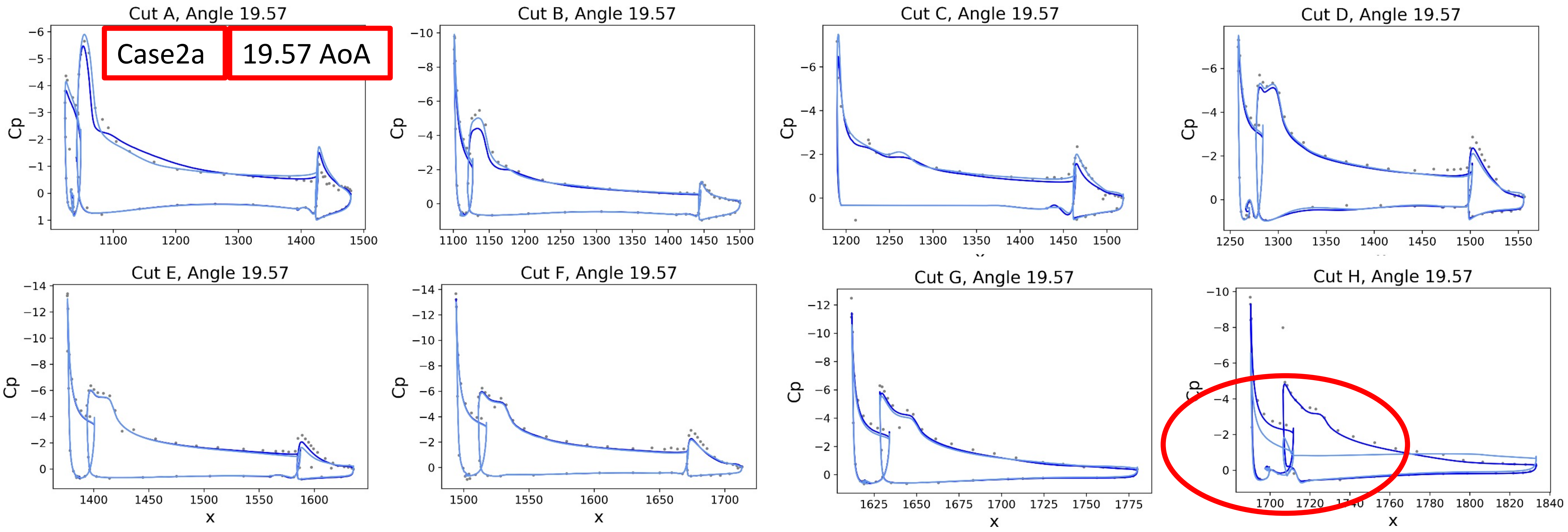






Comparison of RANS to DDES (19.57º)

KQ 1	Do hybrid RANS-LES methods provide improved accuracy over RANS methods to predict CLmax for the right reason (pre and post CLmax to understand separation process)?



- RANS much larger separation outboard (cut H)
- Some differences near root suction peak (Cut A,B); RANS closer to experiment
- Insufficient suction on flap compared to experiment. Sometimes RANS is better, sometimes not

- Exp
- L-001.1 RANS
- L-001.3 DDES

Comparison of RANS to DDES (21.47º)

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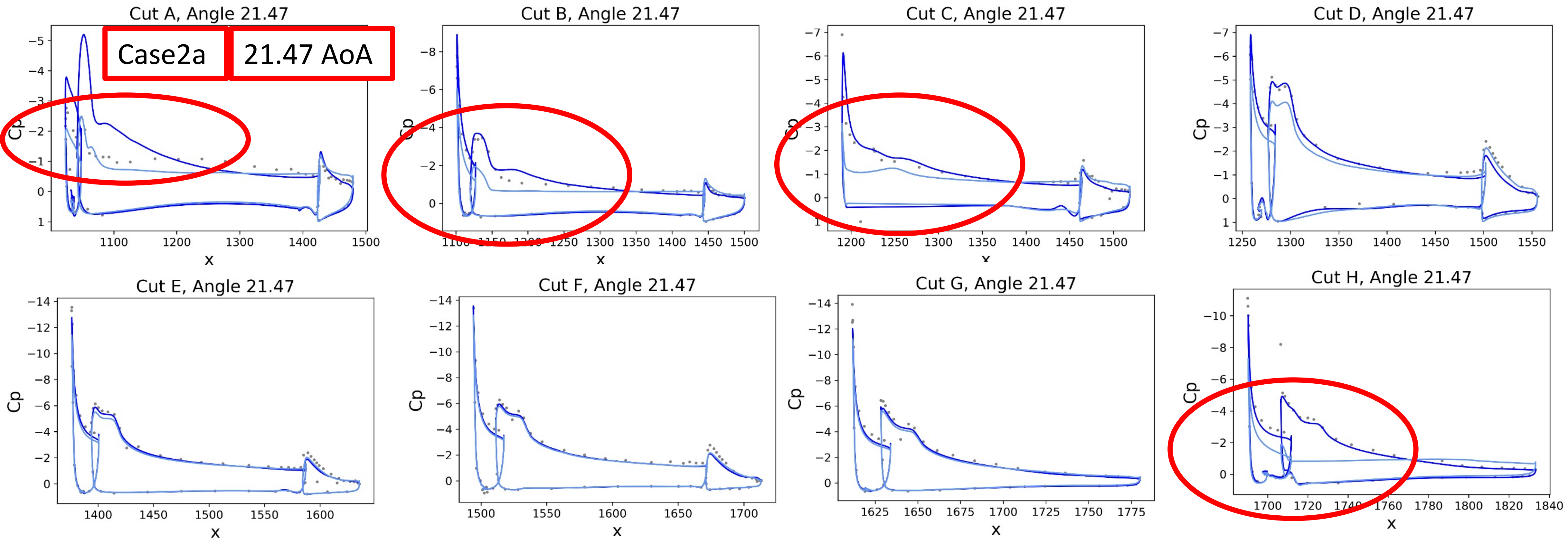


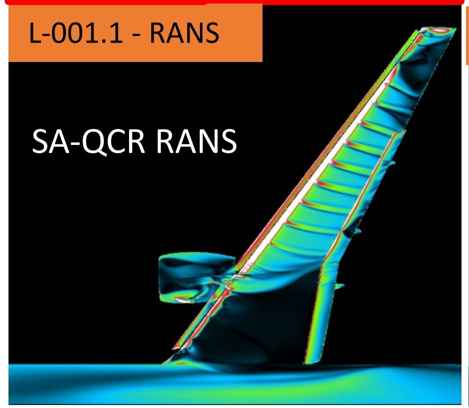
- RANS still shows much larger separation outboard (cut H)
- Now you see RANS over-predict inboard separation (cut C,B) but better for cut A
- DDES matches experiment well apart from Cut A
- Remember this is free-air versus exp. from a wind-tunnel.

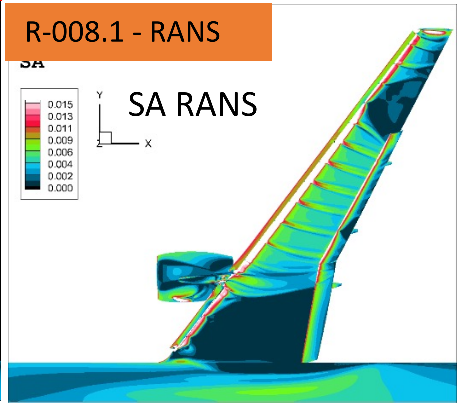
Supporting Evidence

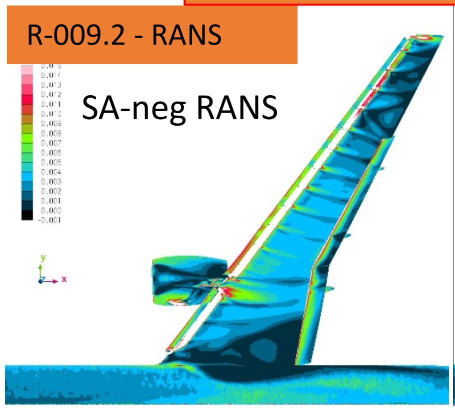
KQ 1	Do hybrid RANS-LES methods provide improved accuracy over RANS methods to predict CLmax for the right reason (pre and post CLmax to understand separation process)?

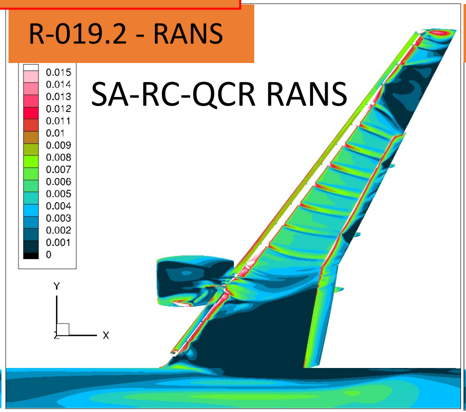
Case2a	21.47 AoA

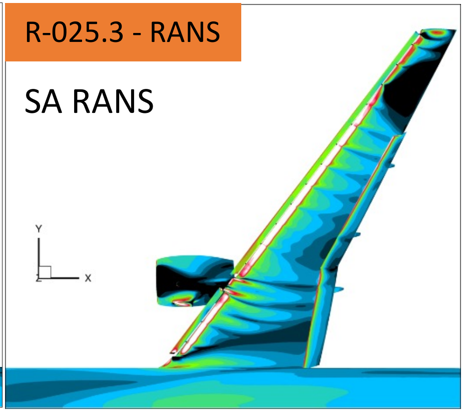
<u>All RANS best-practice</u>

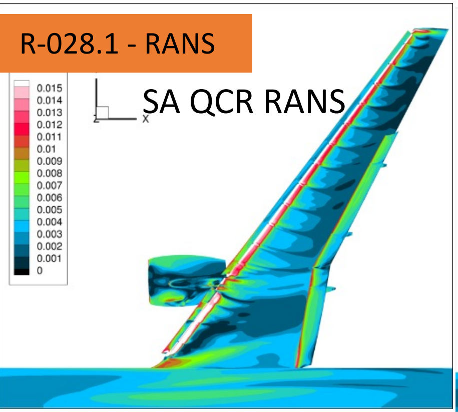


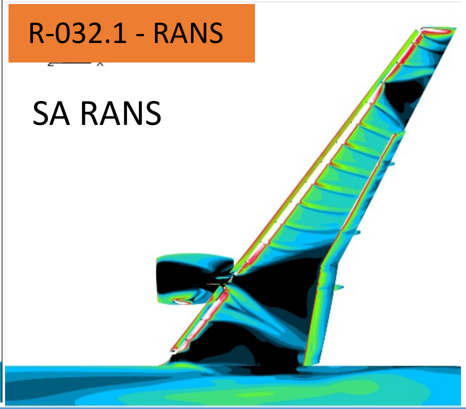


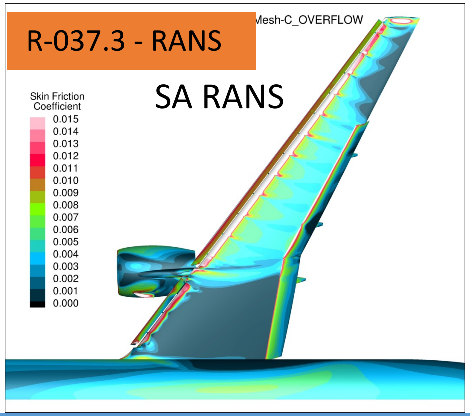


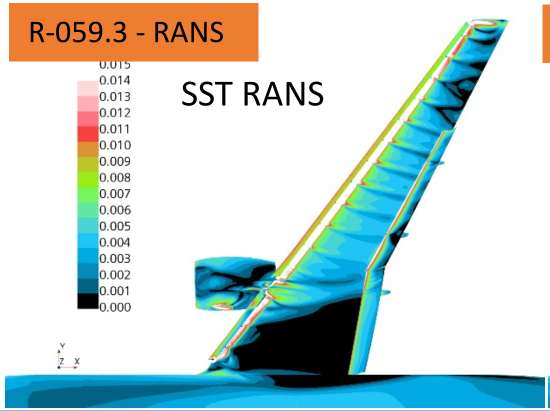


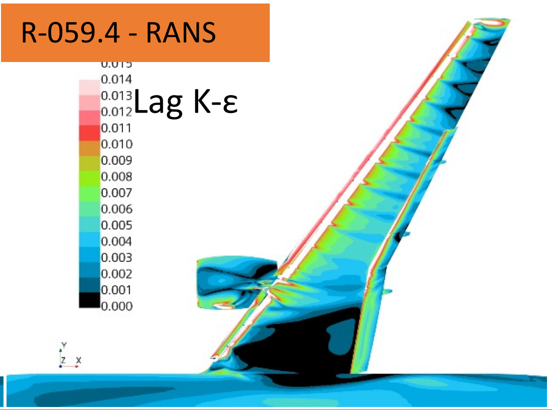












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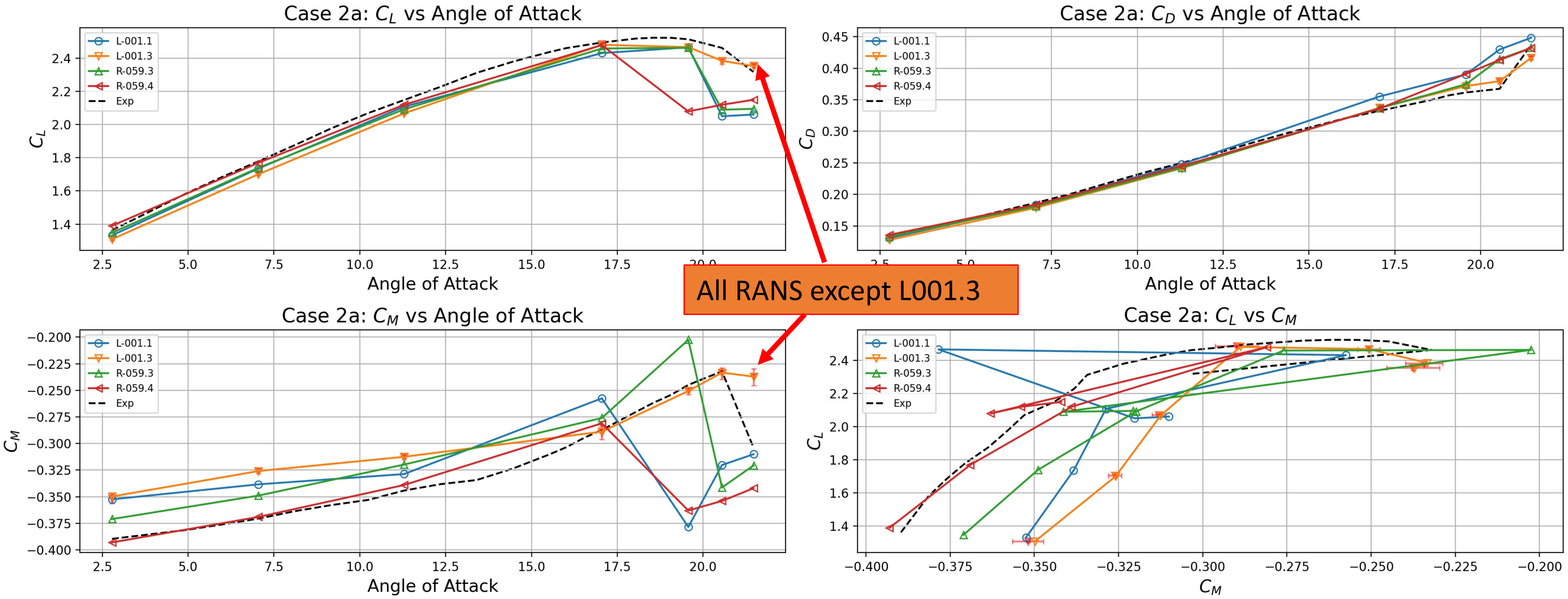

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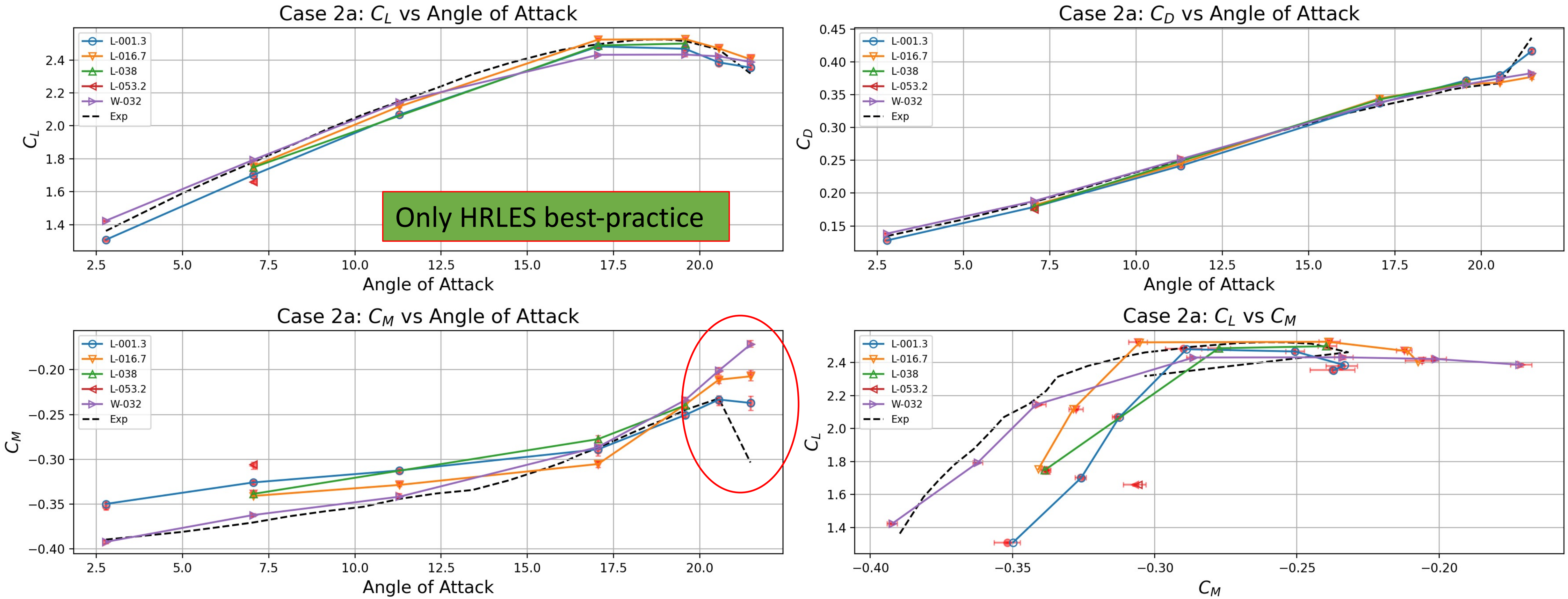
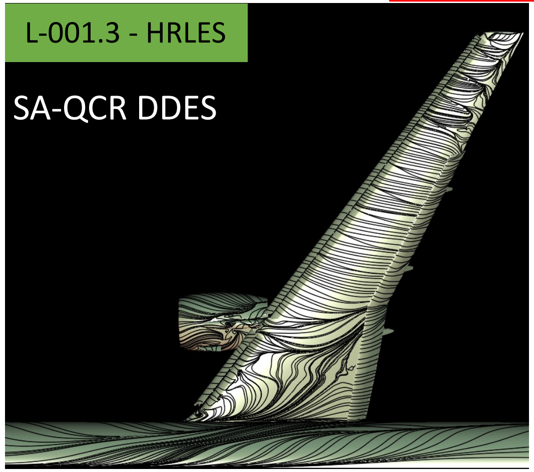


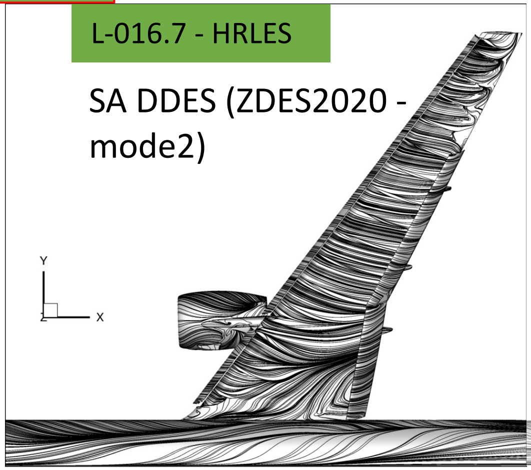
Supporting Evidence

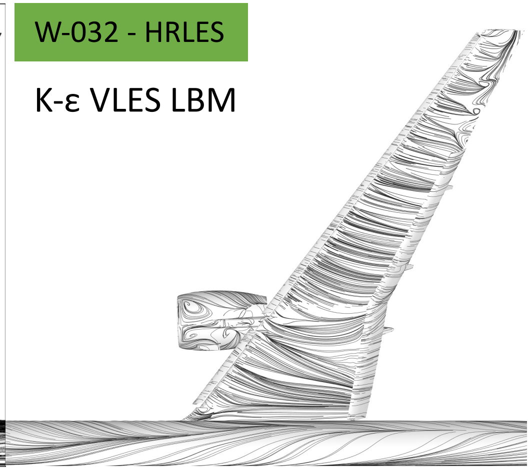
KQ 1	Do hybrid RANS-LES methods provide improved accuracy over RANS methods to predict CLmax for the right reason (pre and post CLmax to understand separation process)?

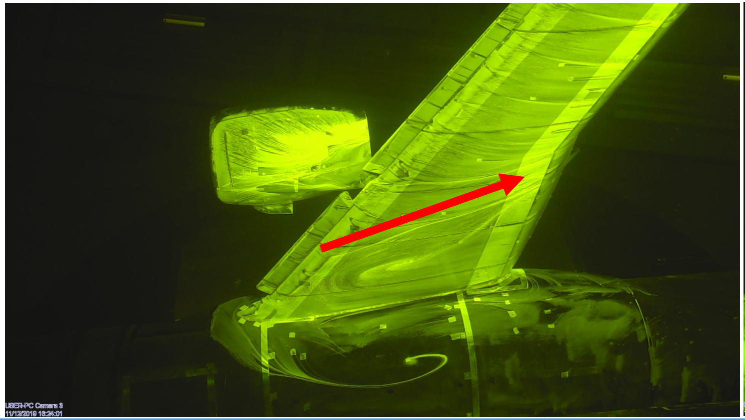
Case2a | 21.47 AoA

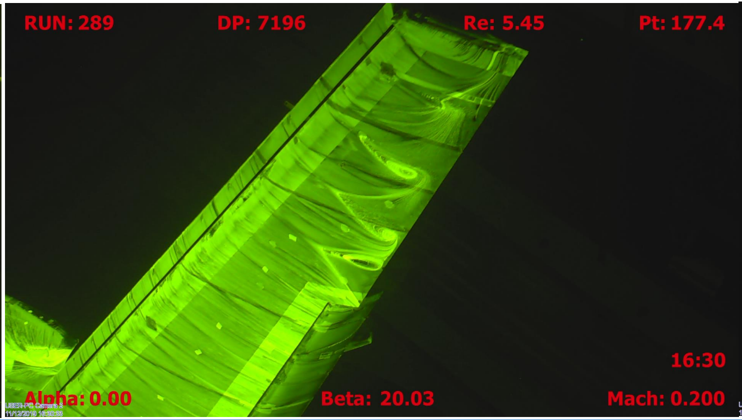
Only HRLES best-practice

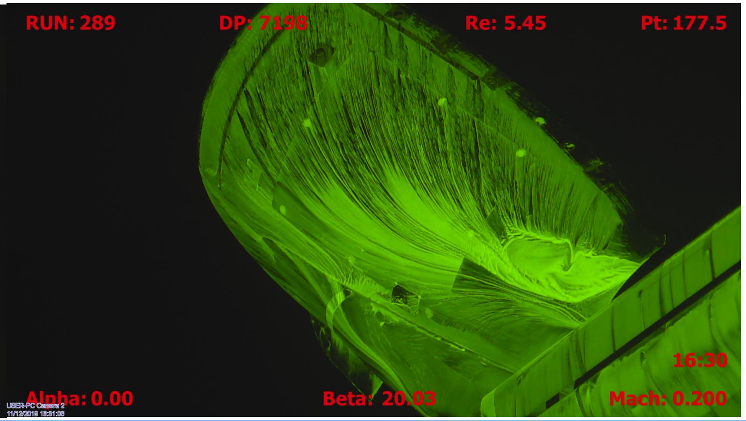












Comparison of DDES Best Practice (7.05º)

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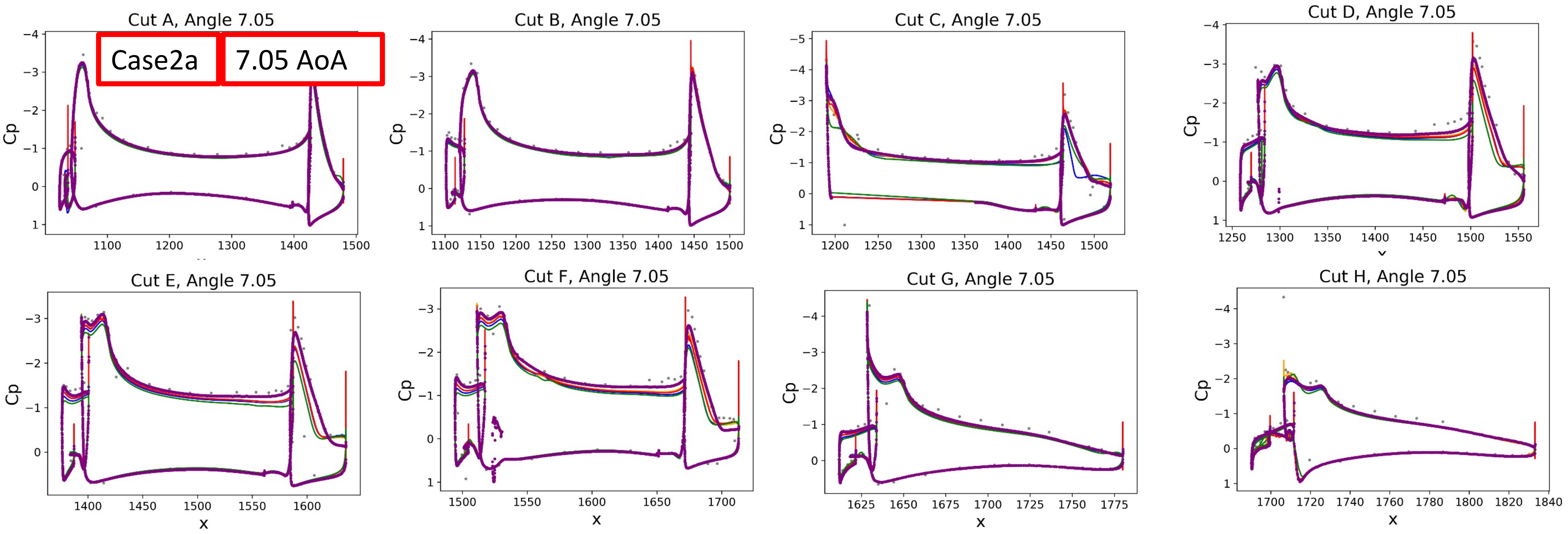

- Exp - L-001.3 - L-016.7 - L-038 - L-053.2 - W-032

Comparison of DDES Best Practice (19.57º)

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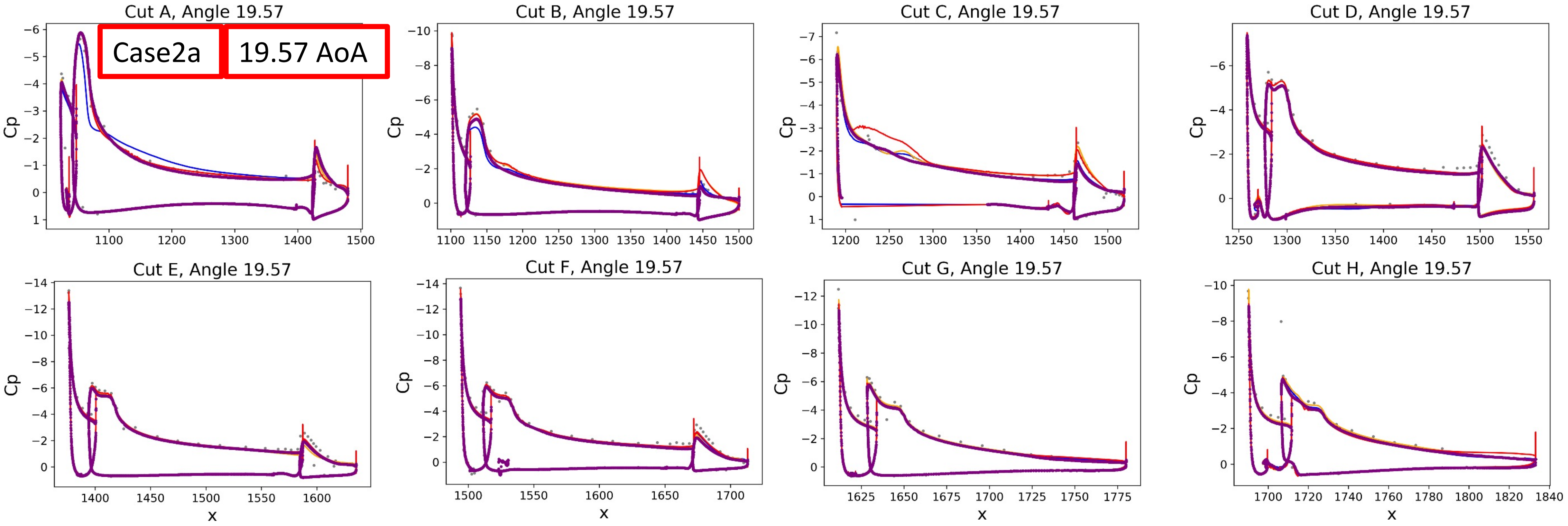

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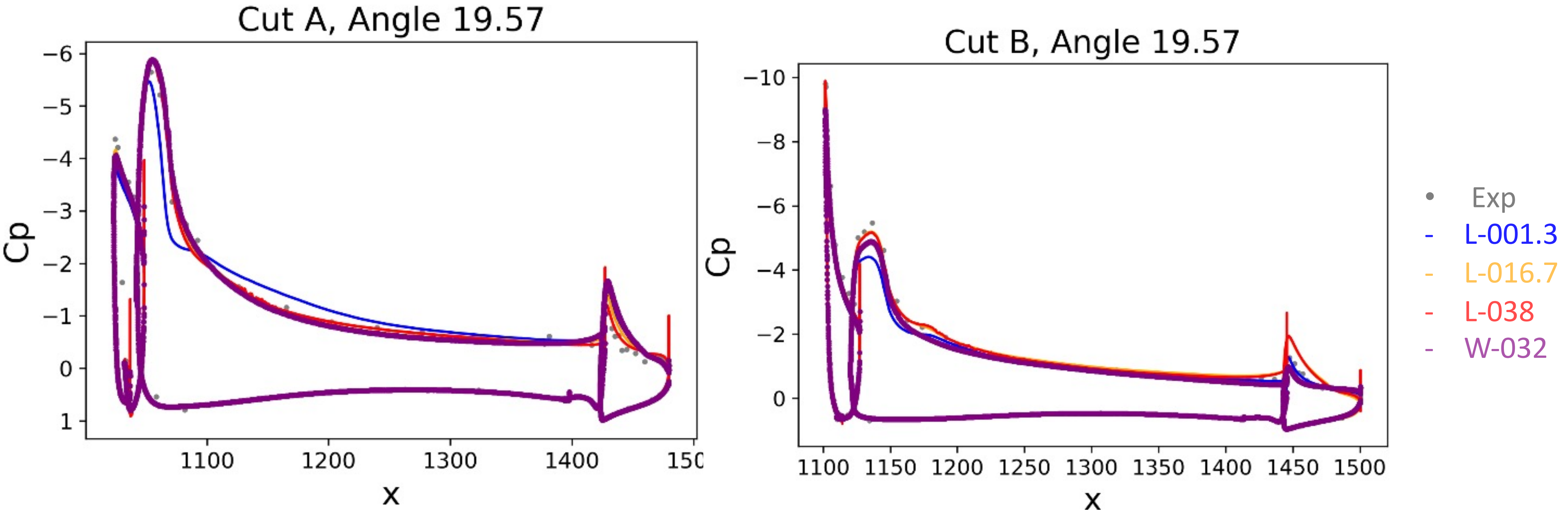
Comparison of DDES Best Practice (19.57º)

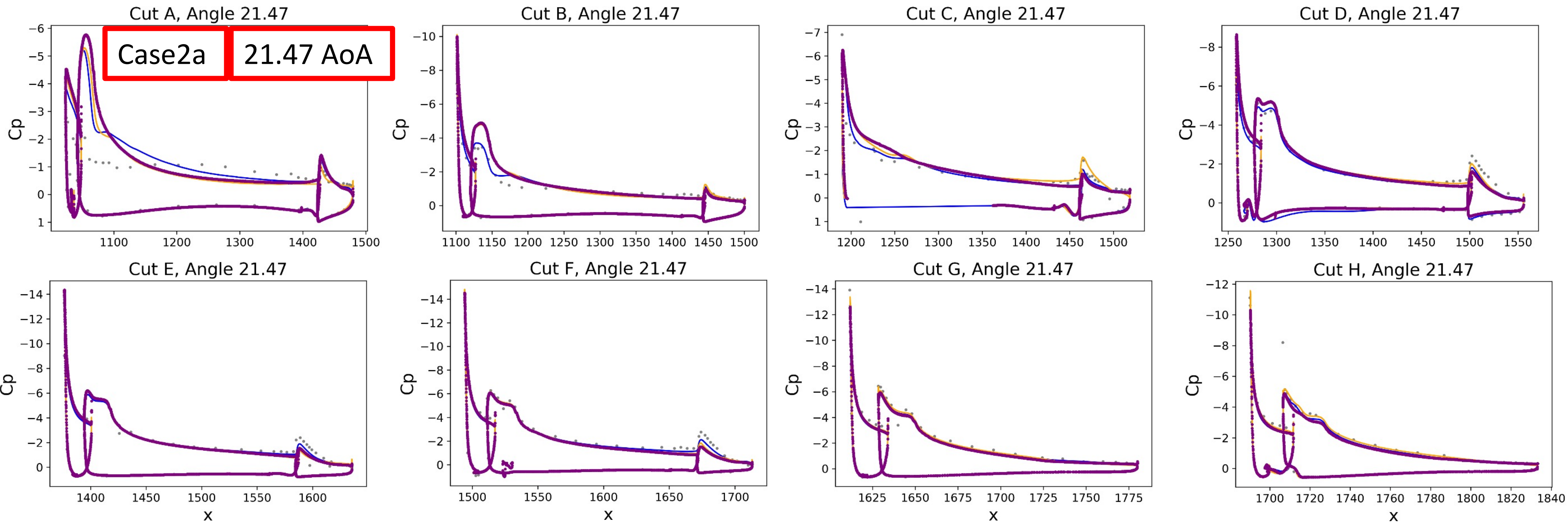
KQ 1	Do hybrid RANS-LES methods provide improved accuracy over RANS methods to predict CLmax for the right reason (pre and post CLmax to understand separation process)?

Case2a | 19.57 AoA



Comparison of DDES Best Practice (21.47º)

KQ 1	Do hybrid RANS-LES methods provide improved accuracy over RANS methods to predict CLmax for the right reason (pre and post CLmax to understand separation process)?

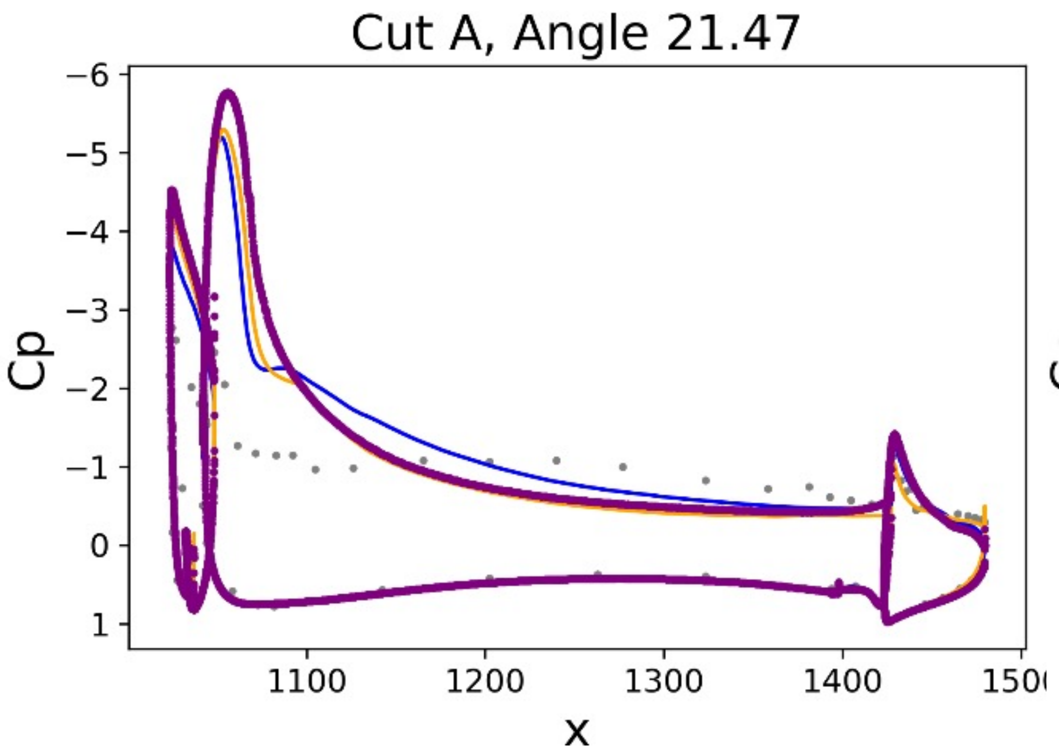


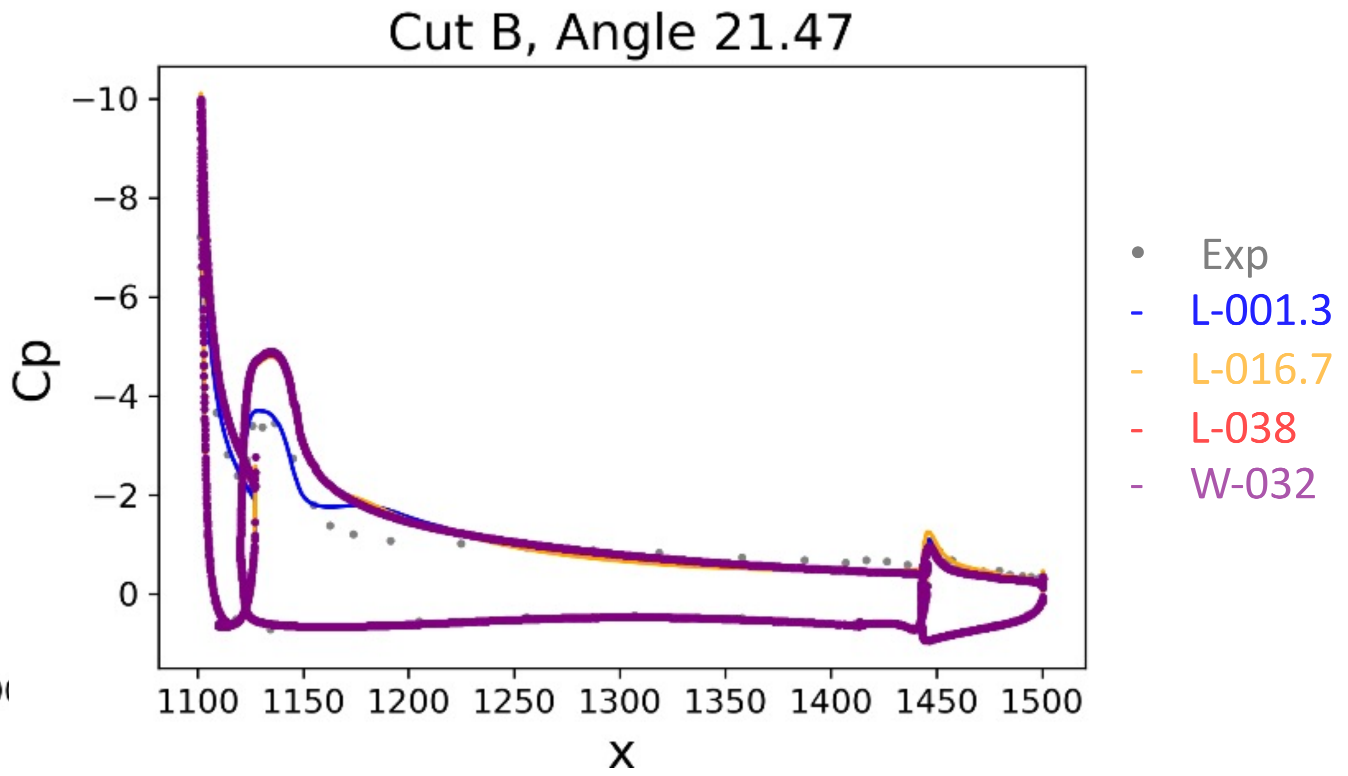
• Exp - L-001.3 - L-016.7 - L-038 - W-032

Comparison of DDES Best Practice (21.47º)

KQ 1	Do hybrid RANS-LES methods provide improved accuracy over RANS methods to predict CLmax for the right reason (pre and post CLmax to understand separation process)?

Case2a | 21.47 AoA





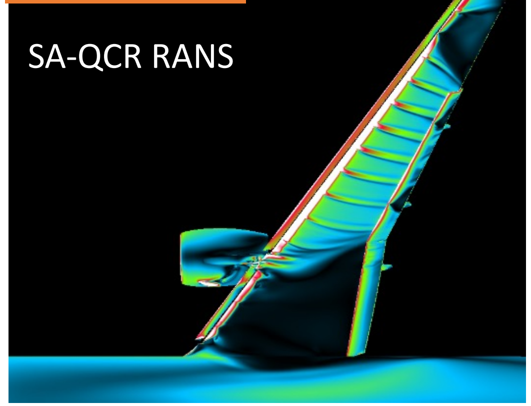
Supporting Evidence

KQ 1	Do hybrid RANS-LES methods provide improved accuracy over RANS methods to predict CLmax for the right reason (pre and post CLmax to understand separation process)?

Case2b | 19.98 AoA

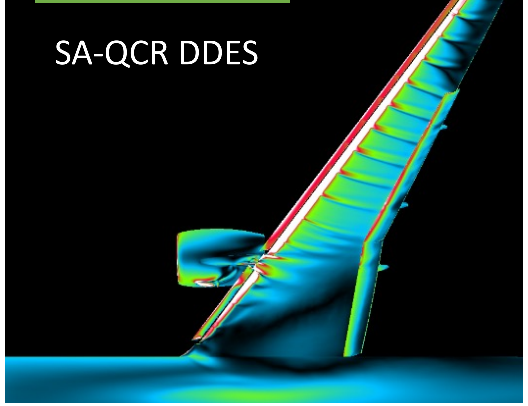
L-001.5 - RANS

SA-QCR RANS



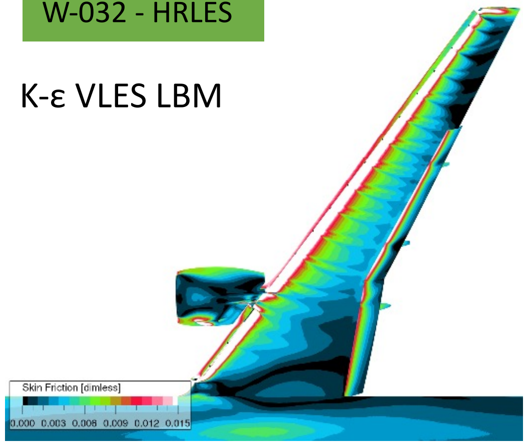
L-001.8 - HRLES

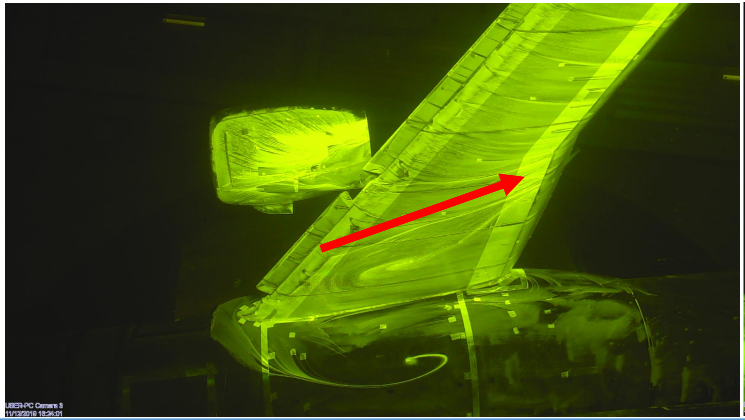
SA-QCR DDES

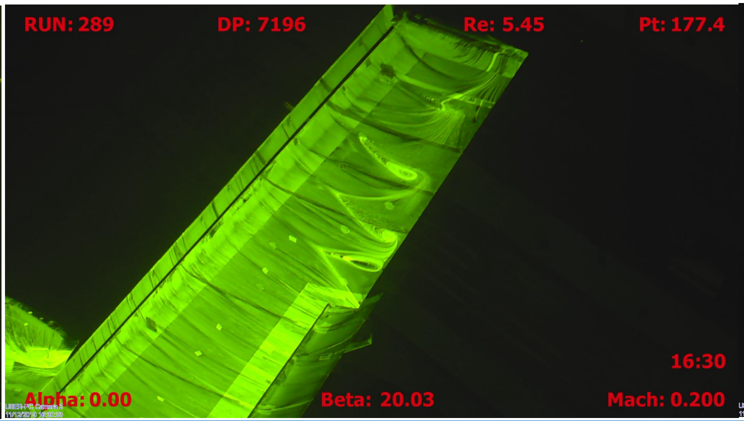


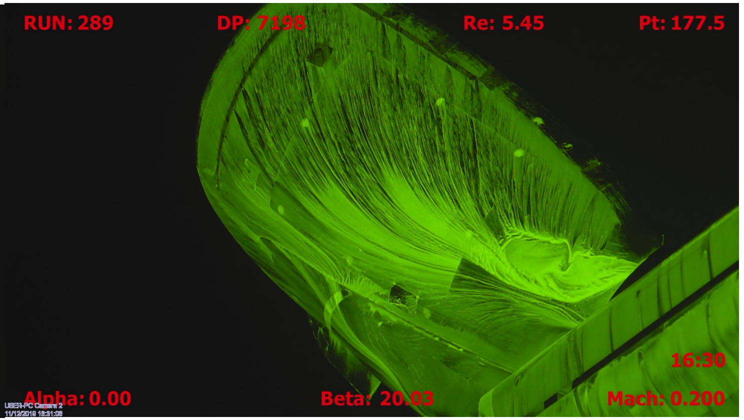
W-032 - HRLES

K-ε VLES LBM







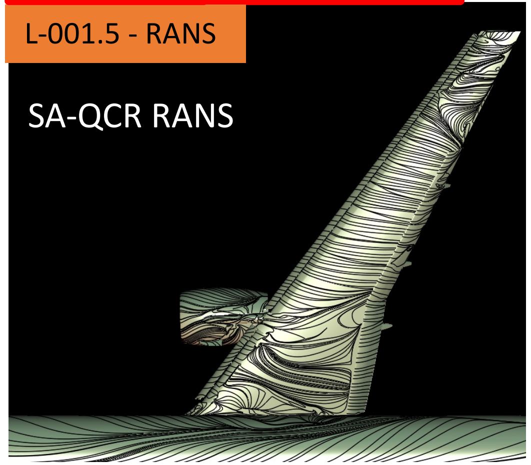


Supporting Evidence

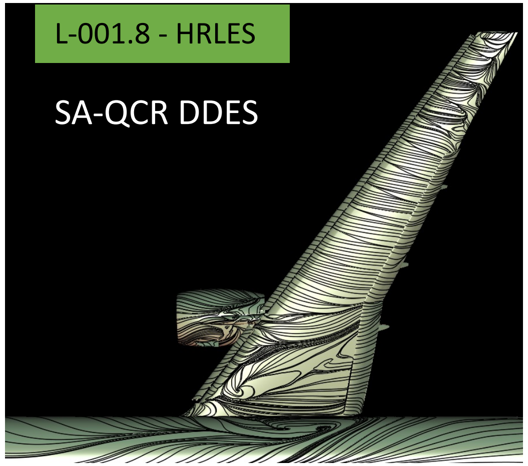
KQ 1	Do hybrid RANS-LES methods provide improved accuracy over RANS methods to predict CLmax for the right reason (pre and post CLmax to understand separation process)?

Case2b	19.98 AoA

L-001.5 - RANS

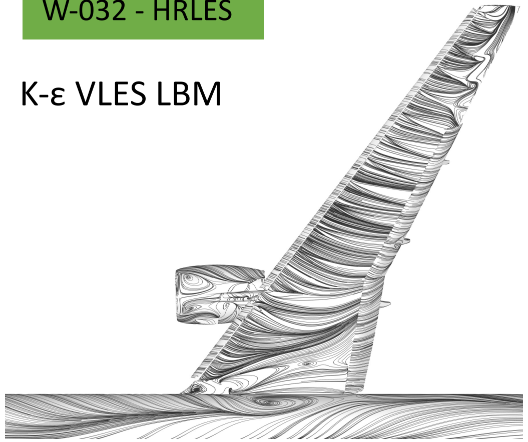


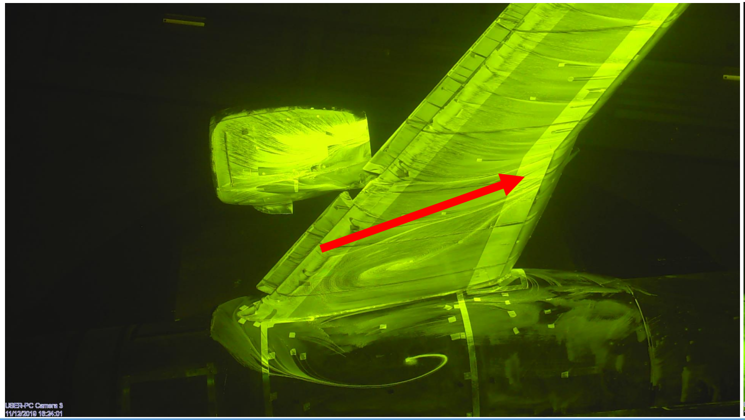
L-001.8 - HRLES

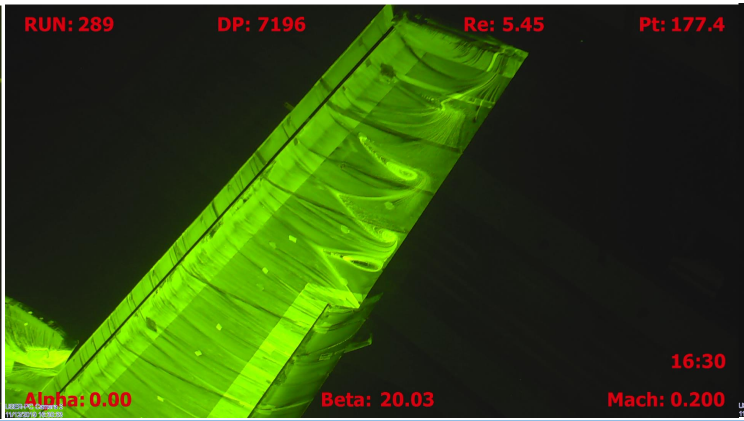


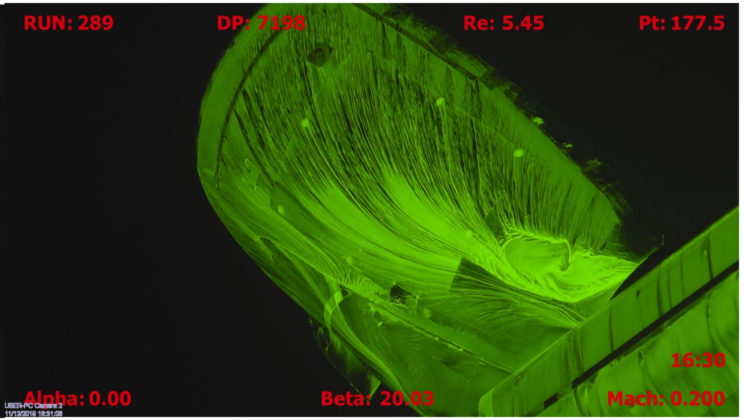
W-032 - HRLES

K-ε VLES LBM





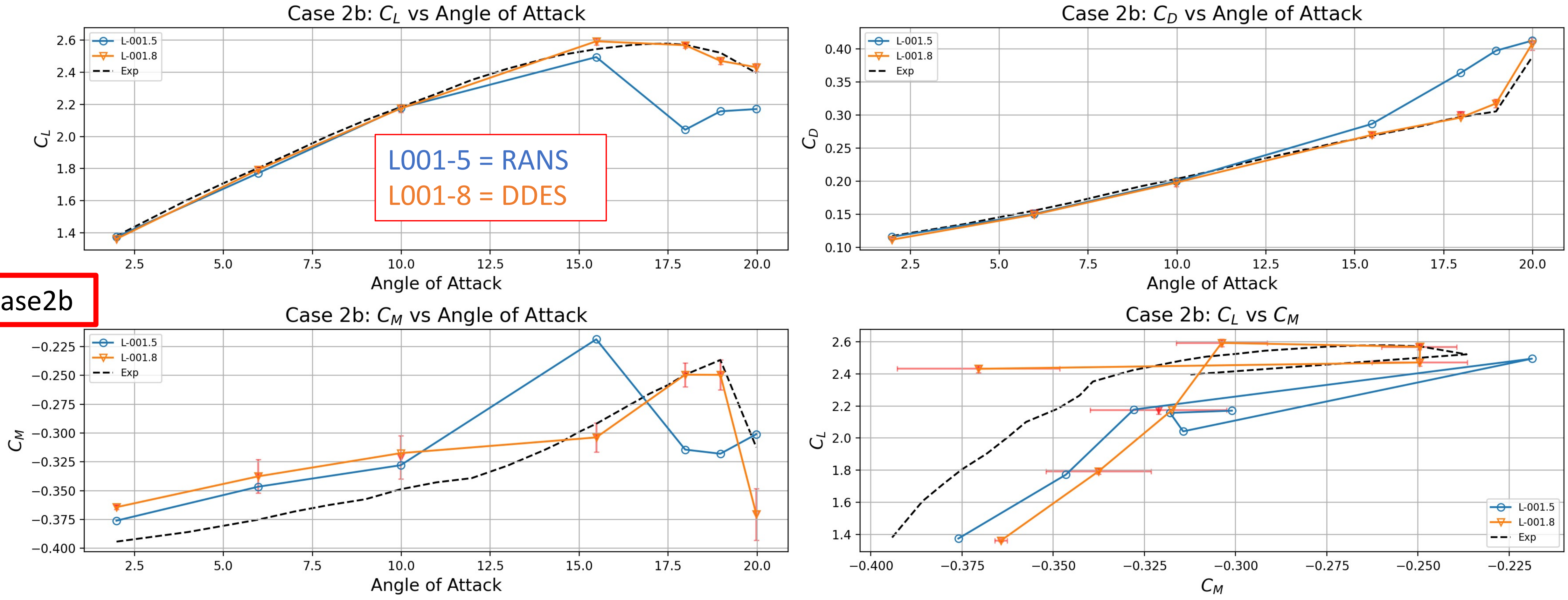




Supporting Evidence

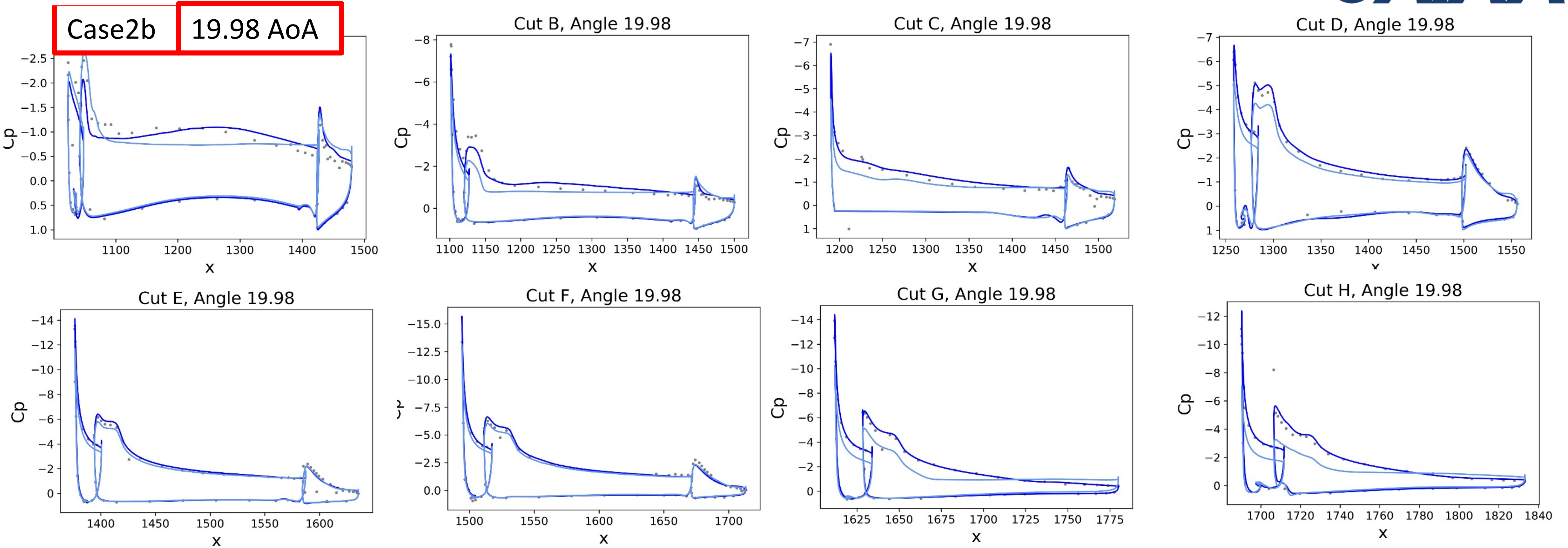
KQ 1	Do hybrid RANS-LES methods provide improved accuracy over RANS methods to predict CLmax for the right reason (pre and post CLmax to understand separation process)?

Case2b



Comparison of RANS to DDES (19.98º)

KQ 1	**Do hybrid RANS-LES methods provide improved accuracy over RANS methods to predict CLmax for the right reason (pre and post CLmax to understand separation process)?**

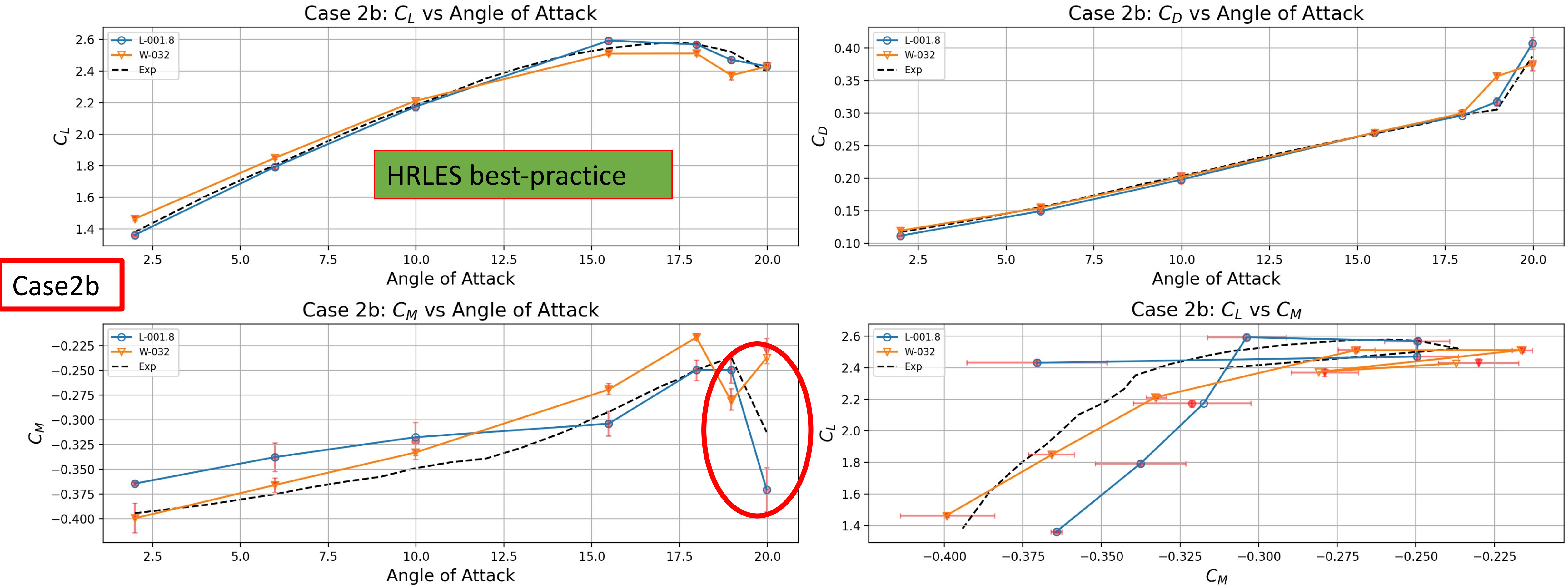


- RANS still shows much larger separation outboard (cut H)
- Now you see RANS over-predict inboard separation (cut C,B) but better for cut A
- DDES closer on cut A than free-air (was one point which was worse than RANS) but for tunnel, it's much more similar.

- Exp
- L-001.5 RANS
- L-001.8 DDES

Supporting Evidence

KQ 1	Do hybrid RANS-LES methods provide improved accuracy over RANS methods to predict CLmax for the right reason (pre and post CLmax to understand separation process)?



Key Findings / Lessons Learned

KQ 1	Do hybrid RANS-LES methods provide improved accuracy over RANS methods to predict CLmax for the right reason (pre and post CLmax to understand separation process)?

Key Findings / Lessons Learned

- In general, for case2a/2b, HRLES methods offer improved accuracy over RANS, mainly due to less outboard separation at the highest AoA which results in improved lift, drag and moment prediction. Not enough data to conclude on case 1a but limited data suggests HRLES find it challenging.
- Near and beyond Cl_Max this improvement is consistent across a range of flow solvers, mesh topologies and by multiple independent participants
- Improvement is consistent for case2a (free-air) and case2b (wind-tunnel)
- The 'why' has still not been fully addressed i.e., whether the failure of RANS models is the underprediction of the turbulent shear-stress or some failure to capture larger-scale unsteady effects – further work is needed to answer this important question
- Still need to be careful with correlation to exp. – future full-span exp. tests will help but for now we need some caution.

Key Findings / Lessons Learned

KQ 2	What mesh resolution/type is required to achieve this accuracy and what is the sensitivity?

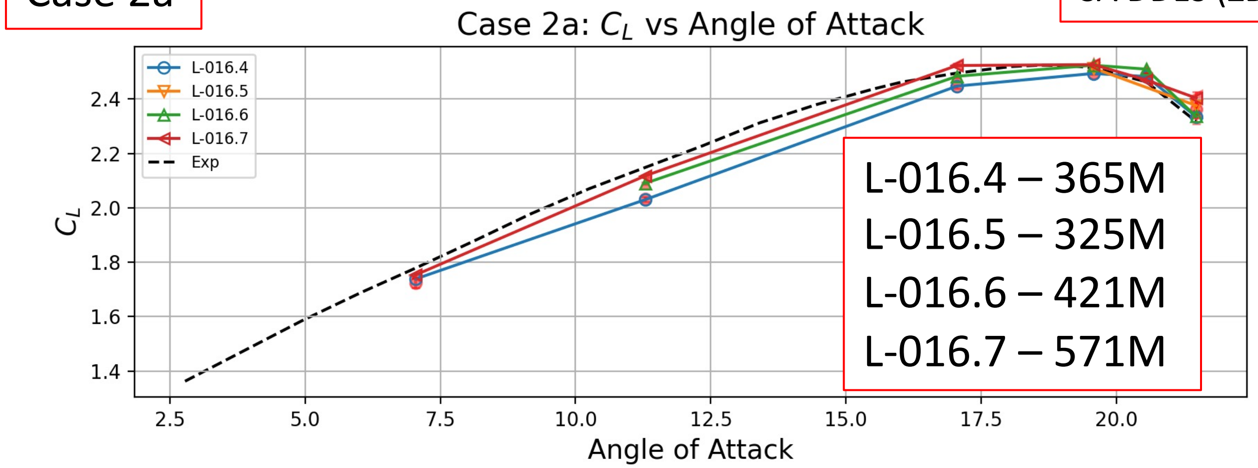
Key Findings / Lessons Learned
• Grid design that leads to RANS mesh convergence does not lead to HRLES mesh convergence
• Increased resolution of separated-flow regions significantly improves HRLES predictions
• Outboard separation shows the clearest trend of coarse HRLES moving to RANS-like flow physics
• Best-practices grids were 280M-550M. However majority used y+~1 but one group didn't. Major question remains around use of wall-functions to reduce the mesh count but assuming y+~1, a cell count >200M seems to be required.

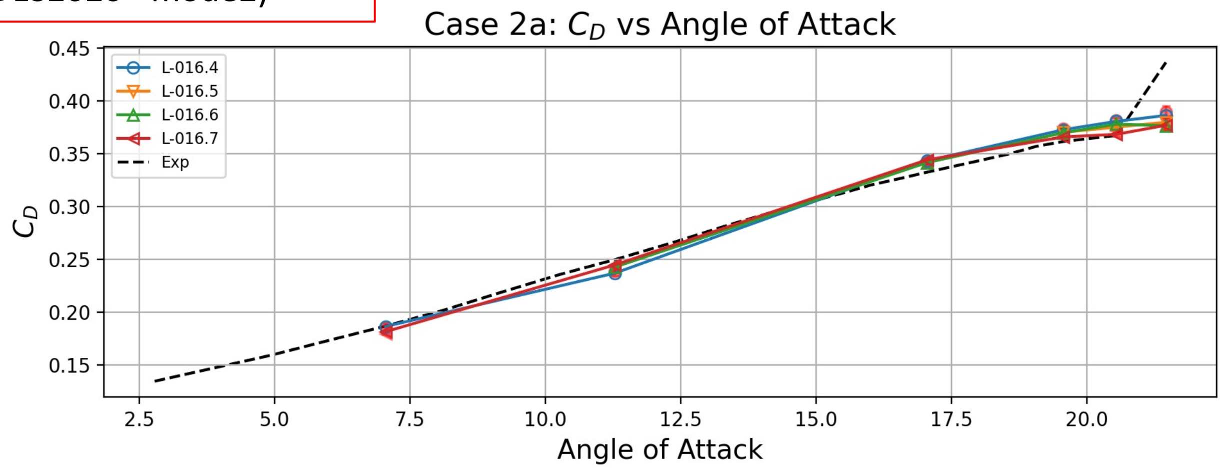
Supporting Evidence

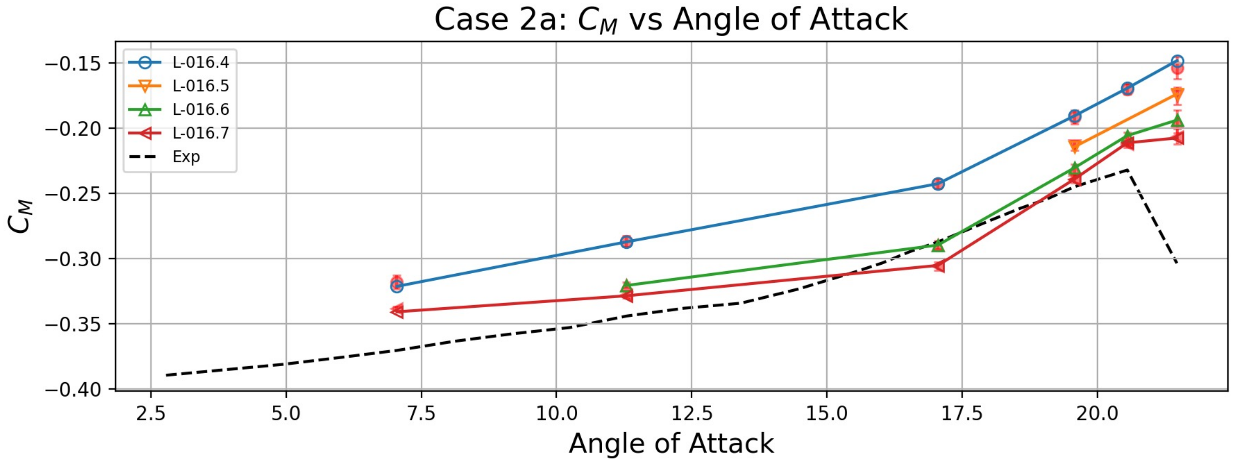
KQ 2	What mesh resolution/type is required to achieve this accuracy and what is the sensitivity?

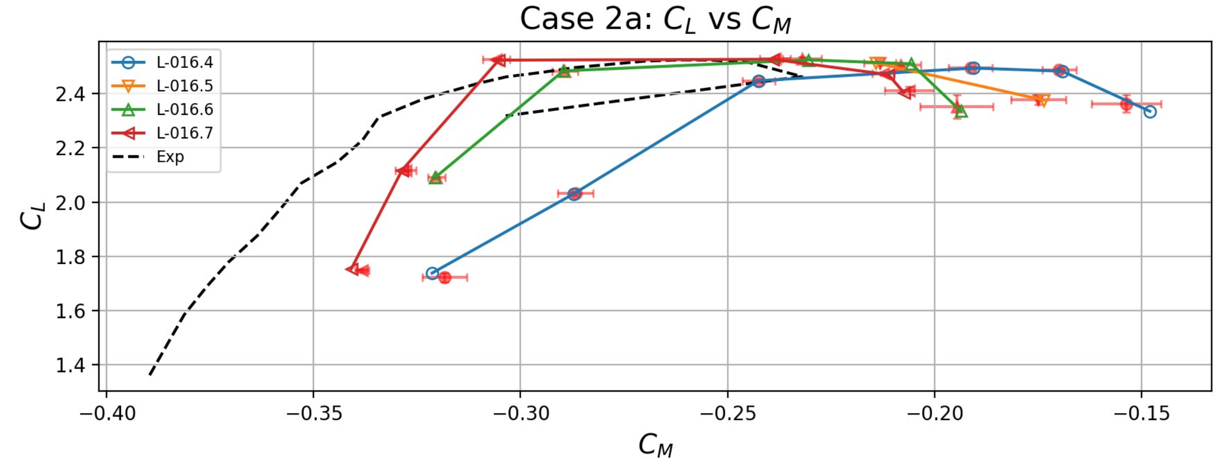
Case 2a

SA DDES (ZDES2020 - mode2)





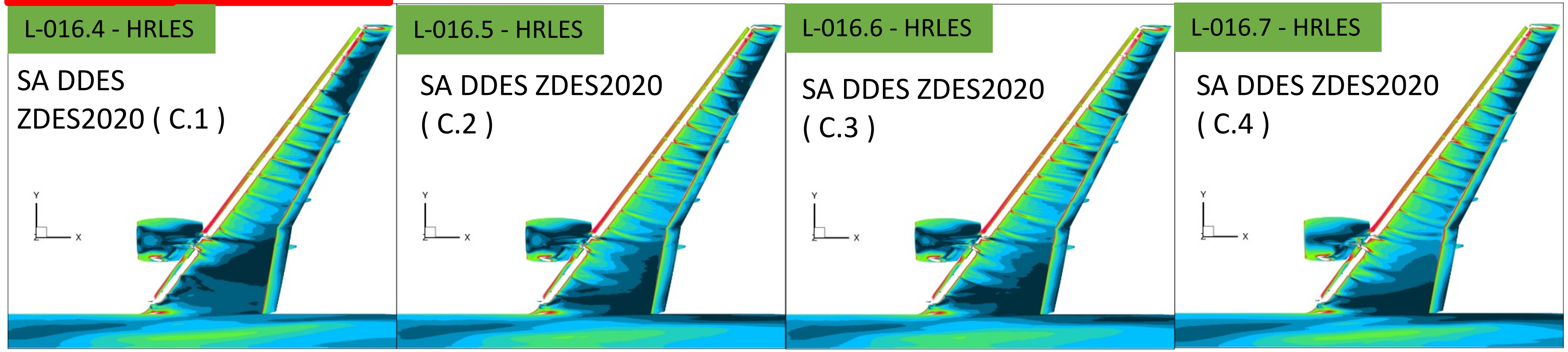




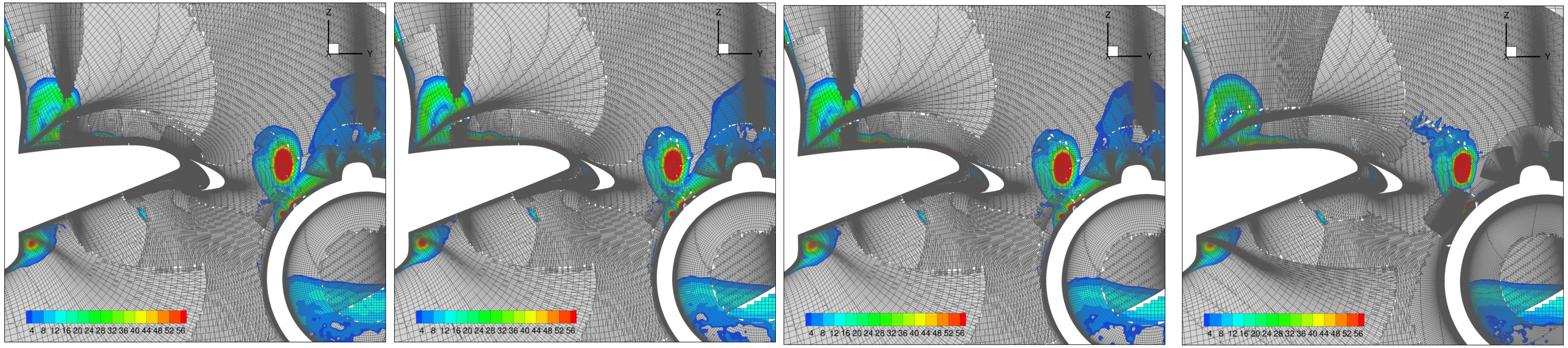
Supporting Evidence

KQ 2	What mesh resolution/type is required to achieve this accuracy and what is the sensitivity?

Case2a	21.57 AoA



365M 325M 421M 571M

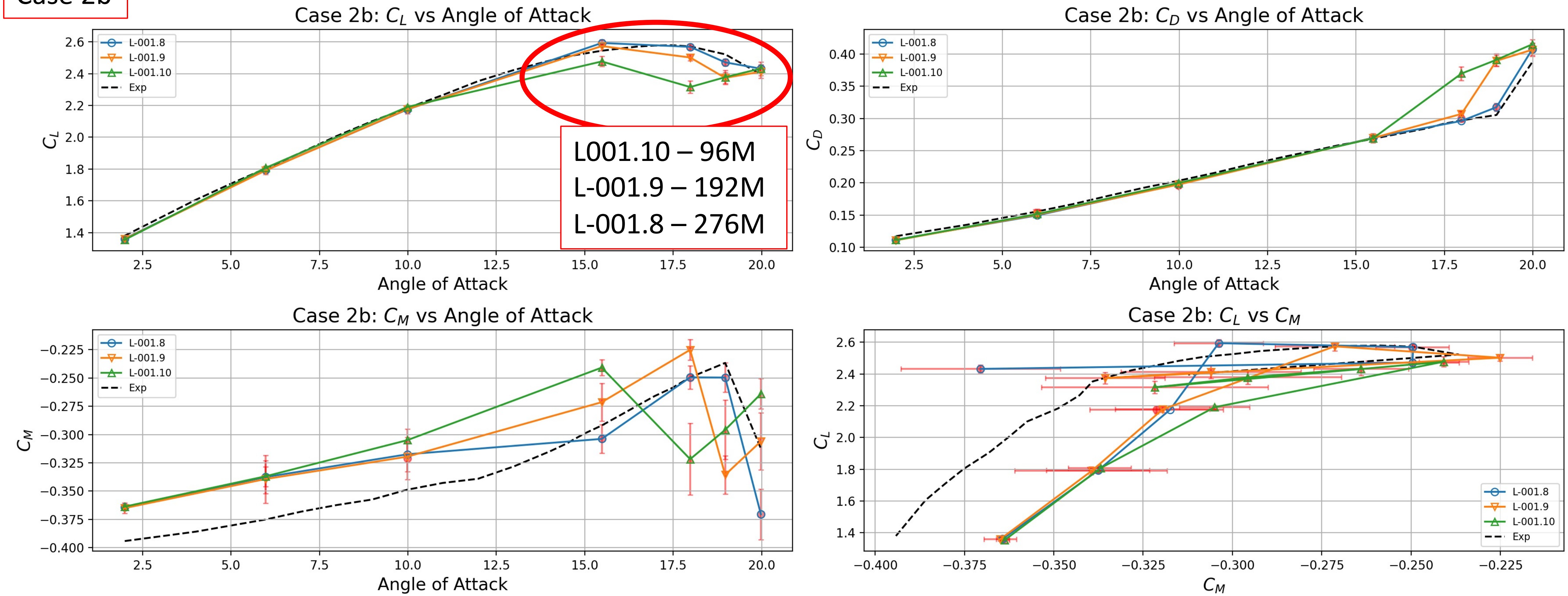


Supporting Evidence

SHAPING THE FUTURE OF AEROSPACE

KQ 2	What mesh resolution/type is required to achieve this accuracy and what is the sensitivity?

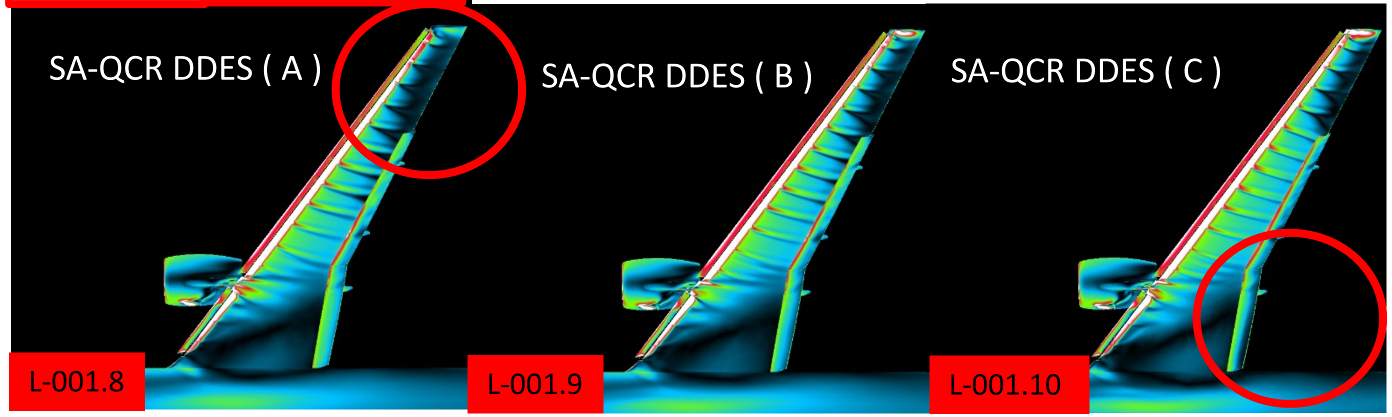
Case 2b

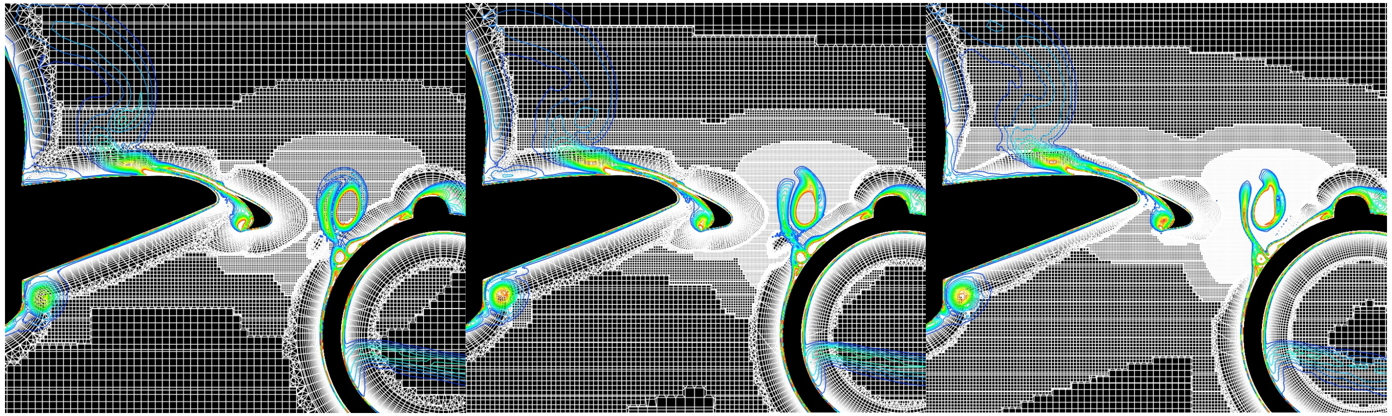


Supporting Evidence

KQ 2	What mesh resolution/type is required to achieve this accuracy and what is the sensitivity?

Case2b | 19.98 AoA



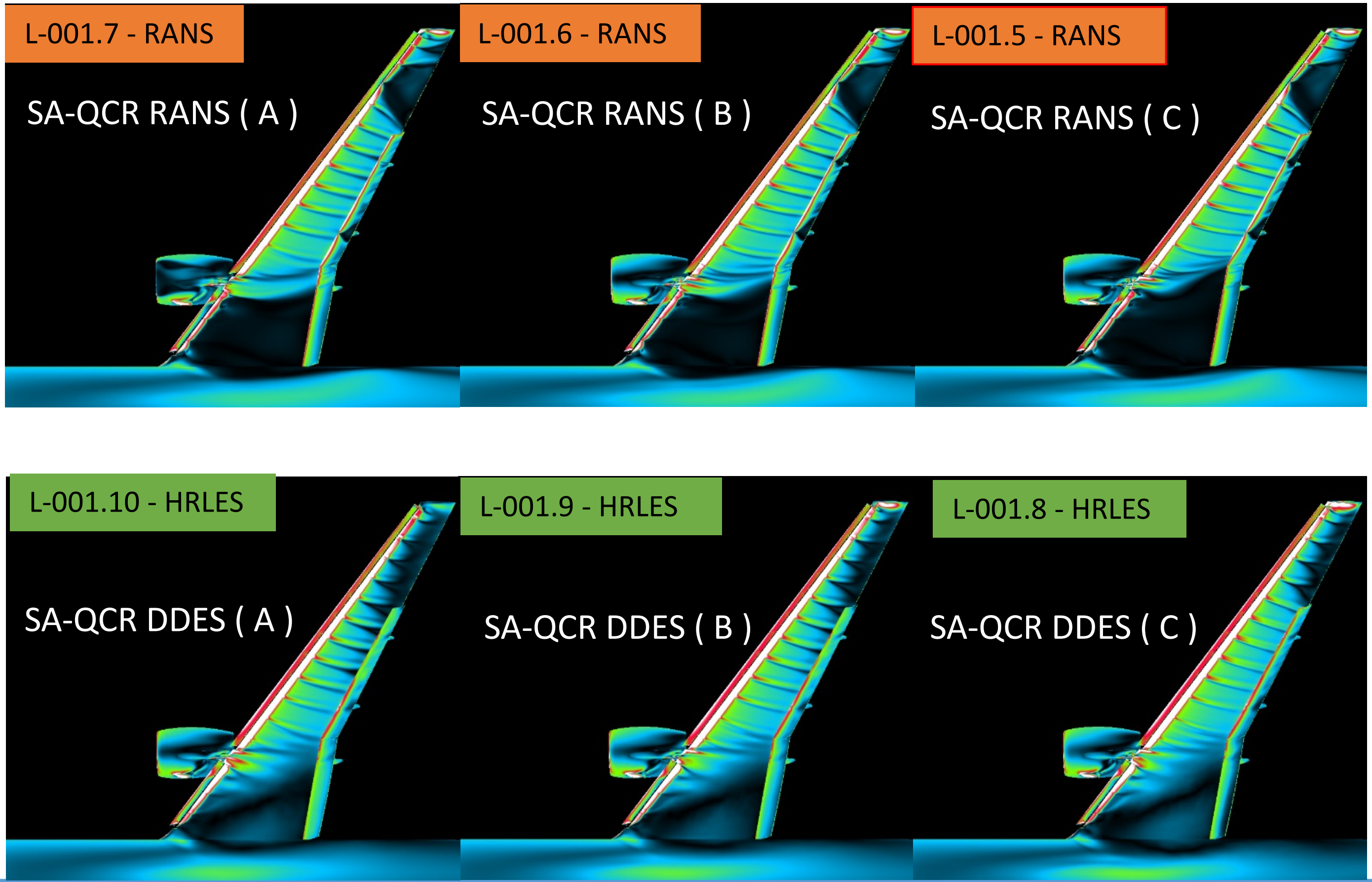


- For DDES, there is a noticeable change in the outboard separation from Mesh A to C and also increase inboard flap separation.

Supporting Evidence

KQ 2	What mesh resolution/type is required to achieve this accuracy and what is the sensitivity?

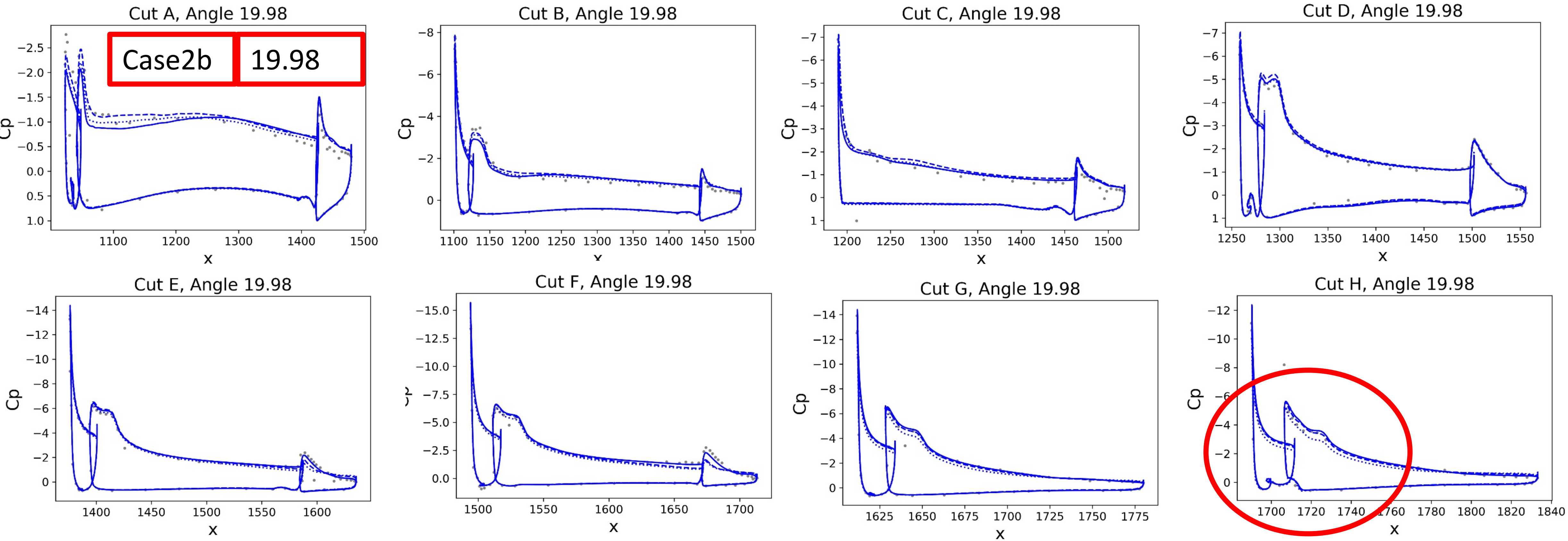
Case2b | 19.98 AoA



- Little difference between RANS for Mesh A-C (96M to 278M)
- For DDES, there is a noticeable change in the outboard separation from Mesh A to C.

Comparison of Grid Size (19.98º)

KQ 2	What mesh resolution/type is required to achieve this accuracy and what is the sensitivity?



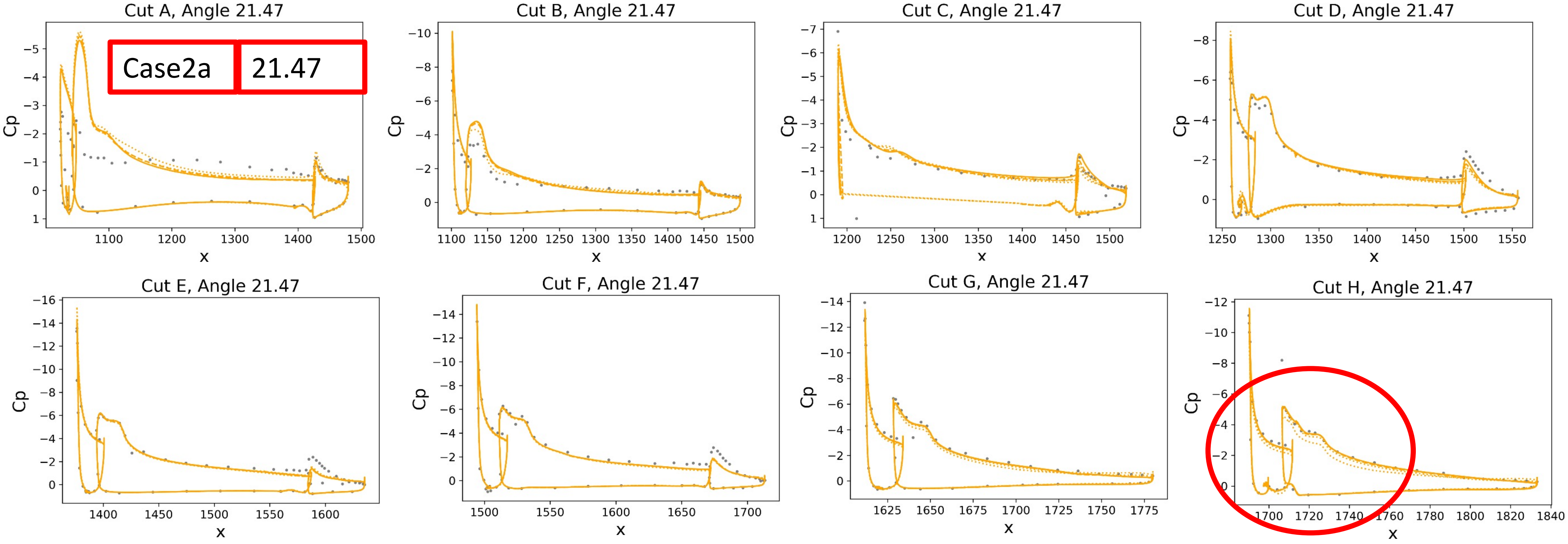
Inboard cut (A) not monotonic
Overall, medium and fine show good agreement except at flap suction peak

- Exp

Dotted – Grid A (coarse) L-001.10
Dashed – Grid B (med) L-001.9
Solid – Grid C (fine) L-001.8

Comparison of Grid Size (21.47º)

KQ 2	What mesh resolution/type is required to achieve this accuracy and what is the sensitivity?



L-016.4-7 DDES

- Exp

Dotted – Grid C.1 Dotted – Grid C.2
Dashed – Grid C.3. Solid – Grid C.4

Key Findings / Lessons Learned

KQ 2	What mesh resolution/type is required to achieve this accuracy and what is the sensitivity?

Key Findings / Lessons Learned
• Grid design that leads to RANS mesh convergence does not lead to HRLES mesh convergence
• Increased resolution of separated-flow regions significantly improves HRLES predictions
• Outboard separation shows the clearest trend of coarse HRLES moving to RANS-like flow physics
• Best-practices grids were 280M-550M. However majority used y+~1 but one group didn’t. Major question remains around use of wall-functions to reduce the mesh count but assuming y+~1, a cell count >200M seems to be required.

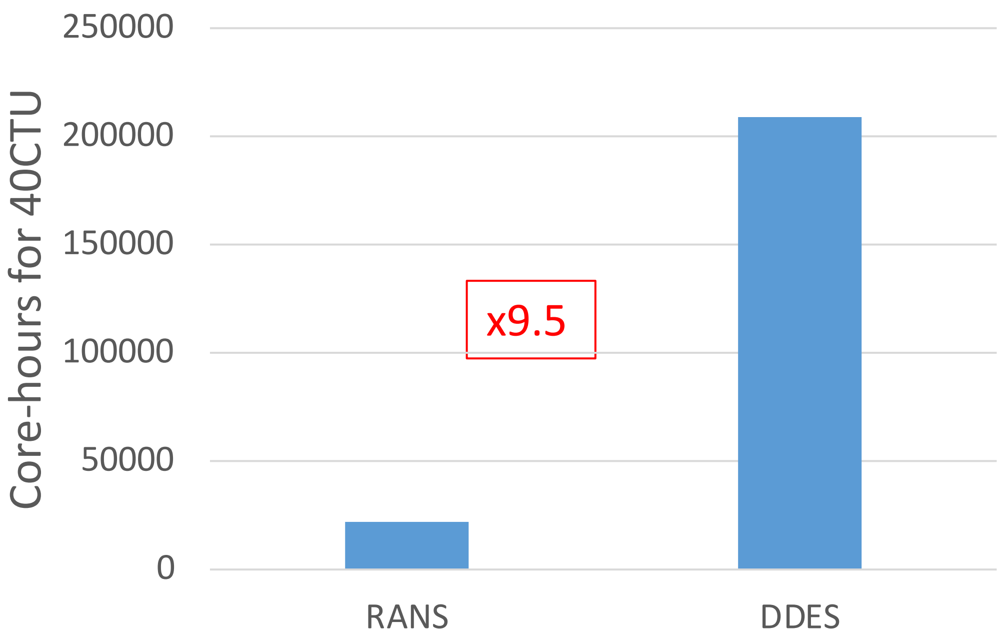
Key Findings / Lessons Learned

KQ 3	What is the HPC cost compared to steady RANS?

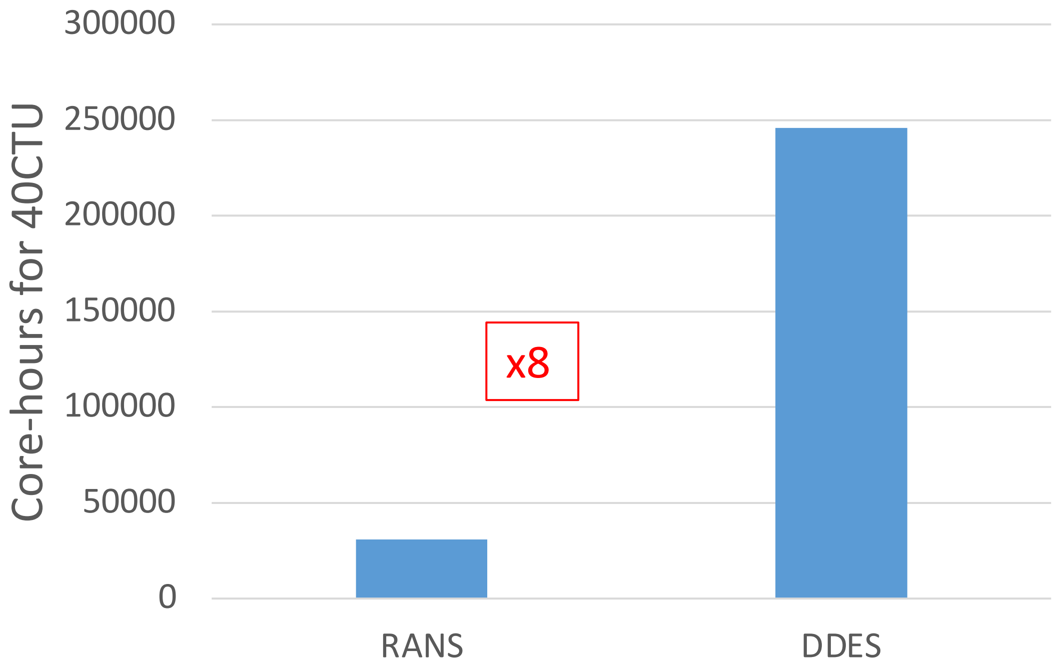
Key Findings / Lessons Learned
• Typically x10-x15 increase in core-hours required per AoA from RANS to HRLES for C-Level Mesh – with exceptions
• ~250,000 core-hours per AoA for C-level mesh i.e., 5-6 days on 2000 cores – with exceptions
• When accounting for the number of cells, computational time for majority of HRLES come together closely, even though HPC optimization has not been a key requirement. There are exceptions.
• Potential to use coarser grid (i.e Mesh B) and still get better accuracy than RANS for only x3.5 more cost than RANS (compared to x11 for DDES)
• Key unknown is the use of wall-functions – all HRLES **except one** were low y+ , but we know the potential of wall-functions from WMLES group. **This could significantly lower computational cost**
• Given that HRLES are very promising, more work is needed to now focus on computational efficiency to improve turn-around time

Supporting Evidence

KQ 3	What is the HPC cost compared to steady RANS?



2nd order unstructured – 276M cells

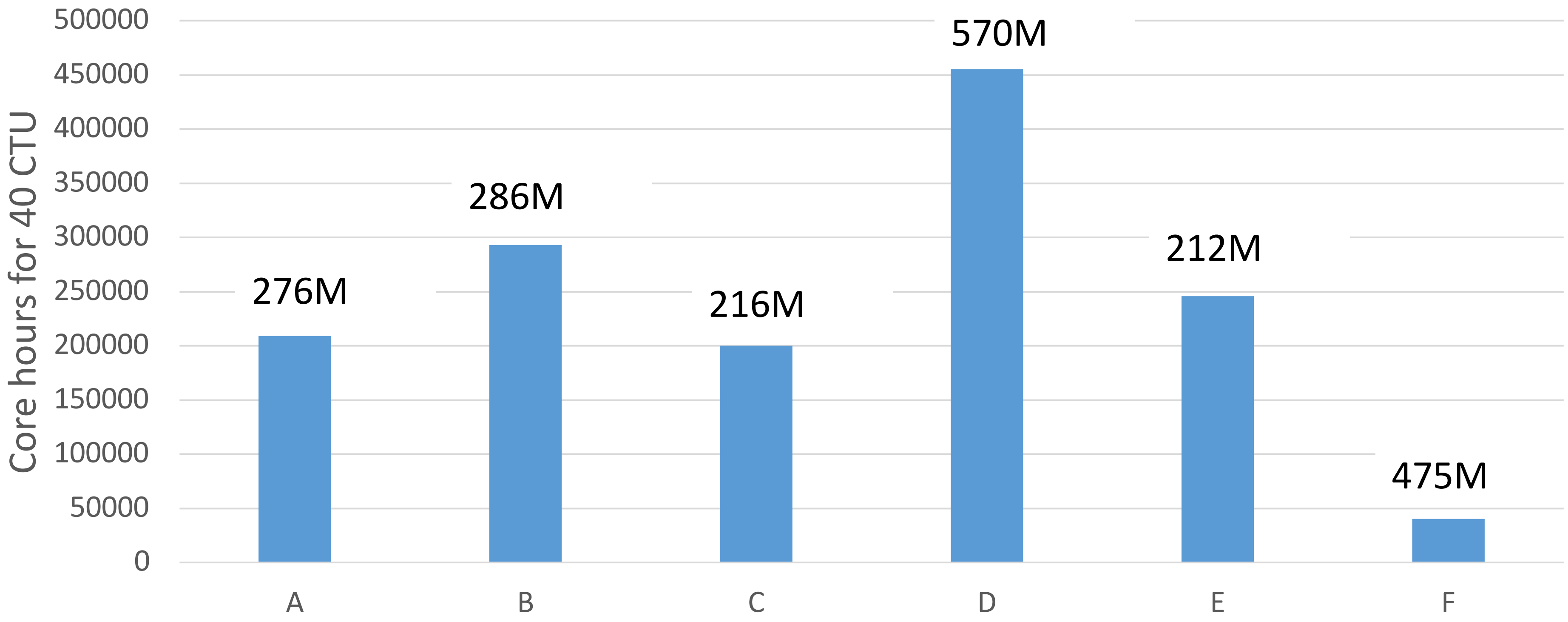


2nd order unstructured – 212M cells

Case 2a	40 CTU for HRLES

Supporting Evidence

KQ 3	What is the HPC cost compared to steady RANS?

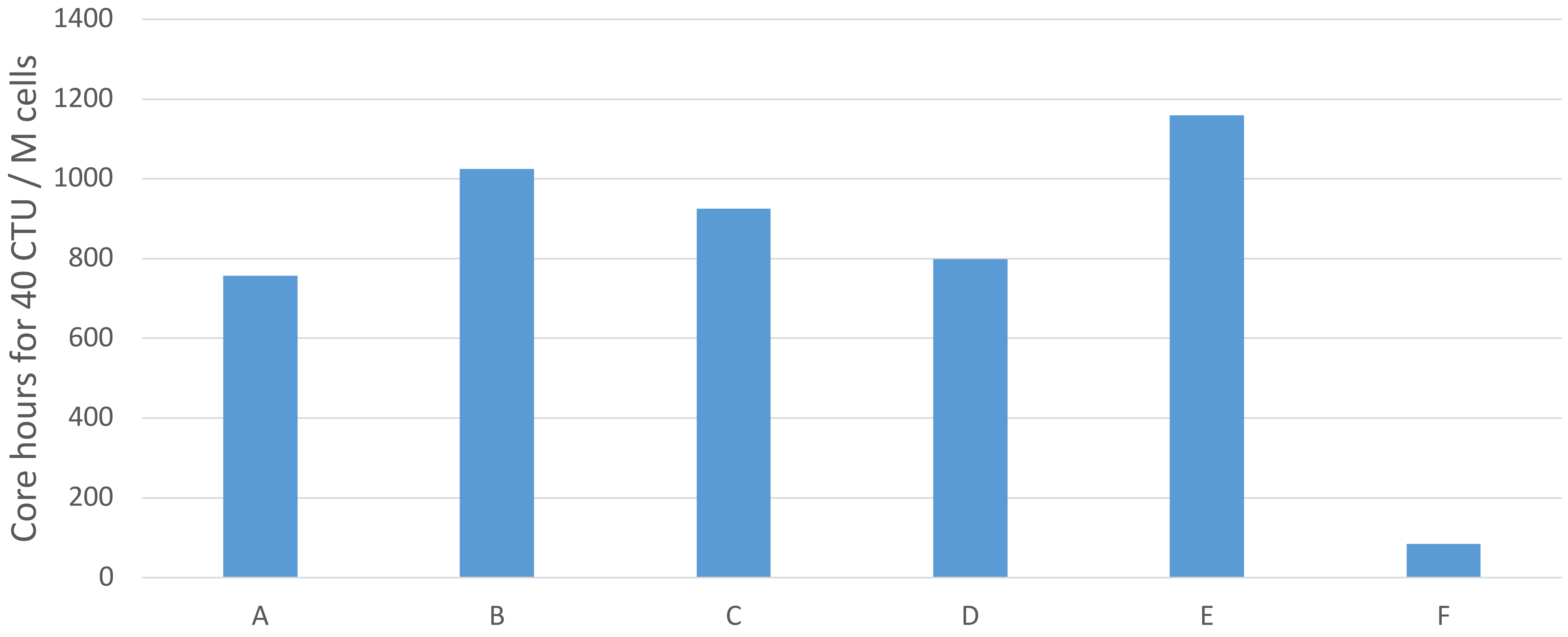


Case 2a	40 CTU for HRLES

Majority of results were not optimized for HPC performance

Supporting Evidence

KQ 3	What is the HPC cost compared to steady RANS?

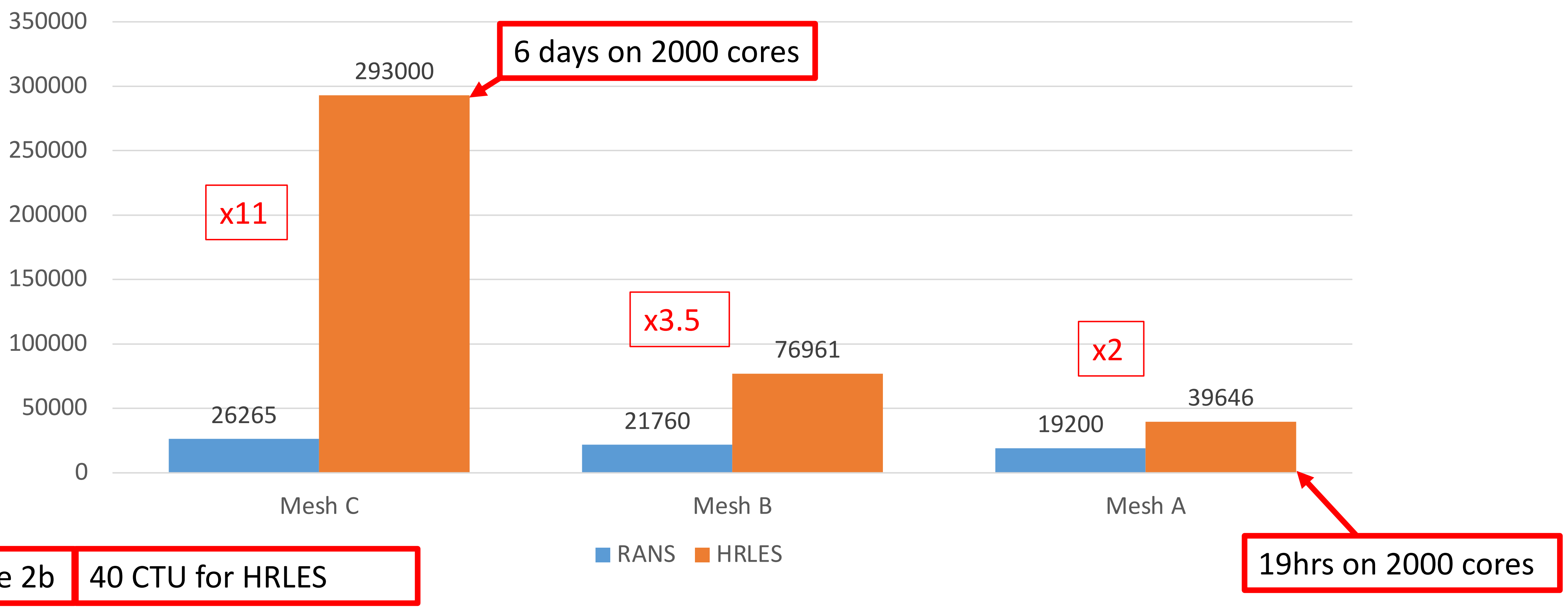


Case 2a	Divide by M cells

Majority need ~2000 cores for 5 days **per AoA – clear need for larger HPC**

Supporting Evidence

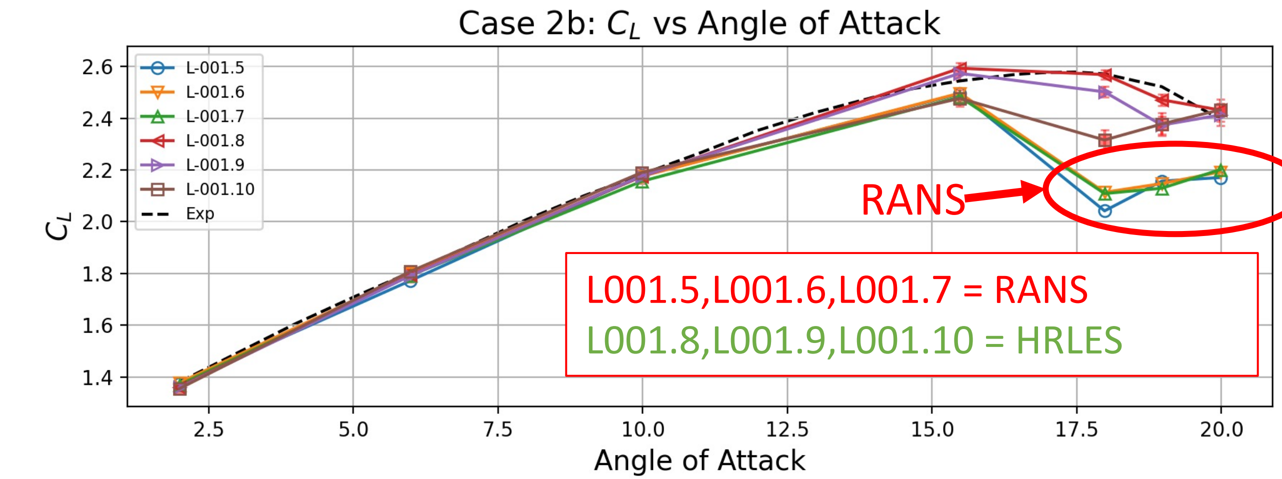
KQ 3	What is the HPC cost compared to steady RANS?

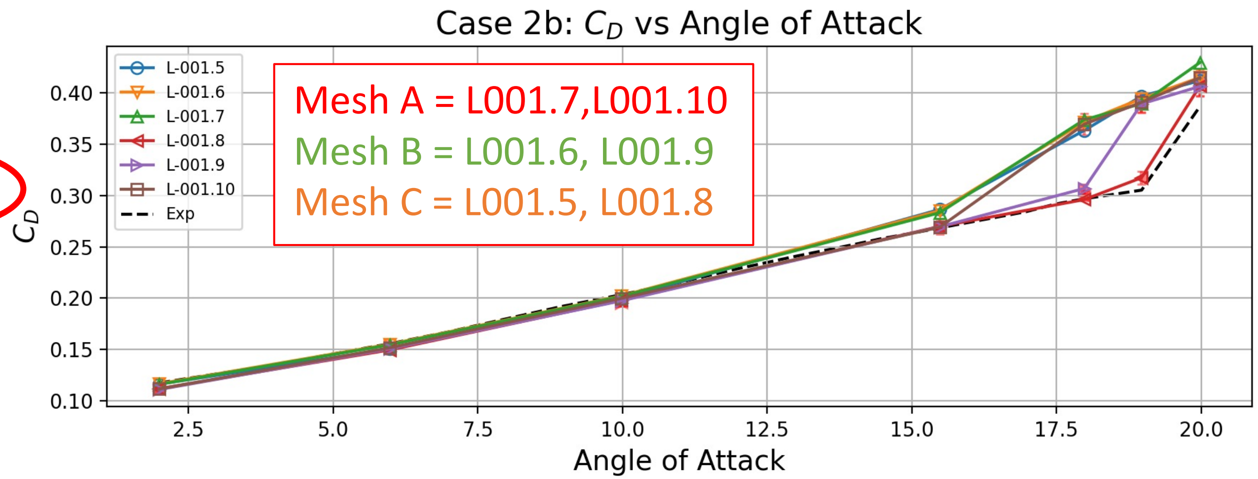


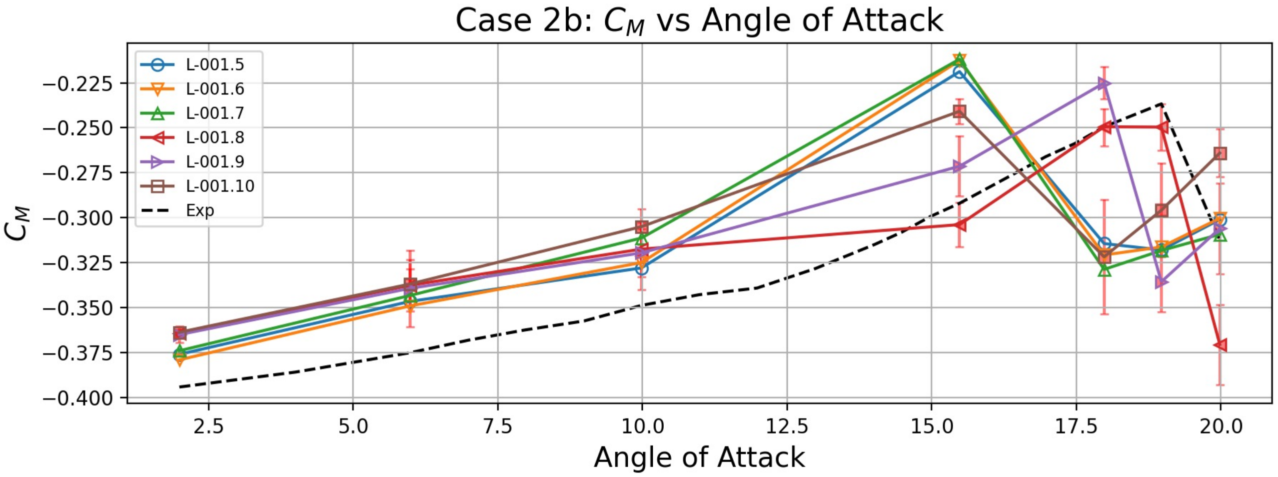
Case 2b	40 CTU for HRLES

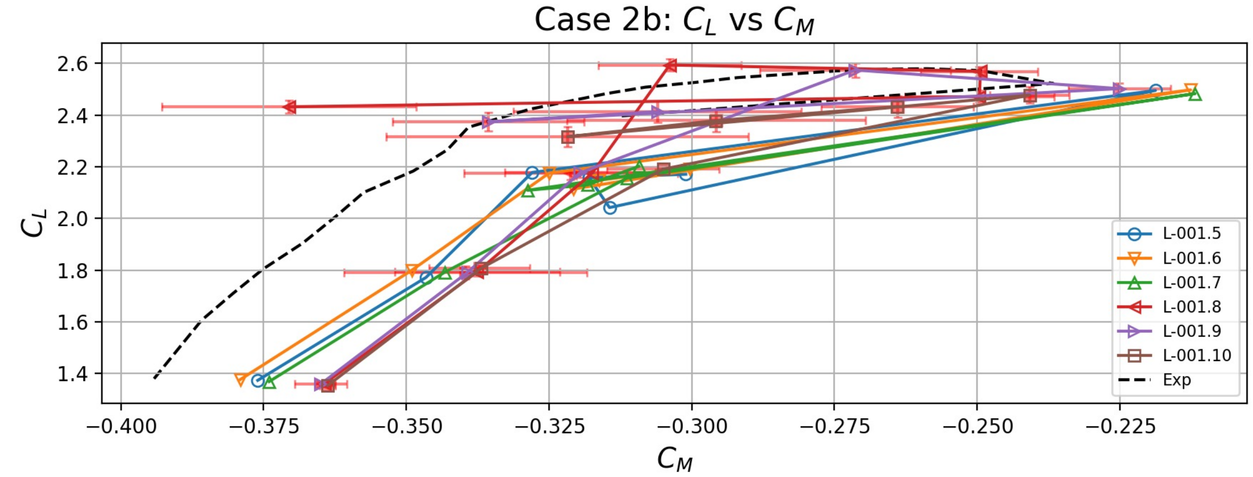
Supporting Evidence

KQ 3	What is the HPC cost compared to steady RANS?









Key Findings / Lessons Learned

KQ 3	What is the HPC cost compared to steady RANS?

Key Findings / Lessons Learned
• Typically x10-x15 increase in core-hours required per AoA from RANS to HRLES for C-Level Mesh – with exceptions
• ~250,000 core-hours per AoA for C-level mesh i.e., 5-6 days on 2000 cores – with exceptions
• When according for the number of cells, the computational time for majority of HRLES come together closely, even though HPC optimization has not been a key requirement
• Potential to use coarser grid (i.e Mesh B) and still get better accuracy than RANS for only x3.5 more cost than RANS (compared to x11 for DDES)
• Key unknown is the use of wall-functions – all HRLES **except one** were low y+ , but we know the potential of wall-functions from WMLES group. **This could significantly lower computational cost**
• Given that HRLES are very promising, more work is needed to now focus on computational efficiency to improve turn-around time

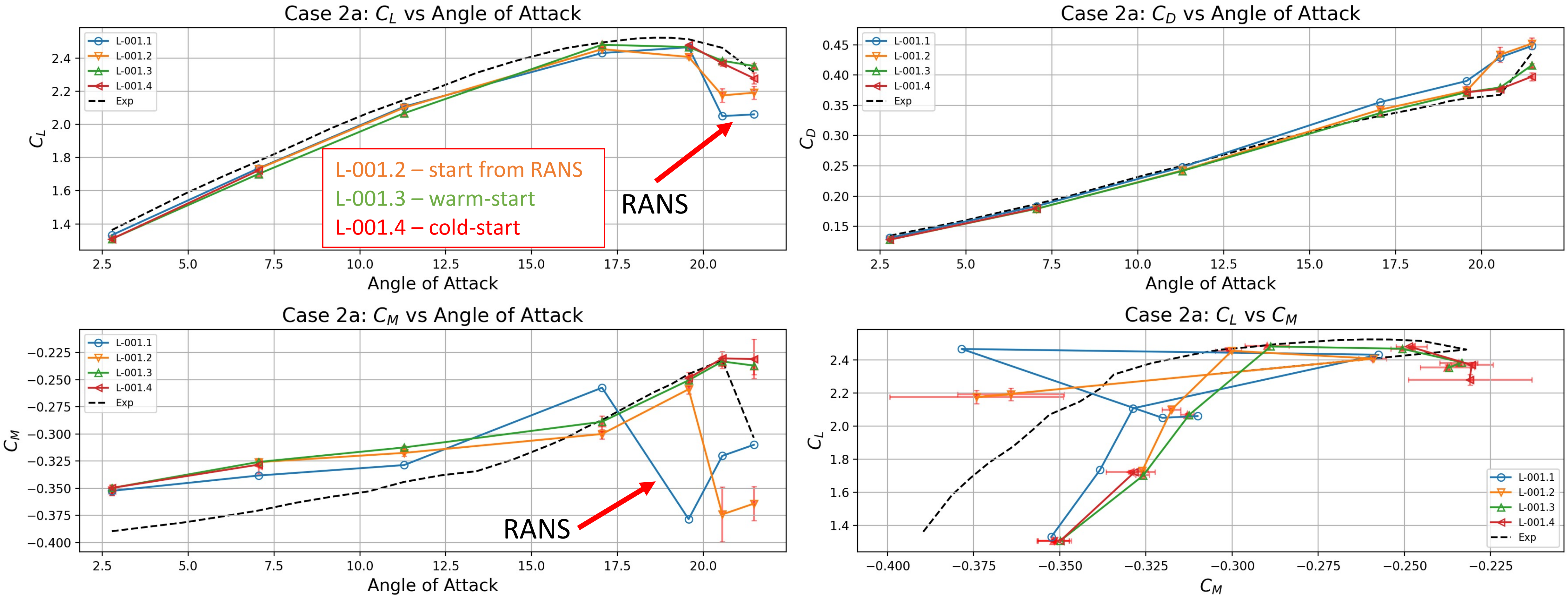
Key Findings / Lessons Learned

KQ 4	Best-Practices to achieve alpha sweeps for hybrid RANS-LES (i.e., address hysteresis and bifurcation)

Key Findings / Lessons Learned
• Common means of starting HRLES is to restart from a steady RANS solution – some evidence that this isn't optimal here
• RANS models often exhibit early stall
• Restart from stalled-RANS solution perpetuates the stall branch (if not indefinitely, then for too long for practical run times)
• Both cold-start and warm start (rotating from prior AoA) found to be superior to restart-from-RANS

Supporting Evidence

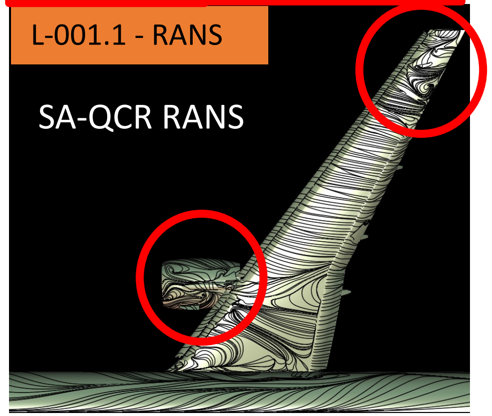
KQ 4 | **Best-Practices to achieve alpha sweeps for hybrid RANS-LES (i.e., address hysteresis and bifurcation)**

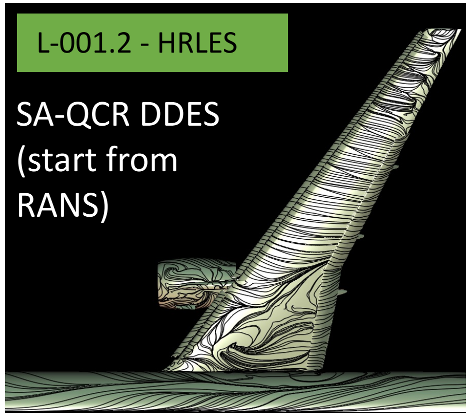


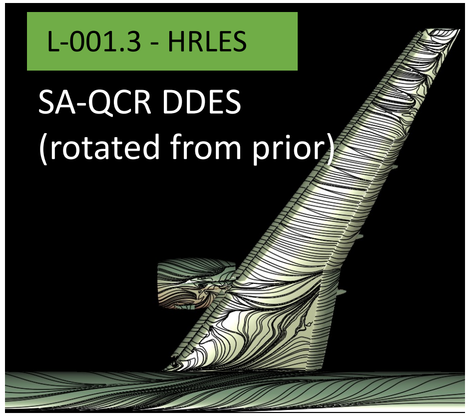
Supporting Evidence

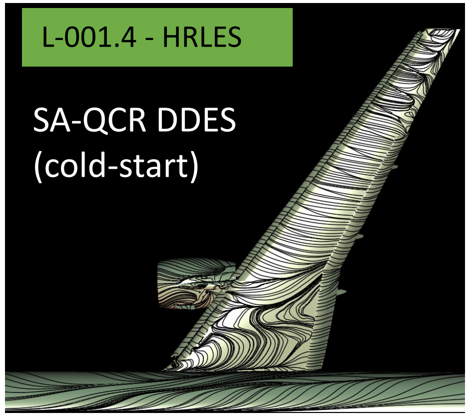
KQ 4	Best-Practices to achieve alpha sweeps for hybrid RANS-LES (i.e., address hysteresis and bifurcation)

Case2a | 21.47 AoA

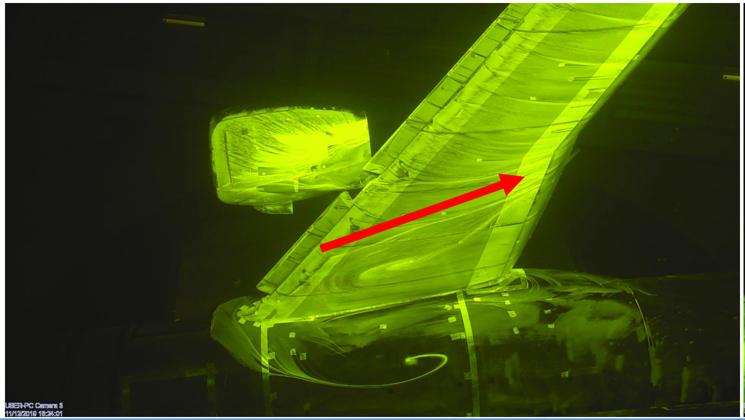


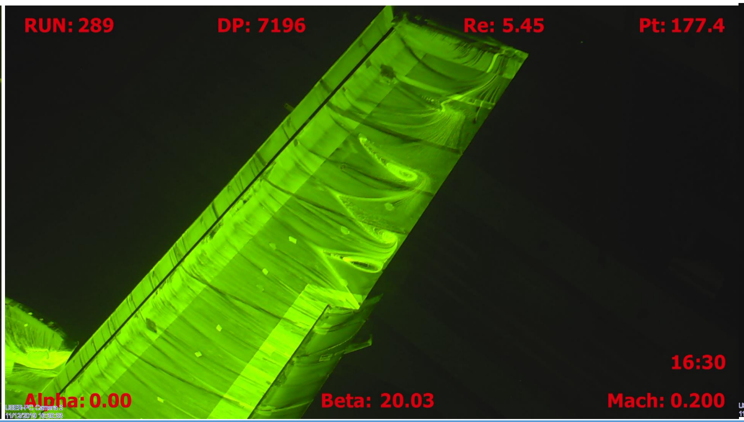


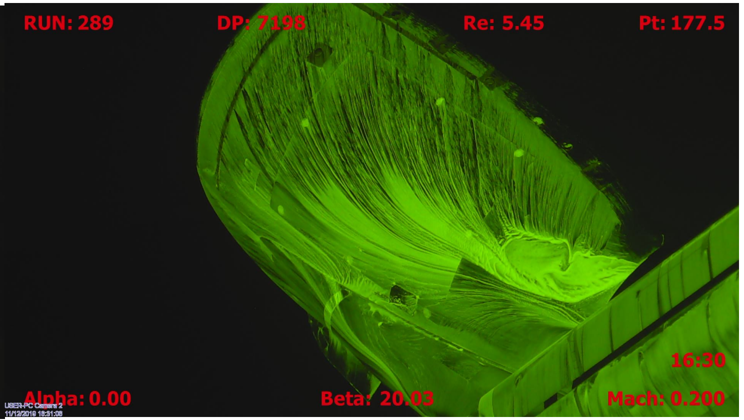




Further analysis required







Key Findings / Lessons Learned

KQ 5	**Best-Practices to achieve statistical convergence for Hybrid RANS-LES simulations (e.g., total time-averaging period and point of time-averaging start)**

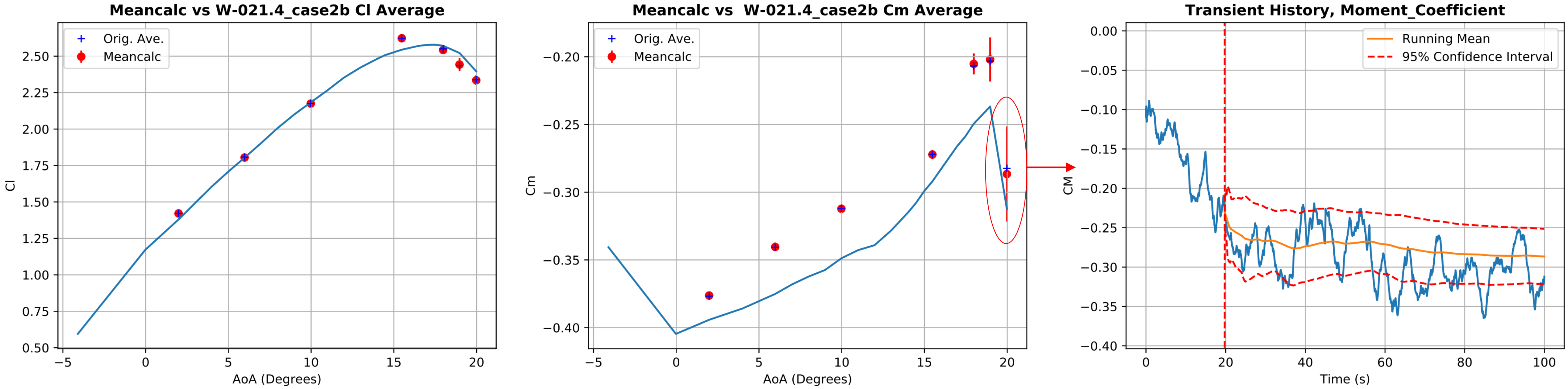
Key Findings / Lessons Learned
• 40 convective time units (CTU’s) are typically sufficient for all AoAs
• Smaller AoA solutions generally require less CTUs
• Producing tight confidence intervals on the running moment averages requires more CTUs than those for Cl or Cd

Supporting Evidence

SHAPING THE FUTURE OF AEROSPACE

KQ 5	Best-Practices to achieve statistical convergence for Hybrid RANS-LES simulations (e.g., total time-averaging period and point of time-averaging start)

- Most contributions in HRLES and WMLES TFGs show good agreement between submitted force data and meancalc-computed averages via submitted iterative data. Example:

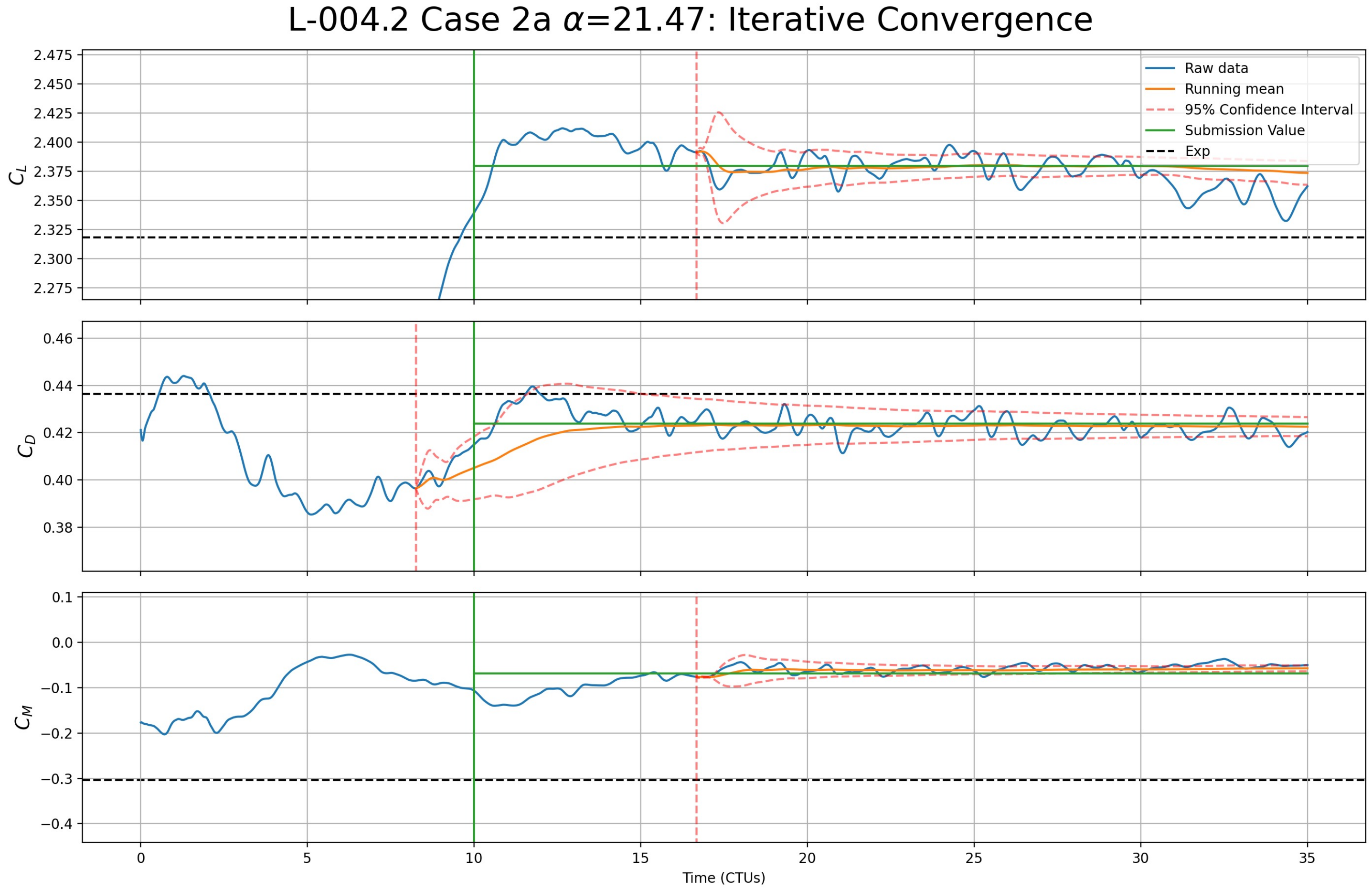


- C. Mockett, T. Knacke and F. Thiele, *Detection of Initial Transient and Estimation of Statistical Error in Time-Resolved Turbulent Flow Data*, 8th International Symposium on Engineering Turbulence Modelling and Measurements - ETMM8, Marseille, France, 2010

Supporting Evidence

KQ 5	Best-Practices to achieve statistical convergence for Hybrid RANS-LES simulations (e.g., total time-averaging period and point of time-averaging start)

Averaging window selected automatically in meancalc – t_0 generally different for each force component



Key Findings / Lessons Learned

KQ 6	Influence of the wind-tunnel on the simulation accuracy

Key Findings / Lessons Learned

- Approach flow is not uniform/parallel across the tunnel
- Thick boundary layer on tunnel walls creates horseshoe vortex as it impinges on model and stand-off
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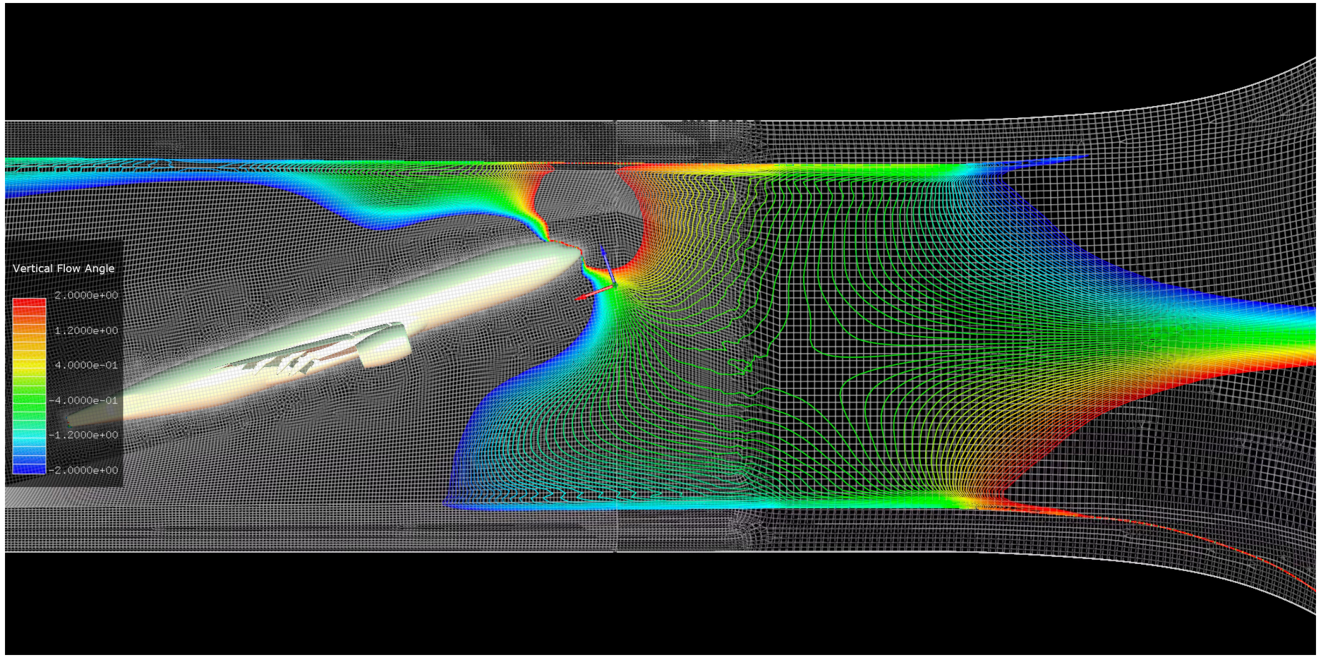
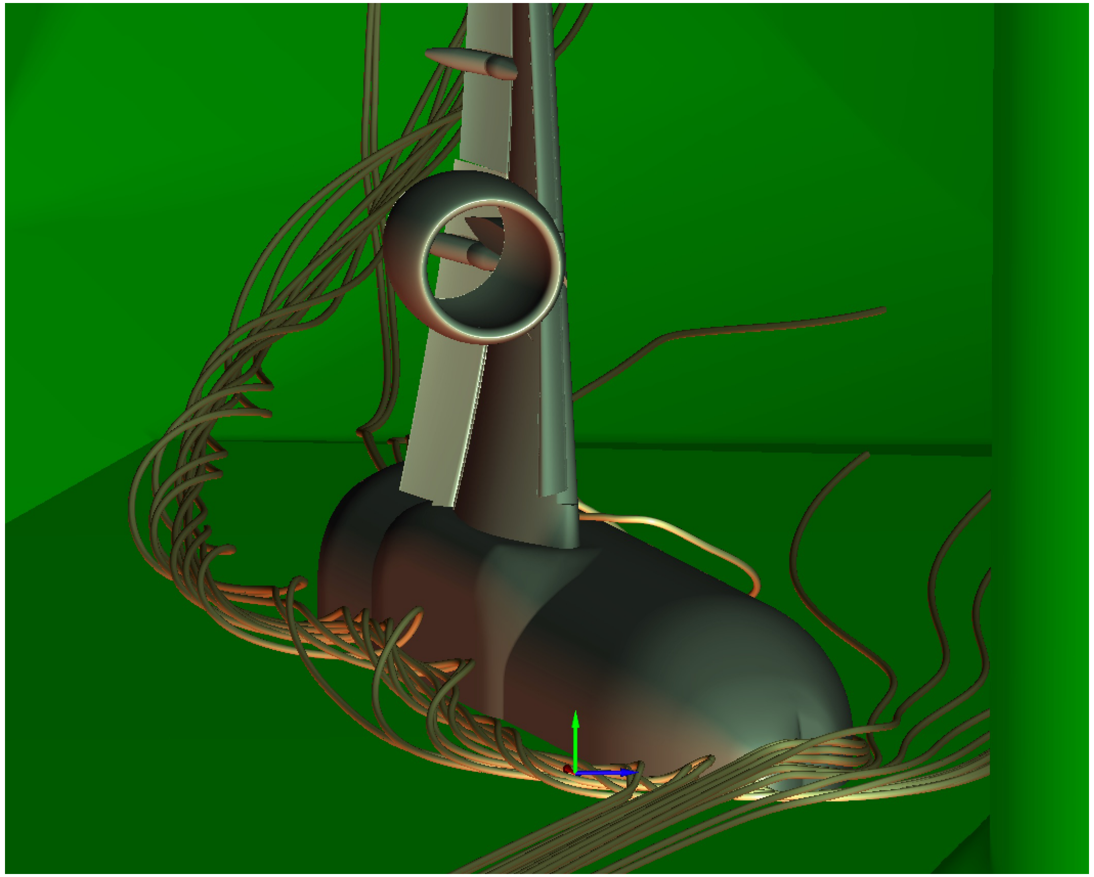
Key Findings / Lessons Learned

KQ 6	Influence of the wind-tunnel on the simulation accuracy



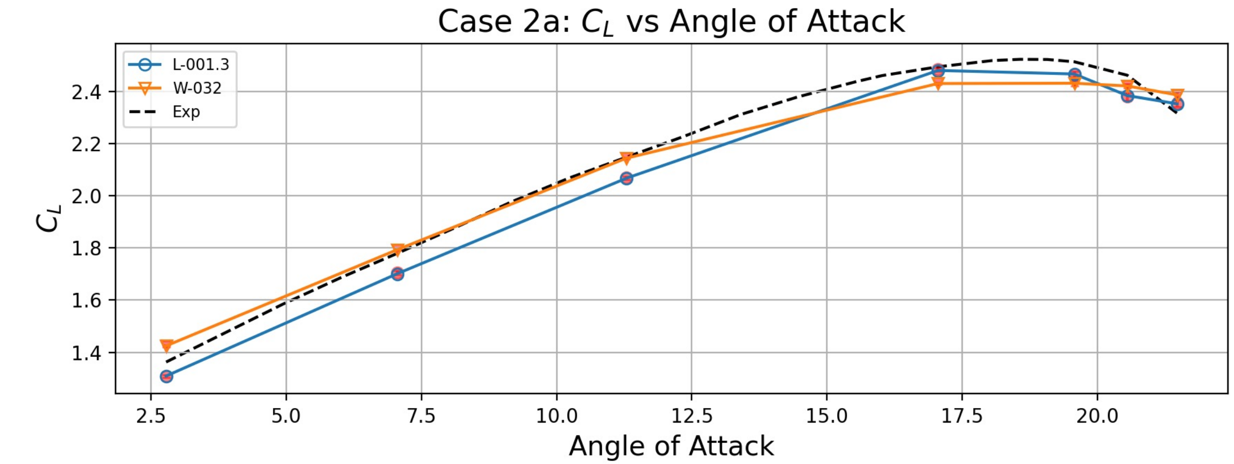


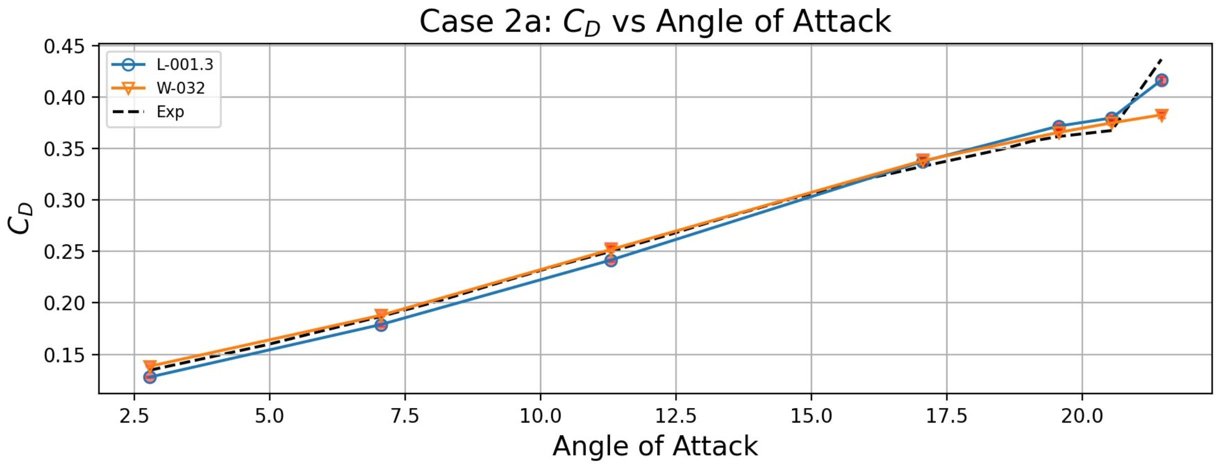
Contours of vertical flow angle (above)

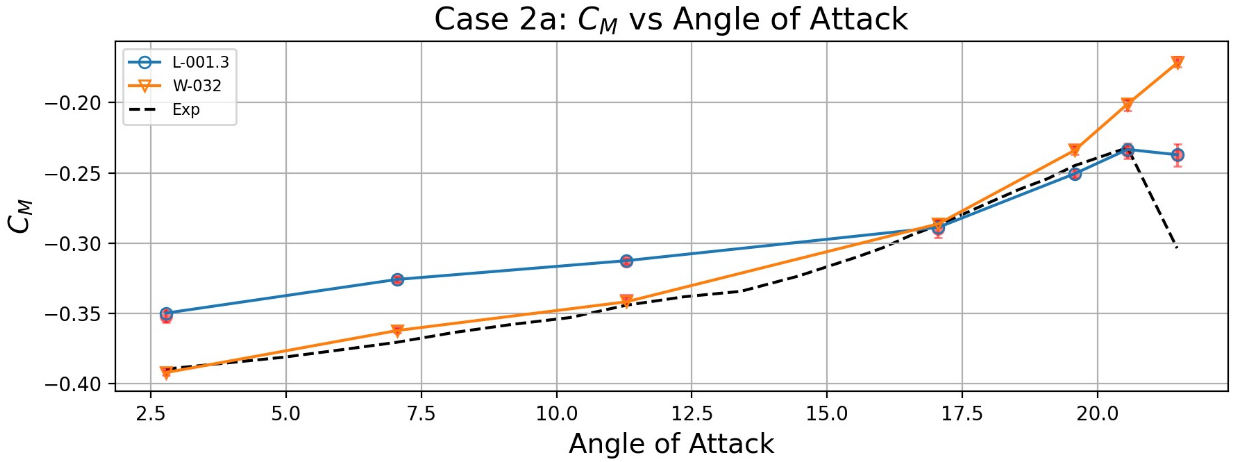
Streamlines approaching model leading edge (right)

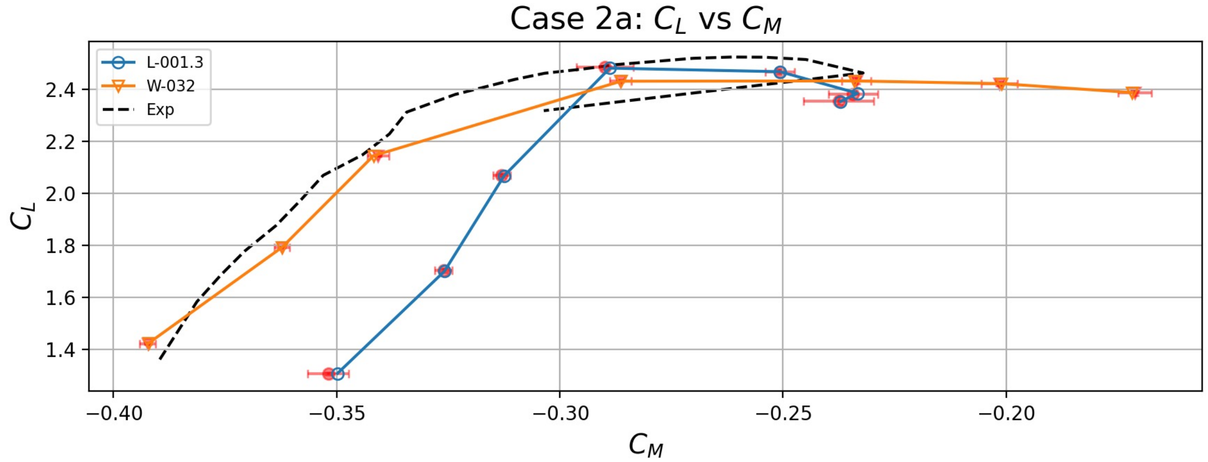
Supporting Evidence

KQ 6	Influence of the wind-tunnel on the simulation accuracy



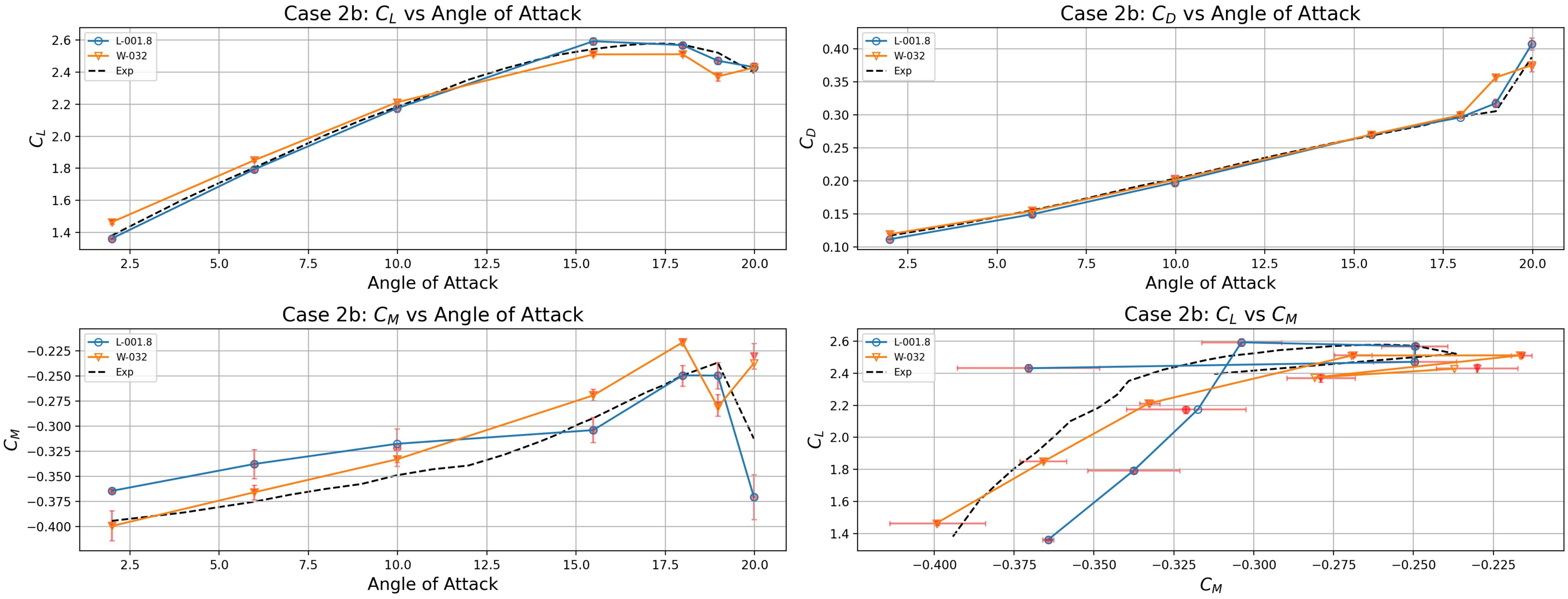






Supporting Evidence

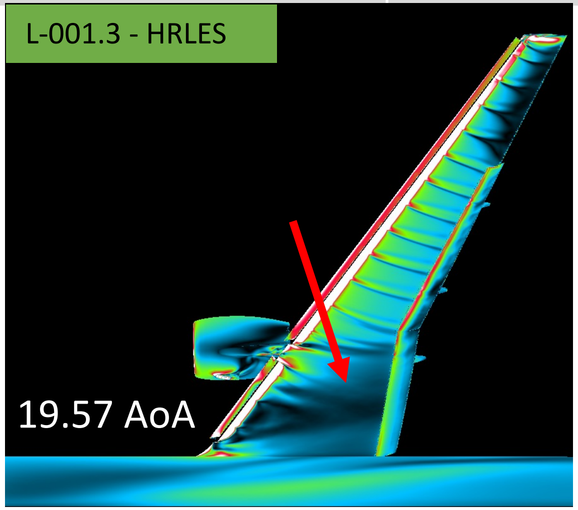
KQ 6	Influence of the wind-tunnel on the simulation accuracy

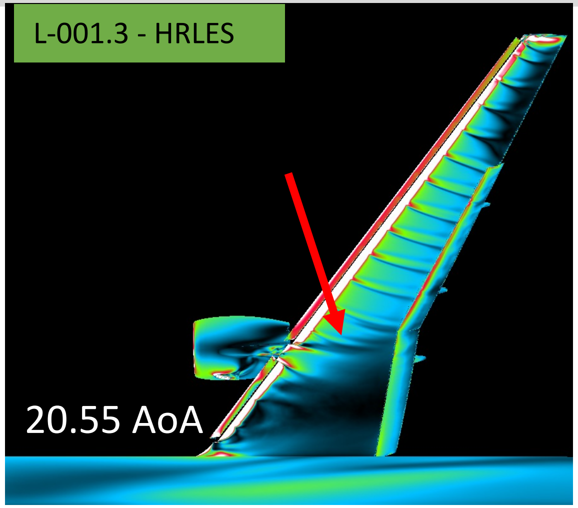


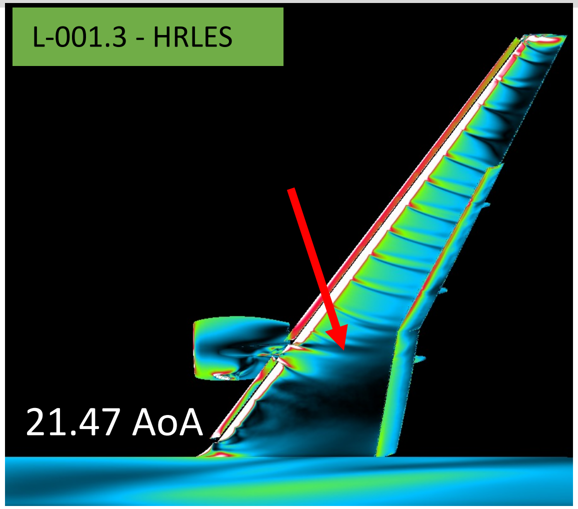
Supporting Evidence

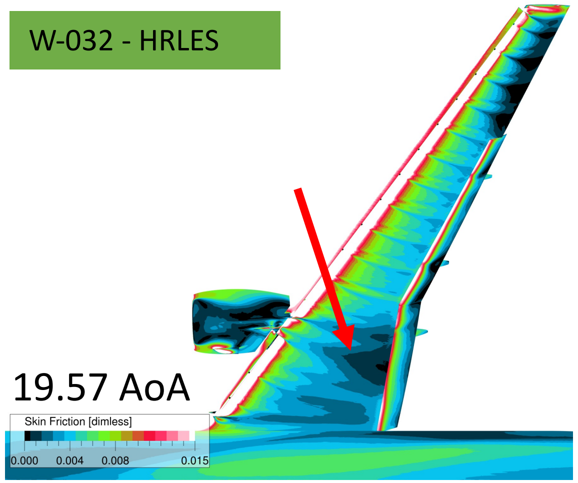
Case 2a – free-air

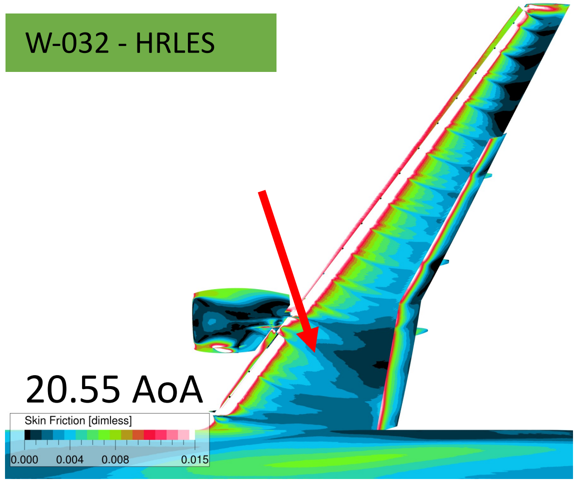
KQ 6	Influence of the wind-tunnel on the simulation accuracy

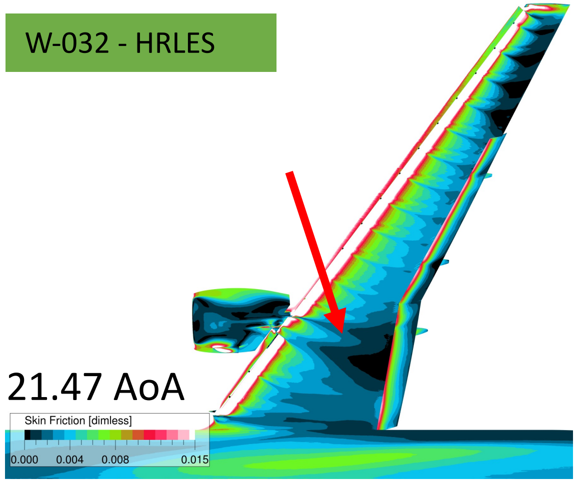








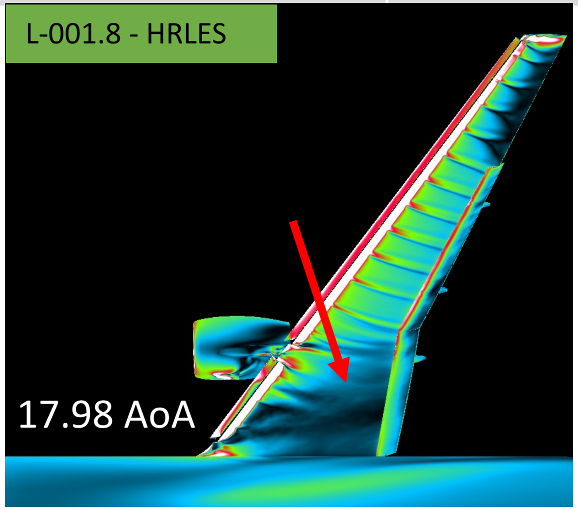


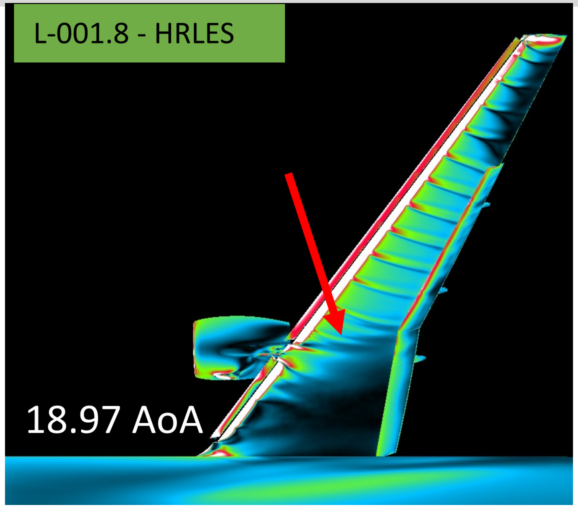


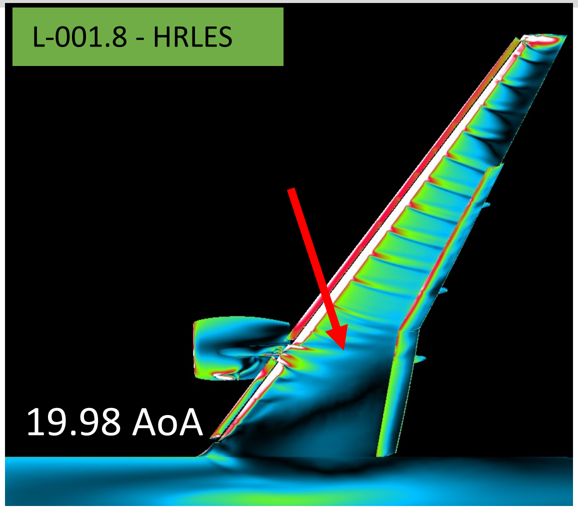
Supporting Evidence

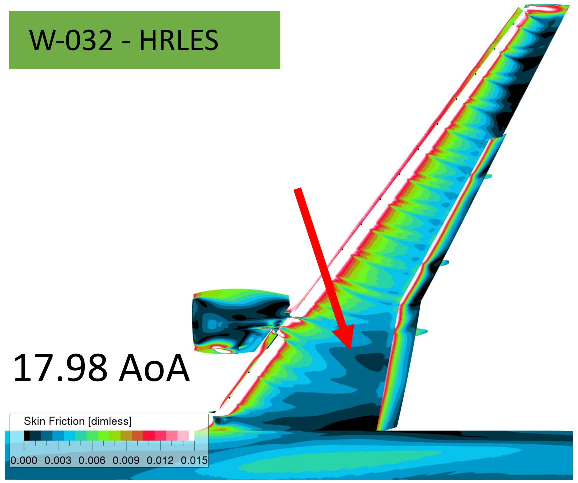
Case 2b – WT

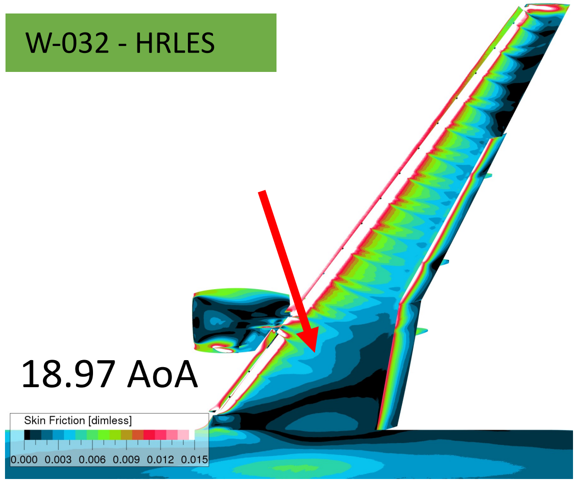
KQ 6	Influence of the wind-tunnel on the simulation accuracy

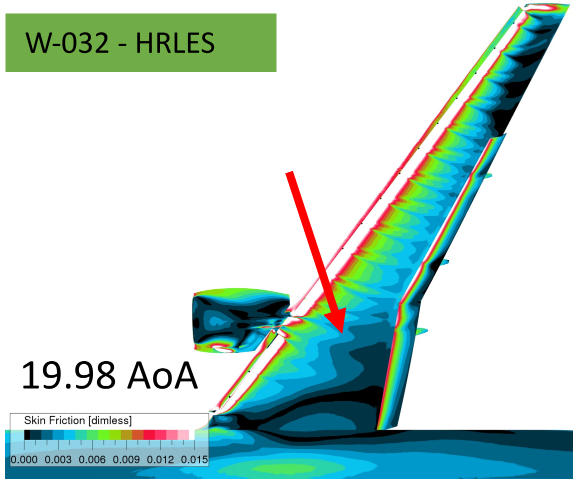






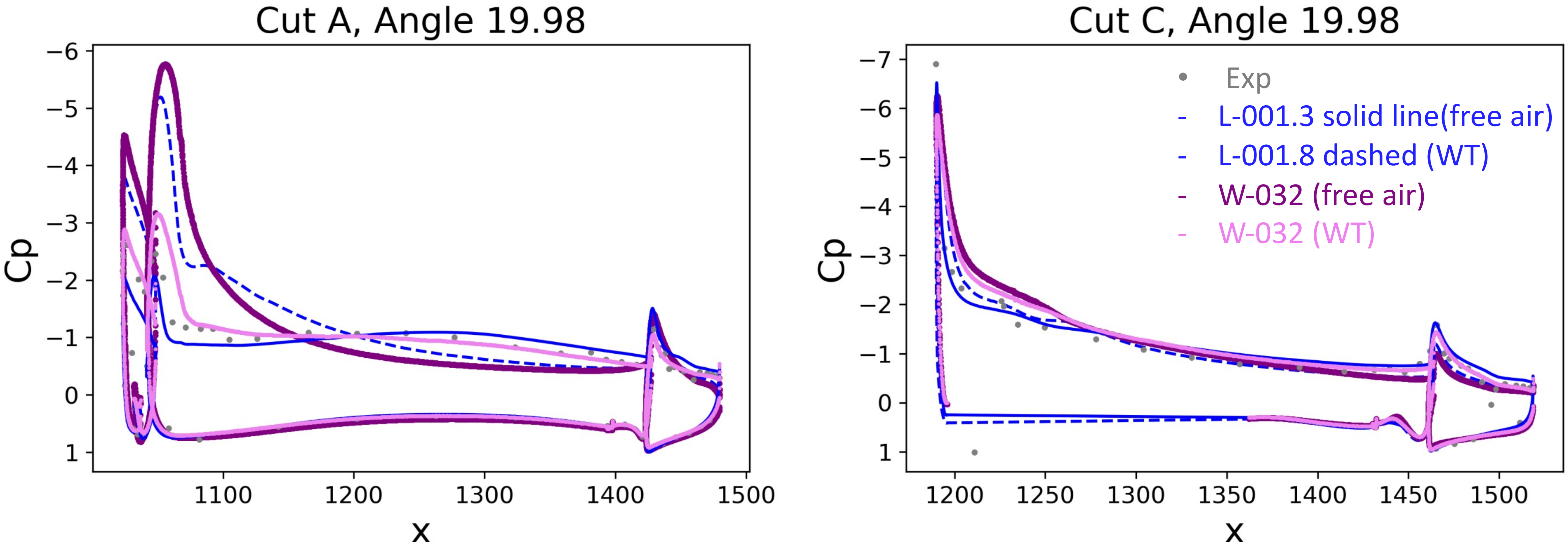






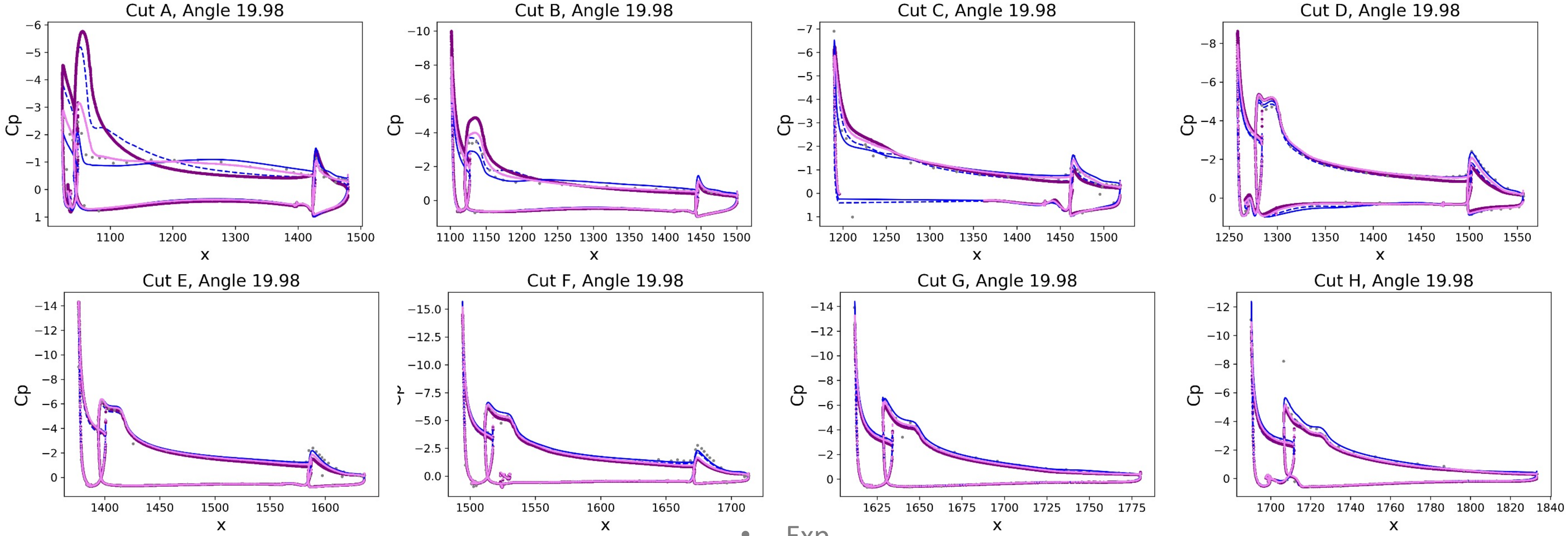
Comparison of Case 2a and 2b (max angle: 19.98º)

KQ 6	Influence of the wind-tunnel on the simulation accuracy



Comparison of Case 2a and 2b (max angle: 19.98º)

KQ 6 | **Influence of the wind-tunnel on the simulation accuracy**



- Exp
- L-001.3 solid line(free air)
- L-001.8 dashed (WT)
- W-032 (free air)
- W-032 (WT)

Key Findings / Lessons Learned

KQ 6	Influence of the wind-tunnel on the simulation accuracy

Key Findings / Lessons Learned
• Approach flow is not uniform/parallel across the tunnel
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Future Plans

- What elements of current KQs need further investigation to answer?
  - Meshing needs to go even finer and even coarser to get a broader idea of best-practices for mesh resolution
  - Need more people to confirm that for these applications, starting from RANS is worse than cold or warm-start
  - More submissions for case2b to better understand the trend and importance of including the WT
  - Much more work on case1a to understand the key sensitivities to capture experimental data
  - More analysis from existing data to identify where the differences are coming from i.e boundary layer profiles
  - Continued work to understand how to more accurately model the WT

Future Plans

- What new KQs are being proposed and why?
  - Sensitivity to the underlying RANS model
  - Influence of numerical dissipation
  - Greater focus on shielding functions and grey-area mitigation
  - Wall-function for HRLES i.e is it beneficial from accuracy and computational cost.
  - HPC i.e benefit of moving to GPUs or dense CPUs
  - Benefit of adaptive approaches to HRLES

Future Plans

- What additional CFD or test data is required for support the KQs?
  - Velocity/Turbulence profiles in shear-layers and upstream BL’s prior to shear-layers
  - PIV to obtain turbulence statistics (or any other method to obtain turbulence statistics)
  - Uncertainty values on all exp. results
  - Specific upstream tunnel conditions
- What additional help is required from the organizing committee to maximum learning?
  - Continue the TFG model to continue the focus on HRLES specific issues
  - Keep the momentum towards the 5th workshop