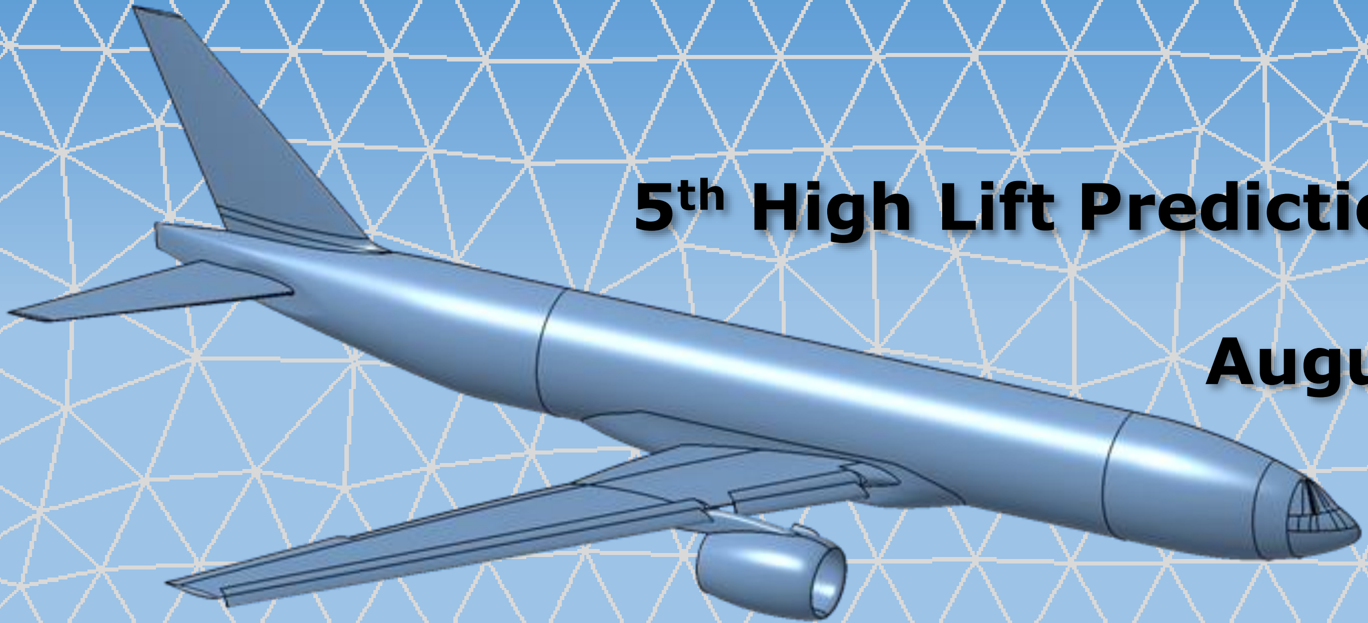
AIAA
SHAPING THE FUTURE OF AEROSPACE



5^{th} High Lift Prediction Workshop

August 2-3, 2024

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

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High-Level Motivations

Scale-resolving methods e.g. Hybrid RANS-LES, Wall-Modelled LES (WMLES), Wall-resolved LES (WRLES) have become more widely used in academia and selected parts of the aerospace external aerodynamics industry for three reasons that have together helped the industry to approach a turning point:

1) HPC hardware has increased in performance over the past decade (both CPUs and GPUs) and the average end-user has access to more compute e.g. industry had ~100's CPU cores per job in 2014 versus ~1000's CPU cores per job in 2024 (+ more recently access to GPUs)
2) Research in scale-resolving turbulence modelling approaches have reached a technology readiness level such that they can transition out of academic codes into production codes and be assessed or used for complex geometries such as high-lift aircraft
3) Growing evidence from public workshops, internal R&D and publications that these methods can* offer improvements over current state-of-the-art RANS/URANS models

** Not all problems are improved by scale-resolving methods and it's accuracy is highly dependent on the mesh, time-step, formulation etc*

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However…

High-Level Motivations

1) **RANS models (largely SA or SST-based) are well understood in the aerospace sector and whilst there are some V&V issues, the average end-user, code provider, companies, has had decades to develop best-practices**
2) Conversely, in general the aerospace industry (outside of select R&D departments) has much less practical experience of scale-resolving methods – especially for full production, at scale.
3) Turbulence Modelling Resource website and prior HLPW's have helped codes to mature their RANS approaches but there is still many unanswered questions for scale-resolving methods – thus this workshop is needed to **educate** and provide **best-practice guidelines** to accelerate their industrial adoption.

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In this talk we focus on Hybrid RANS-LES methods and the following talk by Dr Kiris will focus on WMLES.

What is Hybrid RANS-LES

- Advantages of RANS in attached + advantages of LES in separated
- Makes sense in an existing code i.e. just change RANS formulation (relatively simple to implement)
- Non-zonal (seamless) or zonal approaches
- Resolve to the wall or wall-functions
- Many methods out there but arguably **Detached-Eddy Simulation (Spalart/Strelets et al.)** is the most known, and well used.

Lessons from HLPW4 [1]

"The computational simulation of turbulent flow over high-lift configurations **remains challenging**, but there appears to be room for **cautious optimism** with transient, scale-resolving hybrid RANS/LES methods."

[1] Neil Ashton, Paul Batten, Andrew Cary & Kevin Holst - Summary of the 4th High-Lift Prediction Workshop Hybrid RANS/LES Technology Focus Group, Journal of Aircraft, 2023 https://arc.aiaa.org/doi/abs/10.2514/1.C037329

Lessons from HLPW4 [1]

*"A variety of codes, using a range of HRLES techniques and models, all appear to offer **improved accuracy over SA-based RANS** models in terms of improved force and moment coefficients as well as local flow-field predictions.*

*There have not been sufficient simulations exploring other (non SA-based RANS) models to be able to conclude that **no RANS models can predict this flow type correctly** - but none were observed to **predict the correct flow physics**, forces and moments over the entire envelope and configurations (i.e cases 2.1-2.4) during this workshop."*

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Recent discussions about new HLPW4 tests may change these conclusions (i.e Onera HLPW4 test had C_L 0.06 higher)

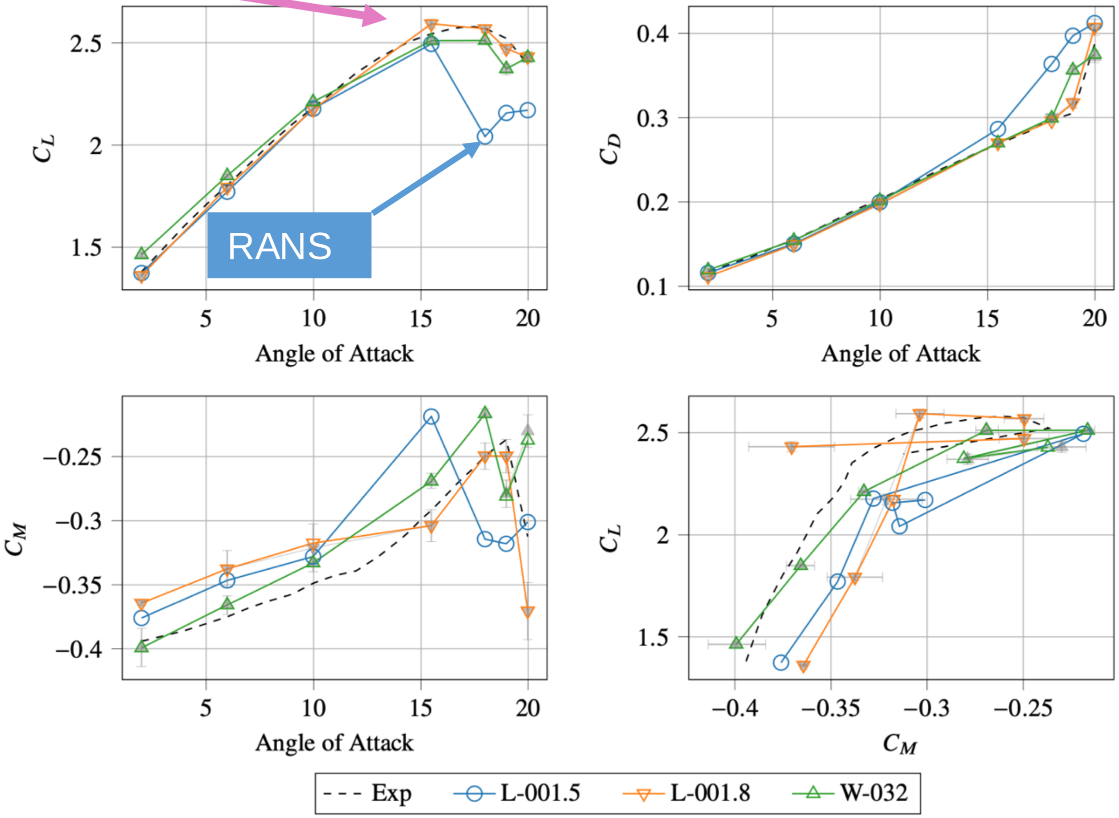

Fig. 20 Test Case 2b - L-001.5 (SA-QCR RANS), L-001.8 (SA-QCR DDES), and W-032 (LBM-VLES)

Lessons from HLPW4 [1]

“At lower angles of attack where ***much of the flap separation remains shallow****, HRLES methods don’t appear to do quite as well and actually show a tendency to return slightly worse moment predictions.”*

[1] Neil Ashton, Paul Batten, Andrew Cary & Kevin Holst - Summary of the 4th High-Lift Prediction Workshop Hybrid RANS/LES Technology Focus Group, Journal of Aircraft, 2023 https://arc.aiaa.org/doi/abs/10.2514/1.C037329

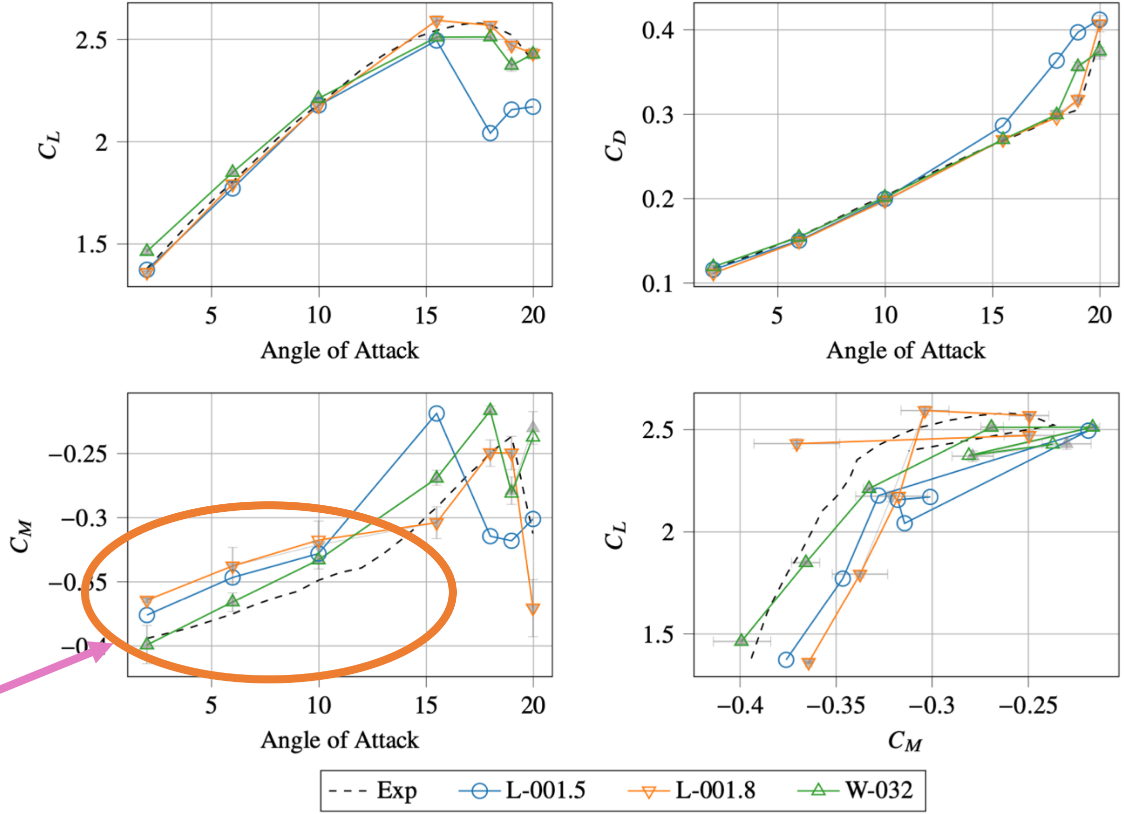

Fig. 20 Test Case 2b - L-001.5 (SA-QCR RANS), L-001.8 (SA-QCR DDES), and W-032 (LBM-VLES)

Recent discussions about new HLPW4 tests may change these conclusions (I.e. closer to Onera HLPW4 test)

Lessons from HLPW4 [1]

“Unfortunately, this paper is not able to draw any conclusions on the specific performance of the shielding functions used in the various HRLES methods, as these weren’t systematically tested or compared by any contributor. Further work could usefully be done to ***explore even larger meshes, to assess whether accuracy improves or, importantly, whether accuracy worsens due to some shielding-function breakdown”***

[1] Neil Ashton, Paul Batten, Andrew Cary & Kevin Holst - Summary of the 4th High-Lift Prediction Workshop Hybrid RANS/LES Technology Focus Group, Journal of Aircraft, 2023 https://arc.aiaa.org/doi/abs/10.2514/1.C037329

Main objective

Given the conclusions from **HLPW4** – how much is still true for **HLPW5**? The sign of a mature method is generalizability between geometries/problems and similar results between different codes and groups.

Key Questions for HLPW5:

1. **Correlation to experiment** (absolute and geometry deltas) (target: C_L +/- 0.03)
2. How close are we to **mesh convergence** and how many cells do we need?
3. Level of **repeatability** between codes/meshes for the same HRLES model
4. Are there modelling issues e.g do we see the **shielding function issues** i.e modeled-stress depletion?
5. What is the **Computational time & cost?**

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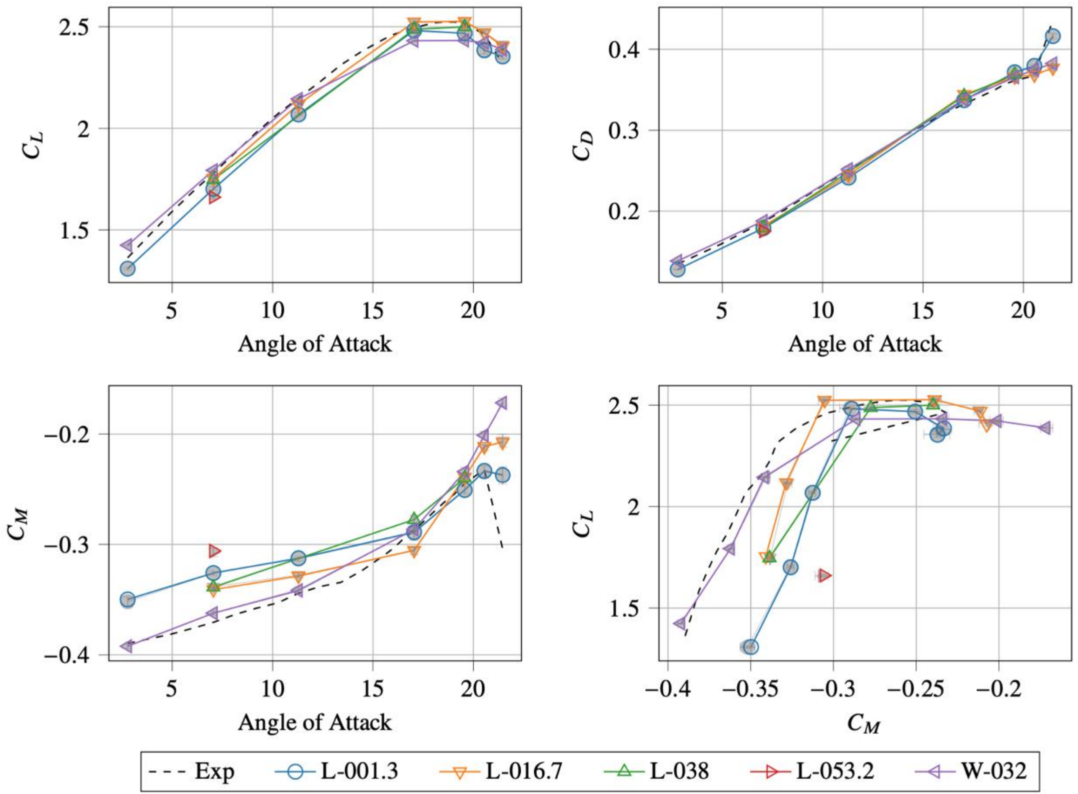
Submissions

		Test Cases		
Group ID	Solver/Company	1	2	3
L-001	Flow360/Flexcompute	x	x	
L-003	FELight/Boeing	x		
L-004	CFD++/Metacomp	x	x	
L-005	Fluent/Ansys	x		
L-009	FUN3D/Gulfstream		x	
L-013	Kestrel/USAF		x	
L-015	Pacefish/Numeric Systems	X	x	

Big thank you to all these groups who spent the past 2 years meeting bi-weekly, running millions of compute hours – often outside of their 'day' job.

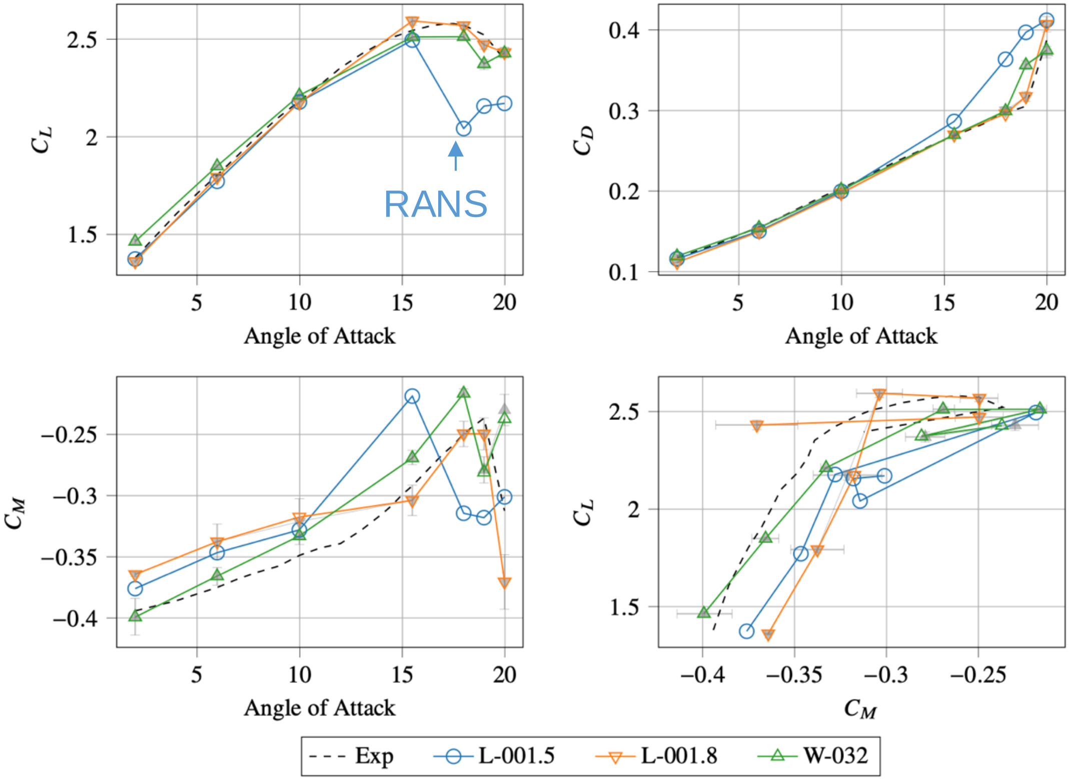
Executive Summary

HLPW4 - Free-air



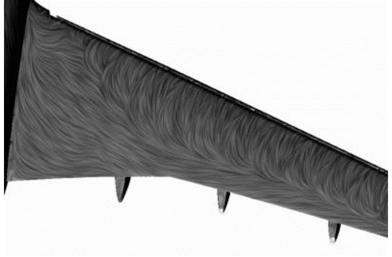
Executive Summary

HLPW4 - WT



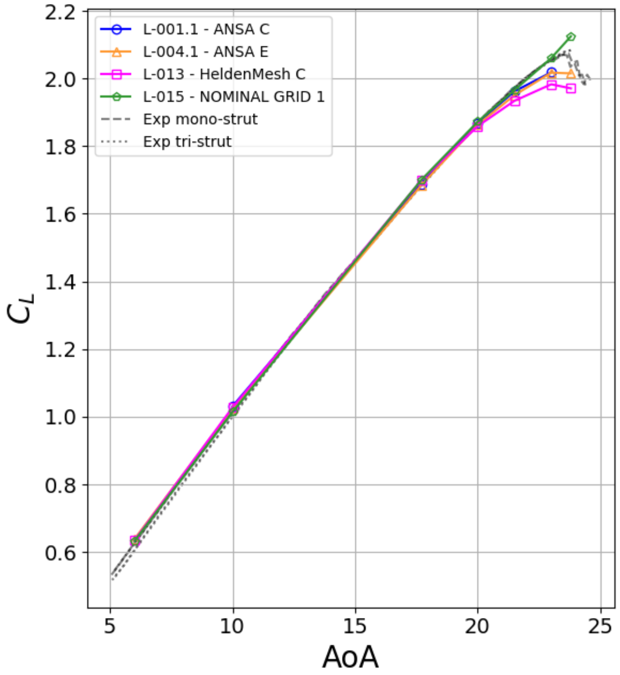
Executive Summary (2.2)

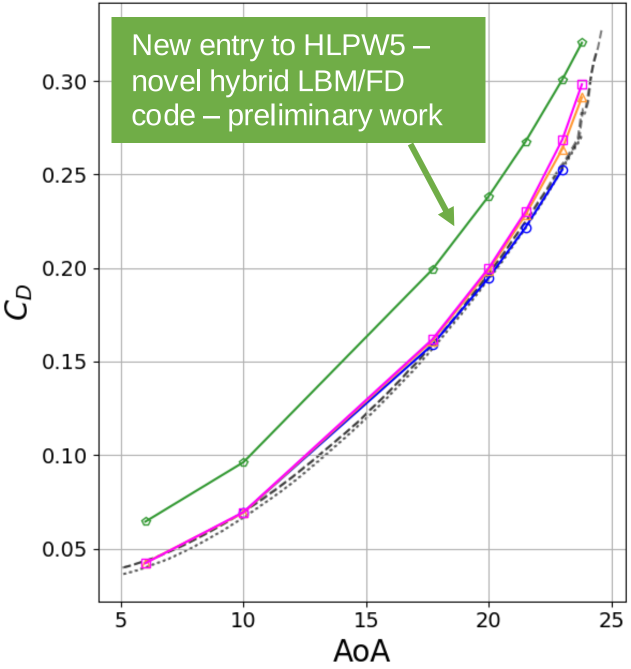
ANSA C = 178M cells
ANSA E = 566M cells
HeldenMesh C = 413M cells
Nominal Grid 1 = 472M cells

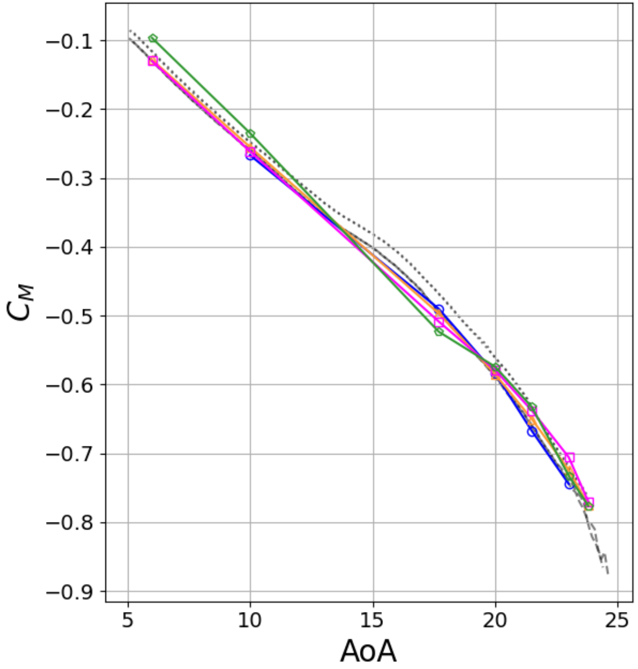


HLPW5 - Best-Practice grid/setup

Case 2.2: Forces and Moments







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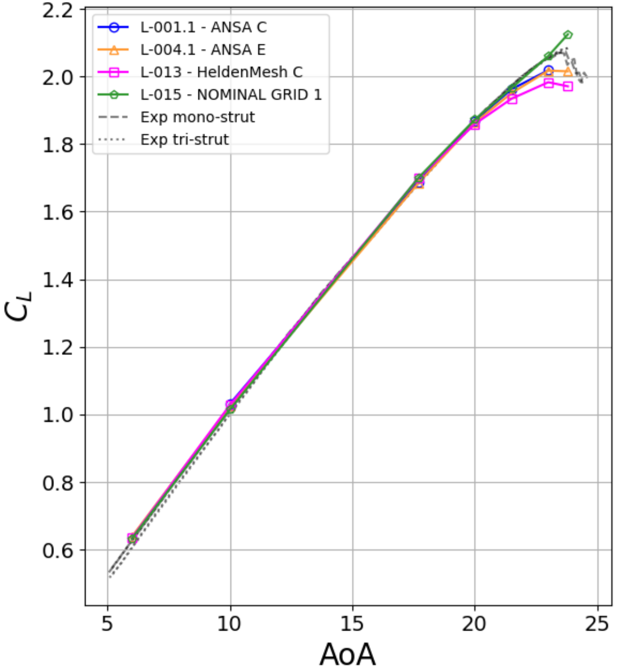
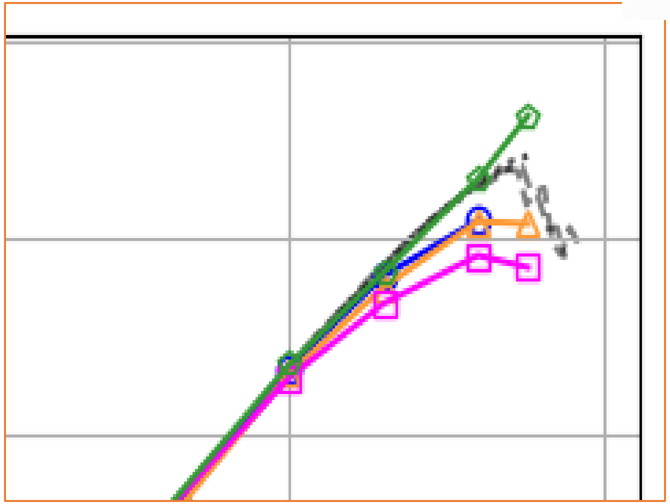


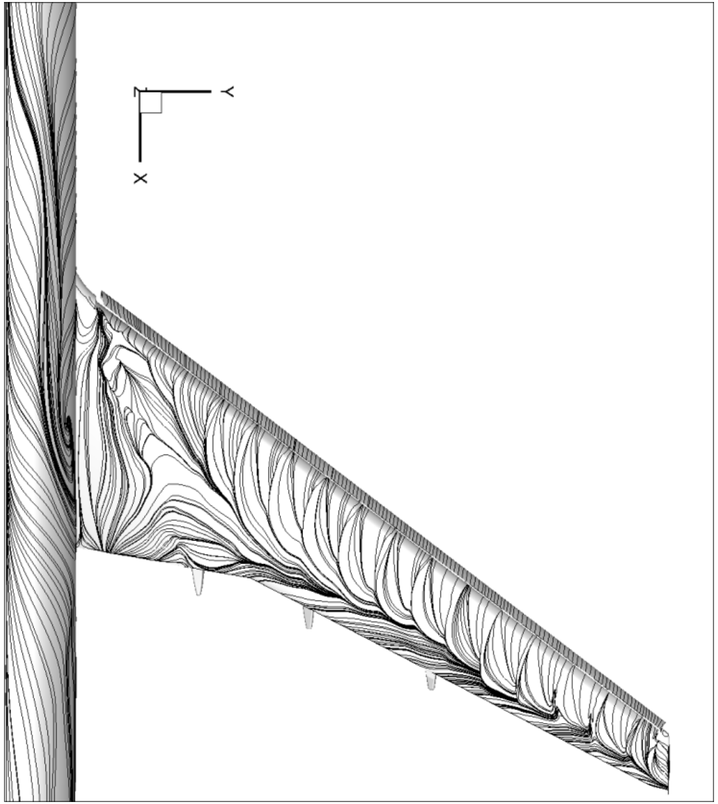


C_{Lcfd}-C_{Lexp}~0.06 i.e < 3% error

Best-Practice grid/setup

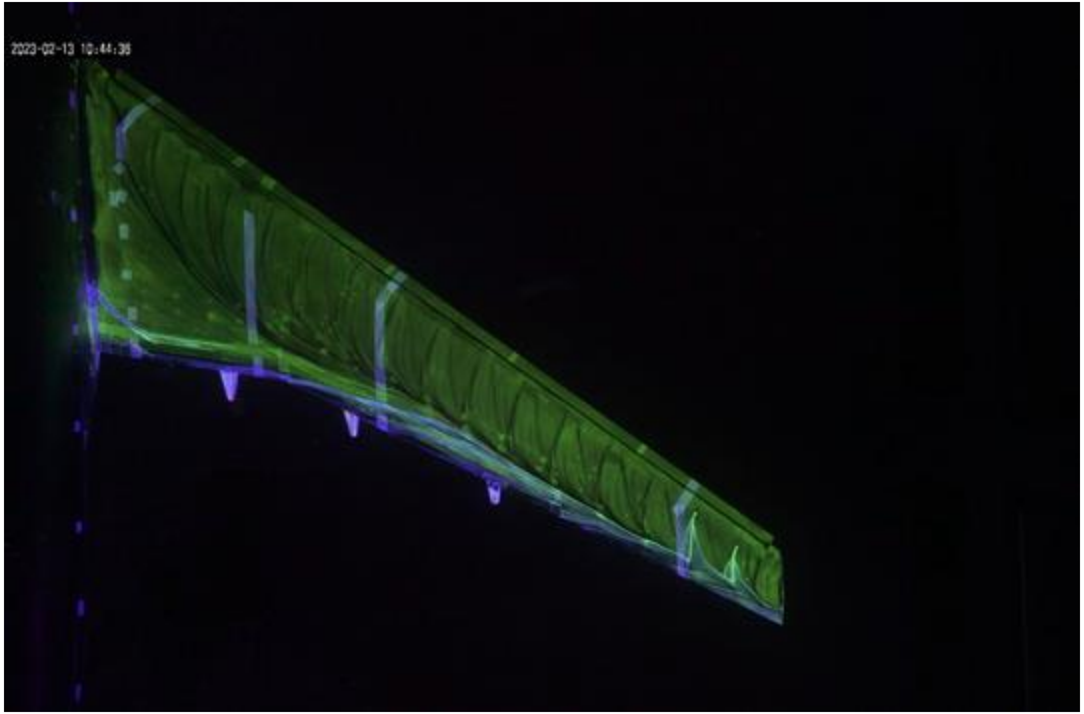
Executive Summary (2.2)

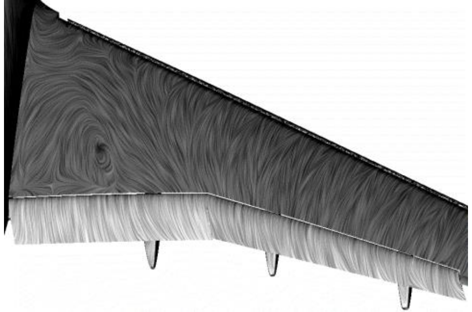
Example comparison



L-001 – SA-QCR DDES

Very strong spanwise flow by 23.8deg AoA





Executive Summary (2.3)

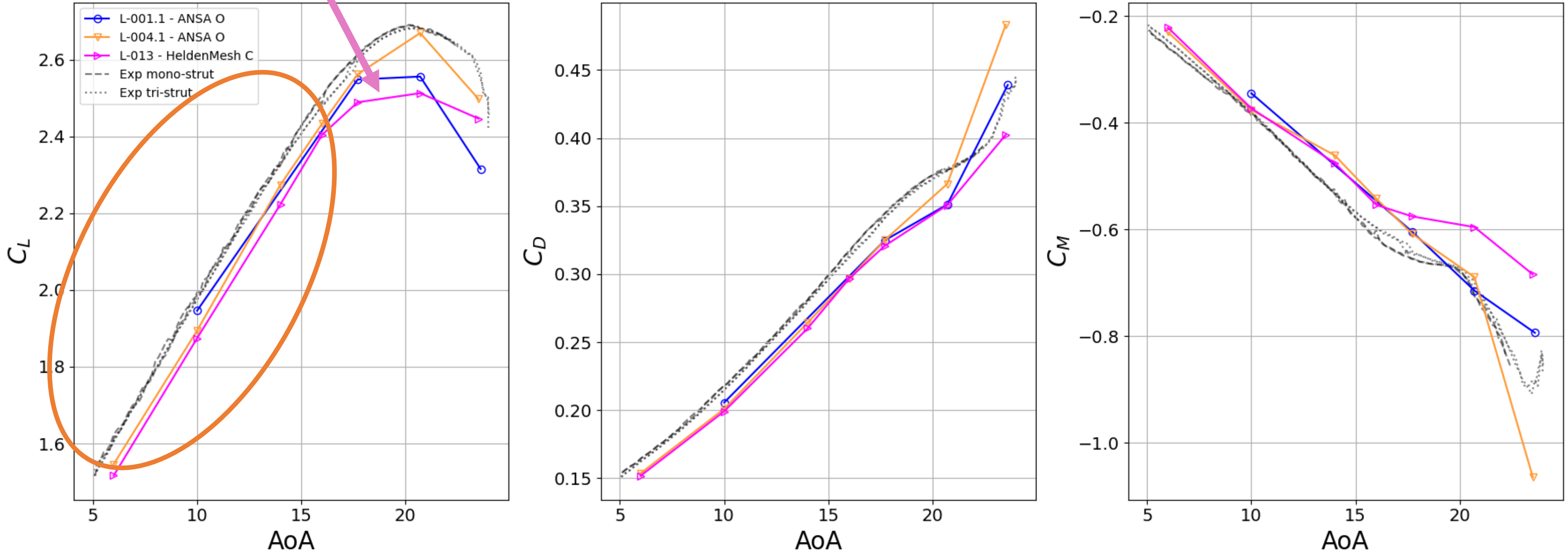
L-013 had less grid mesh convergence than L-004.1 and L001.1 (shown later)

Summary paper will have more analysis of the flap prediction issue at low-mid AoA

ANSA 0 = 306M cells
HeldenMesh C = 473M cells

Case 2.3: Forces and Moments

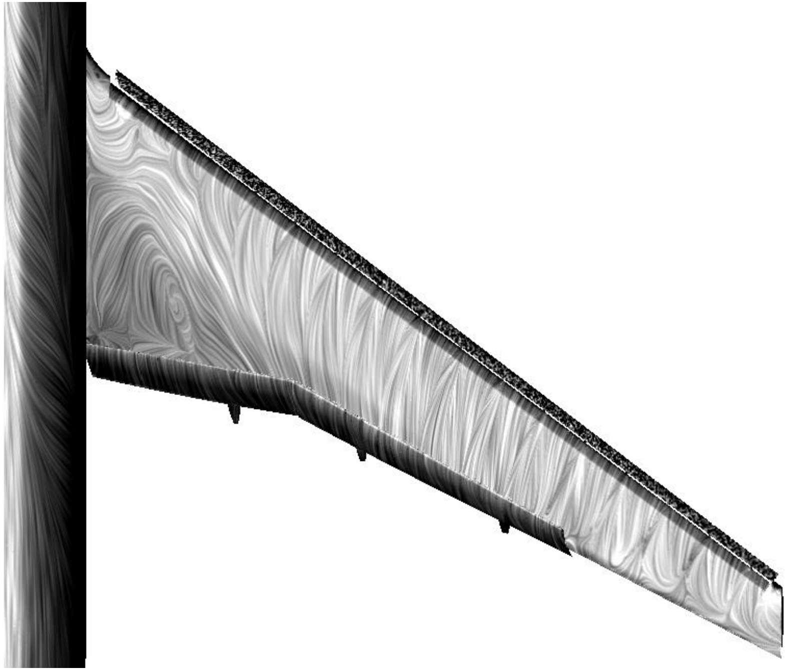
Best-Practice grid/setup



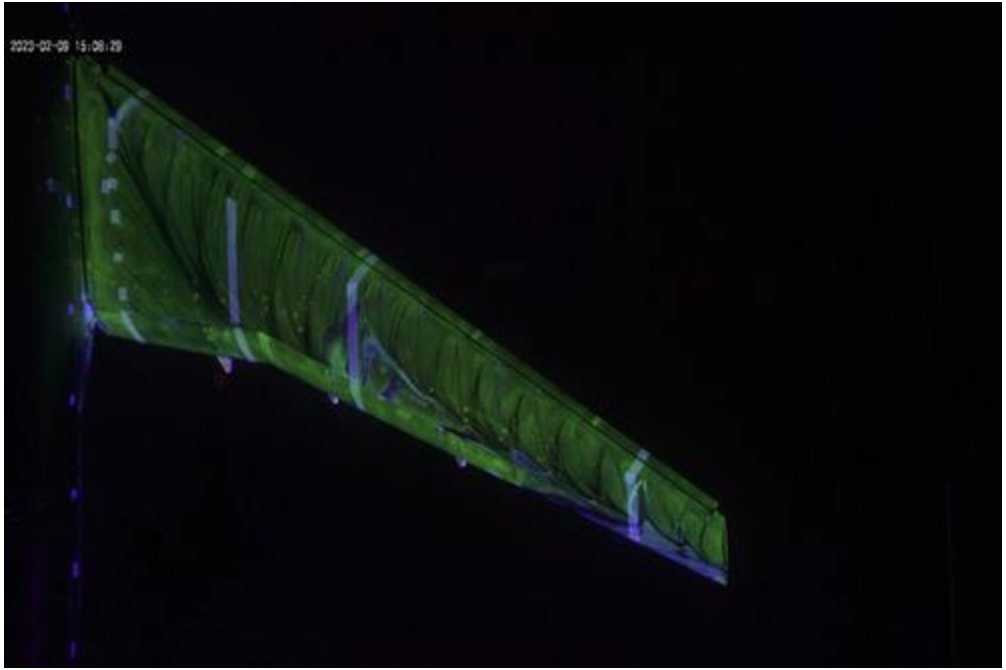
Executive Summary (2.3)

Example comparison

Similar strong spanwise flow at 23.5 as 2.2, but flaps restrict it mainly inboard

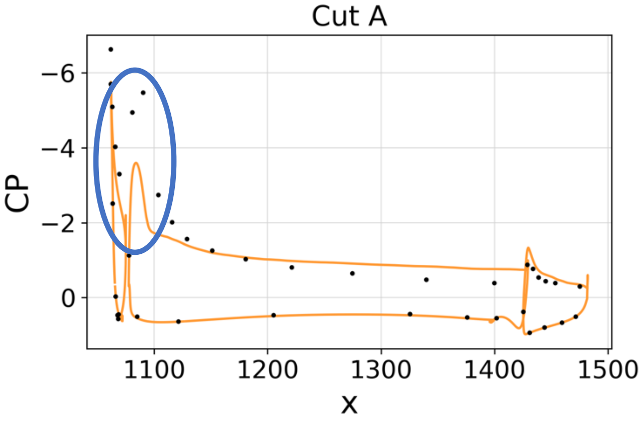


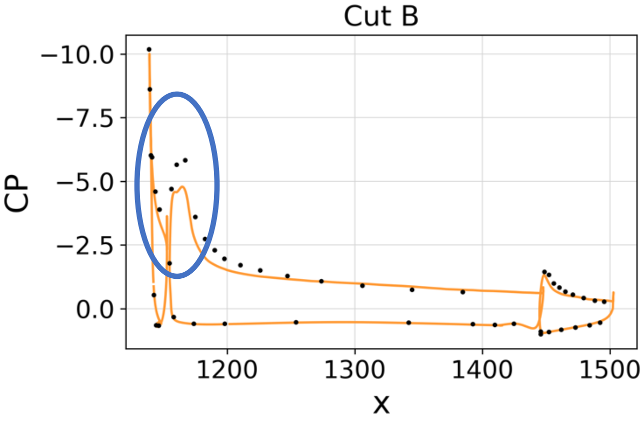
L-004 SA-QCR DDES



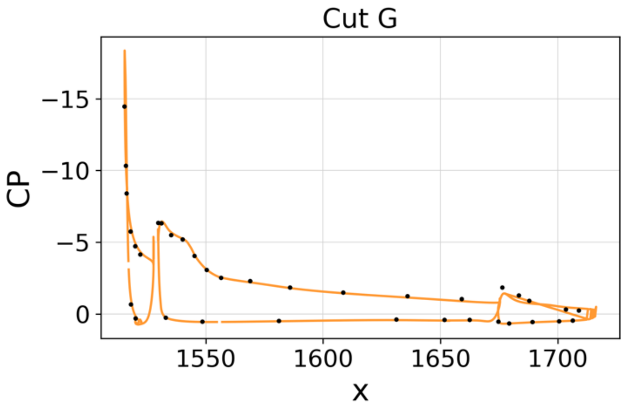
Executive Summary (2.3)

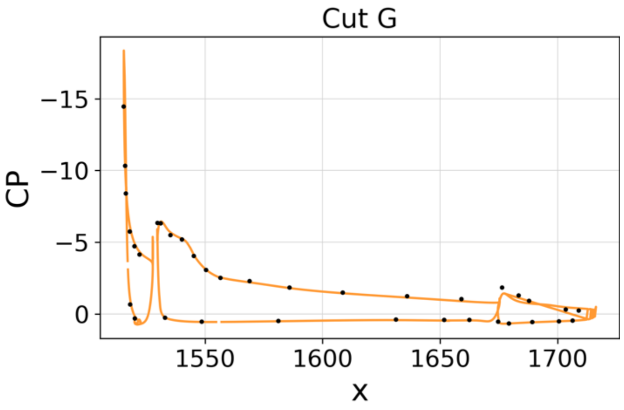
23.5deg AoA

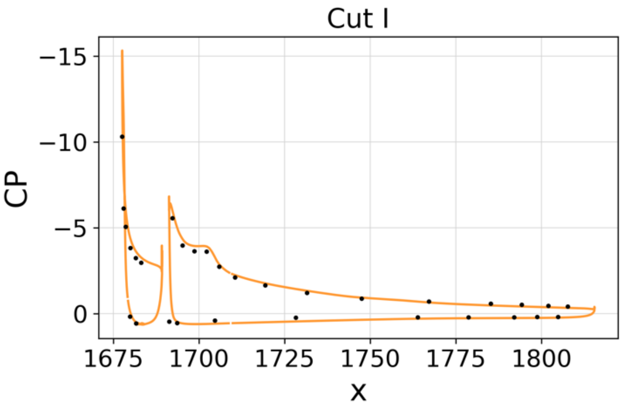




L-004: Orange, Exp: black



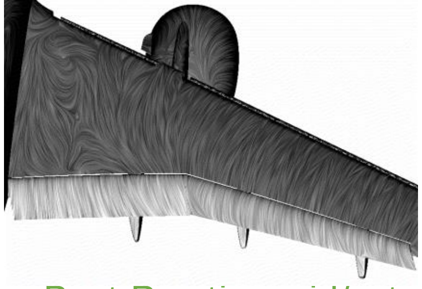




Executive Summary (2.4)

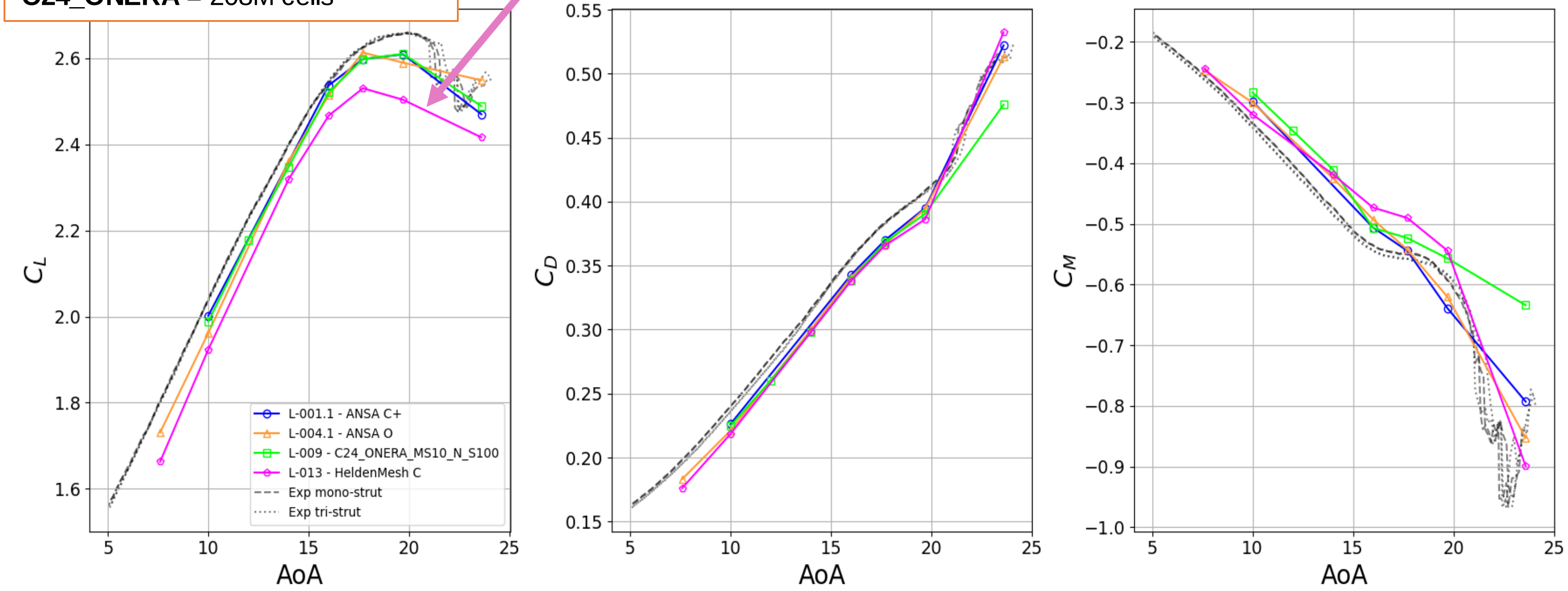
L-013 may require further mesh refinement (discussed later)

ANSA 0 = 337M cells
ANSA C+ = 281M cells
HeldenMesh C = 528M cells
C24_ONERA = 208M cells



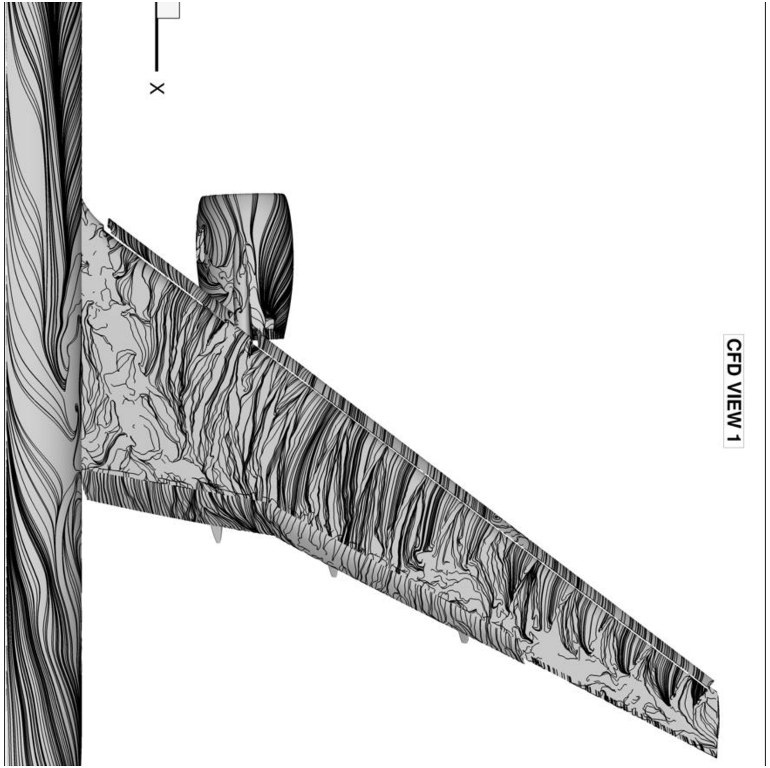
Best-Practice grid/setup

Case 2.4: Forces and Moments



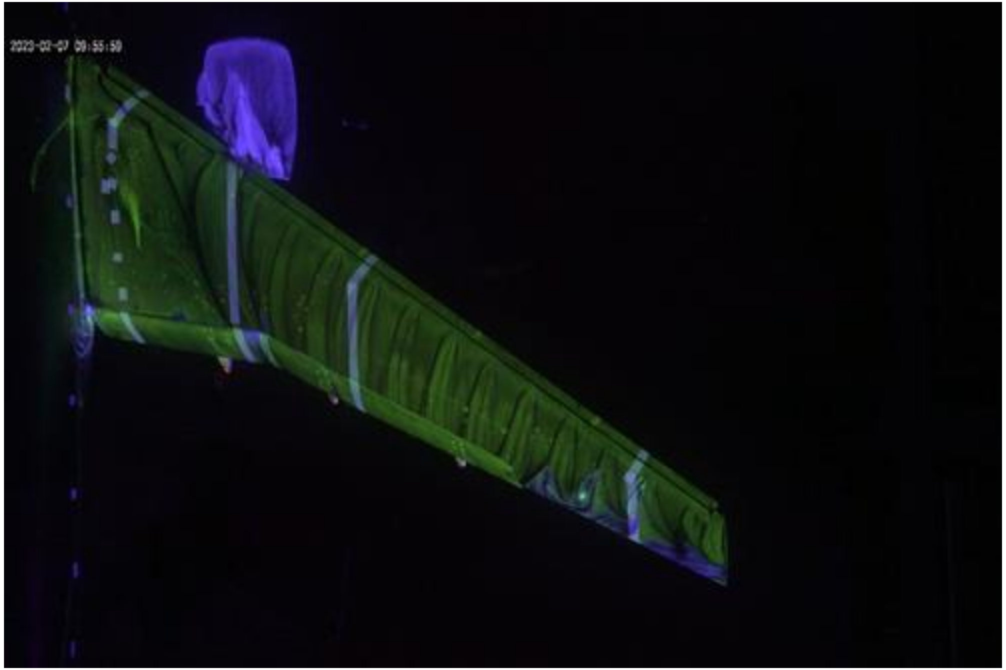
Executive Summary (2.4)

Example comparison



Case 2.4 – L-009

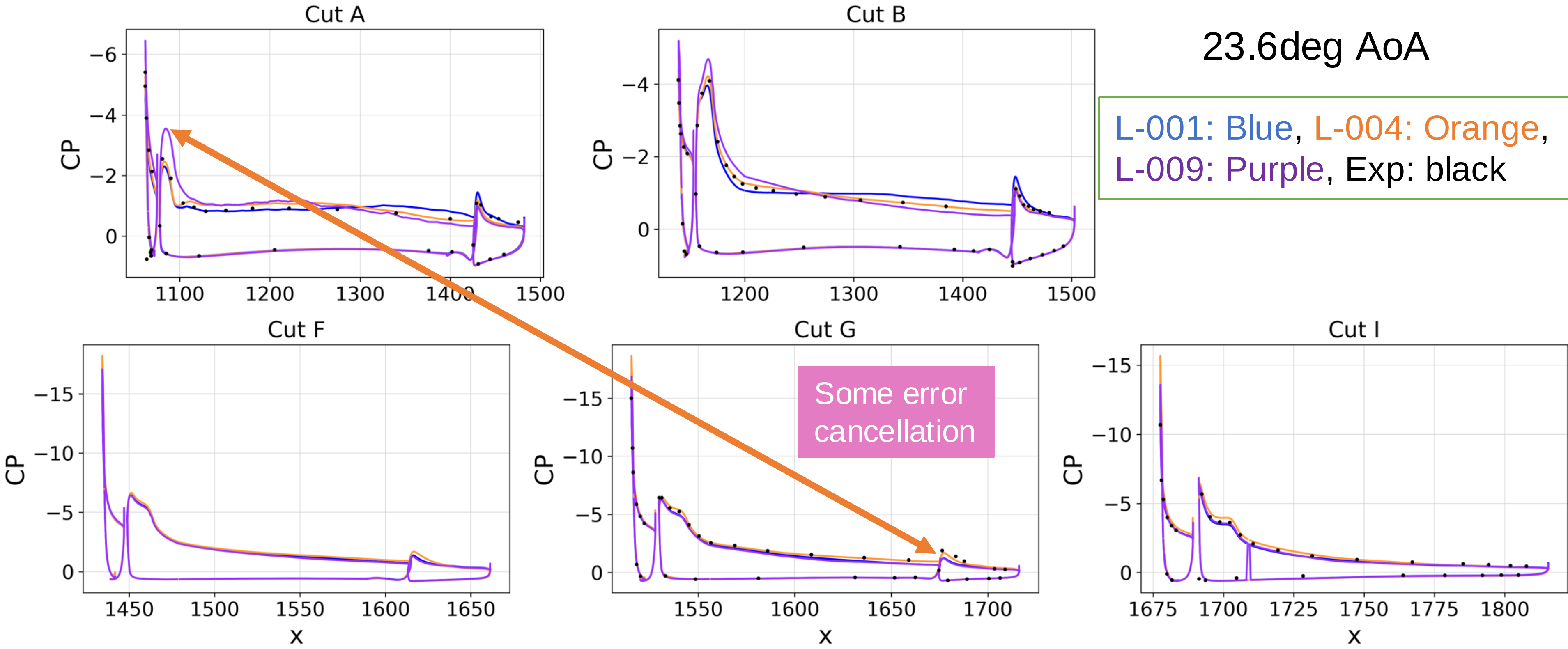
23.6 AoA



Executive Summary (2.4)

23.6deg AoA

L-001: Blue, L-004: Orange, L-009: Purple, Exp: black



Correlation looks closer for 2.4 than 2.3 for Cp inboard cuts – but now outboard cut is under-predicted – which may be responsible for Cm correlation

Executive Summary

- Does the constant offset cancel out if we look at the delta between 2.4 and 2.2?
- Trends are well captured by HRLES (all SA-DDES variants) by three separate codes, with different meshes.
- Low AoA (i.e 6 degrees) remains a challenge for absolute + delta means many unanswered questions
- Important to note that for some submissions the change different 2.2 and 2.4 is not only geometry (i.e best-practice changed) so please treat this as initial analysis only

Executive Summary

Full configuration of HLPW5 has ultimately been a more difficult test-case to predict than HLPW4 (*although new insights from Onera HLPW4 WT may challenge this*). There is still positive news:

1. HRLES still shows the same overall improvements over SA-based RANS (i.e better C_{Lmax} prediction) and better flow-field correlation
2. Addition of the flaps (2.3 and 2.4) has been challenging for all groups (including other TFGs) and there remains many unanswered questions around transition & mesh refinement requirements i.e. issues not unique to HRLES
3. When sufficient mesh resolution and a low dissipation scheme is used, there is good agreement between different codes for HRLES (SA DDES variants) which suggests a maturity of the method for industry. **However all submissions need further mesh refinement.**
4. Low AoA configurations with flaps remains a challenge (absolute and deltas) – as seen with HLPW4 flap deflection study
5. More work to do to address the unknowns related to HLPW5 and more analysis by the TFG – which will be shown in the SciTech summary paper.

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3. **When sufficient mesh resolution and a low dissipation scheme is used, there is good agreement between different codes for HRLES (SA DDES variants) which suggests a maturity of the method for industry. However all submissions need further mesh refinement.**
4. Low AoA configurations with flaps remains a challenge (absolute and deltas) – as seen with HLPW4 flap deflection study
5. More work to do to address the unknowns related to HLPW5 and more analysis by the TFG – which will be shown in the SciTech summary paper.

Executive Summary

Full configuration of HLPW5 has ultimately been a more difficult test-case to predict than HLPW4 (*although new insights from Onera HLPW4 WT may challenge this*). There is still positive news:

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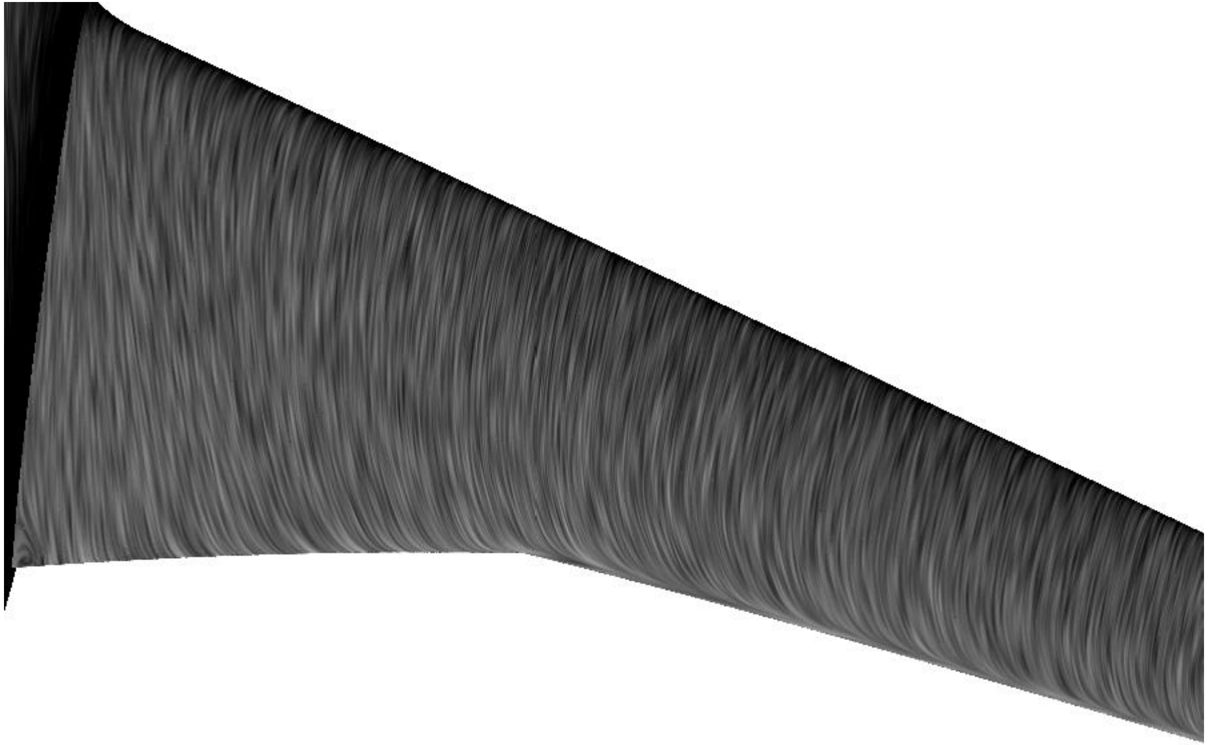
Detailed Analysis

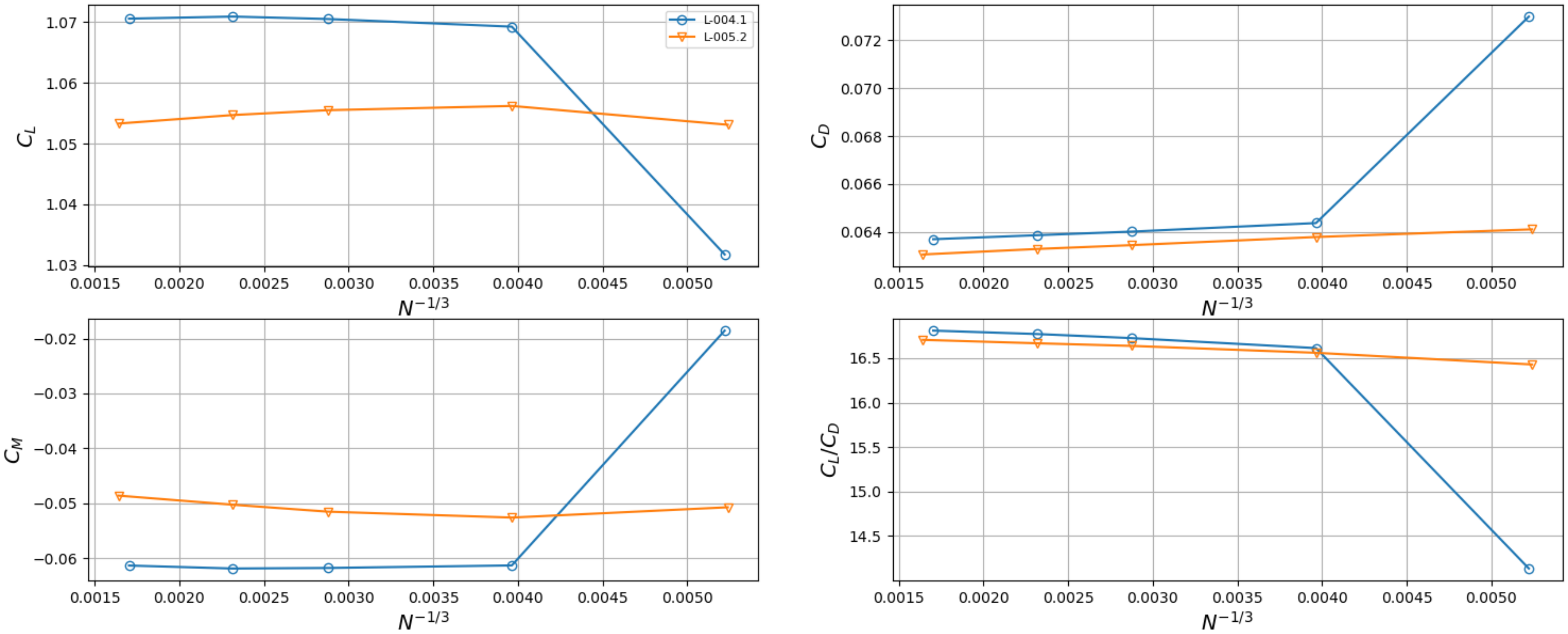
Case 1



Case 1 Submission details

PID	Lead	Code	Notes	Model	Grid
L-001.1	Fitzgibbon	Flow360	SA-DDES, low diss cold start, various ANSA (BEST-PRACTICE)	SA-neg-DDES	2.L.01
L-001.2	Fitzgibbon	Flow360	SA-DDES, cold start, ANSA grids	SA-neg-DDES	2.L.01
L-001.3	Fitzgibbon	Flow360	SA-QCR-DDES, cold start, ANSA grids	SA-neg-QCR2000-DDES	2.L.01
L-003.1	Ahrabi	FELight	Custom development	SA-neg-DDES-N5	self
L-004.1	Batten	CFD++	RANS	SA-QCR-RANS	2.L.01
L-004.3	Batten	CFD++		SA-QCR-DDES	2.L.01
L-004.4	Batten	CFD++	Addition of Deck-Renard	SA-QCR-DDES + Deck-Renard	2.L.01
L-005.2	Berg	ANSYS		SST SBES	2.L.02
L-015	Riegel	PACEFISH	First work in the aerospace field - validating/developing the code	SST-DDES	self

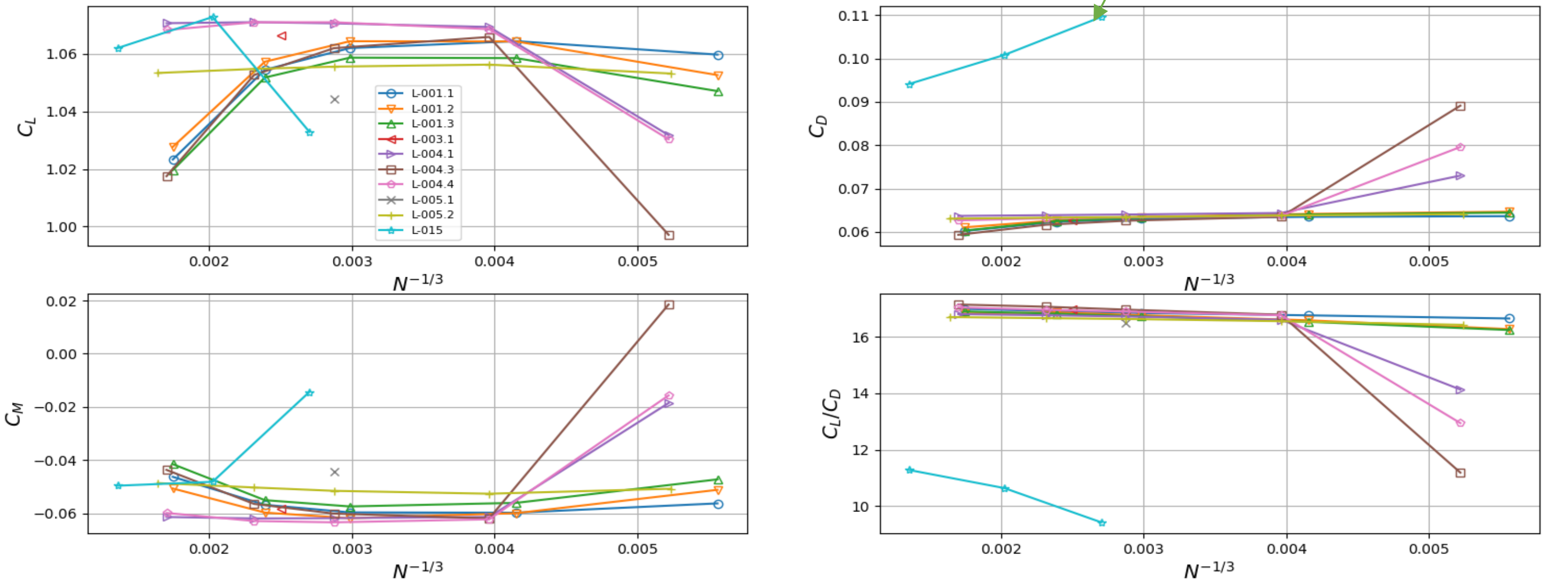
Forces & moments - RANS



L-004.1 – SA-QCR RANS , L005.2 – SST-RANS

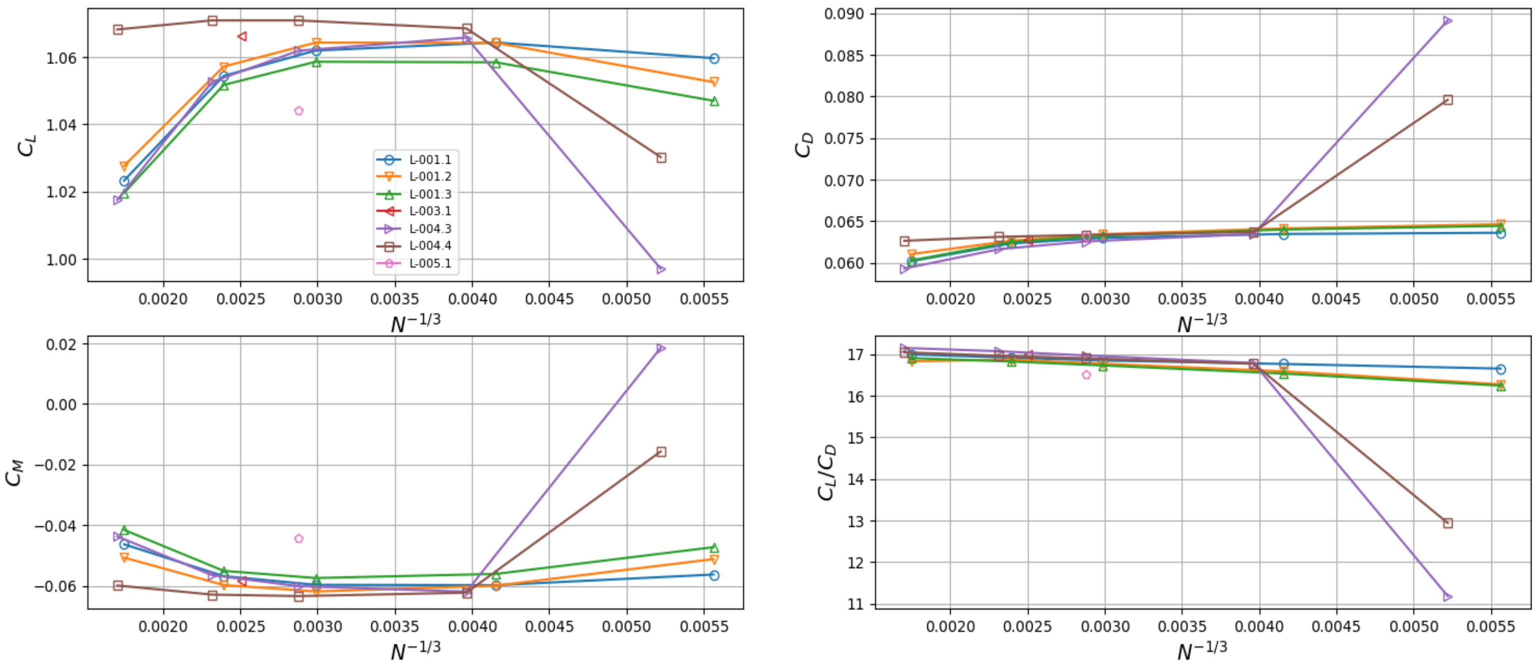
Forces & moments - ALL

New entry to HLPW5 – novel hybrid LBM/FD code – preliminary work



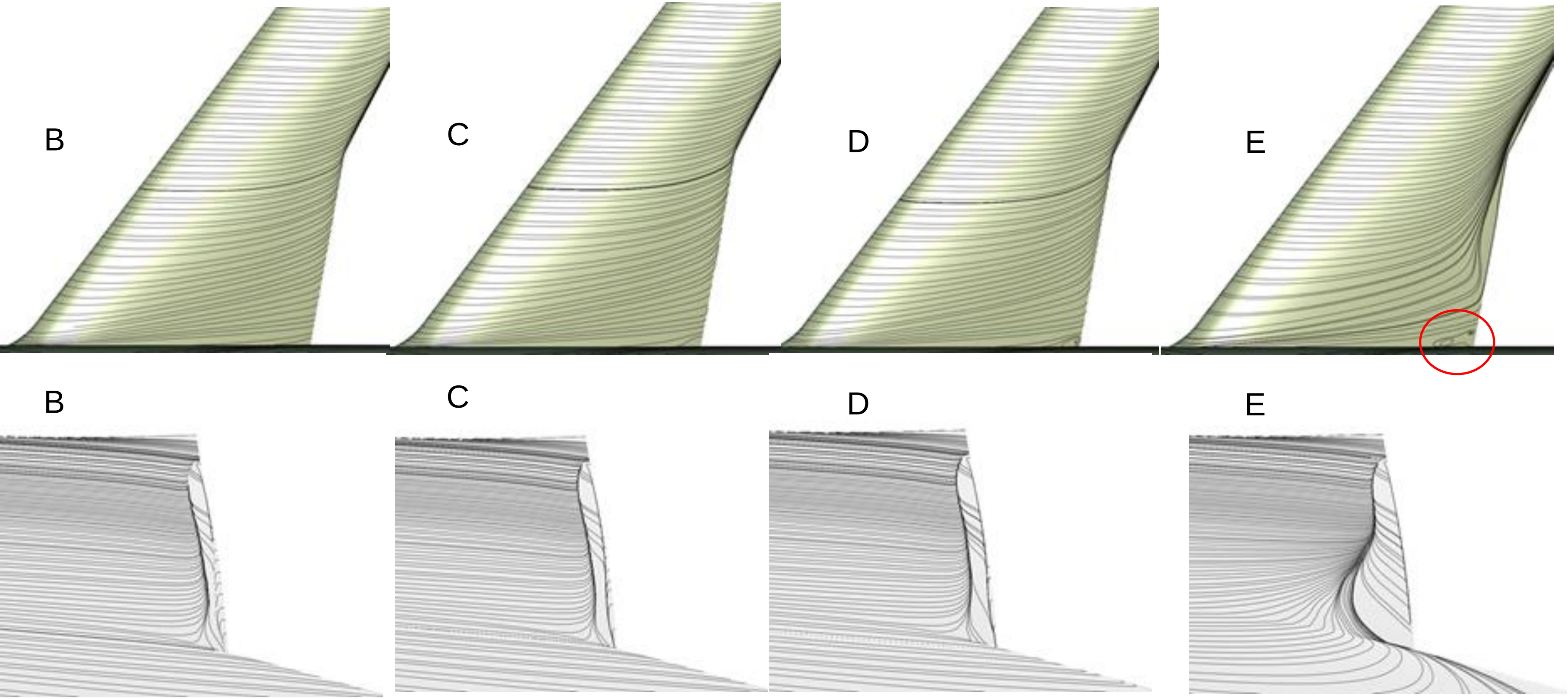
L-001.1 – SA-DDES-low-diss, L-001.2 - SA-DDES, L-001.3 - SA-QCR DDES, L-003.1 – SA-DDES-custom (Custom Pointwise Grid), L-004.1 – SA-QCR RANS, L-004.3 – SA-QCR DDES, L-004.4 SA-QCR-DDES-DR, L-005.1 – SST-SBES, L-005.2 – SST-RANS, L015 – SST-DDES

Forces & moments - HRLES

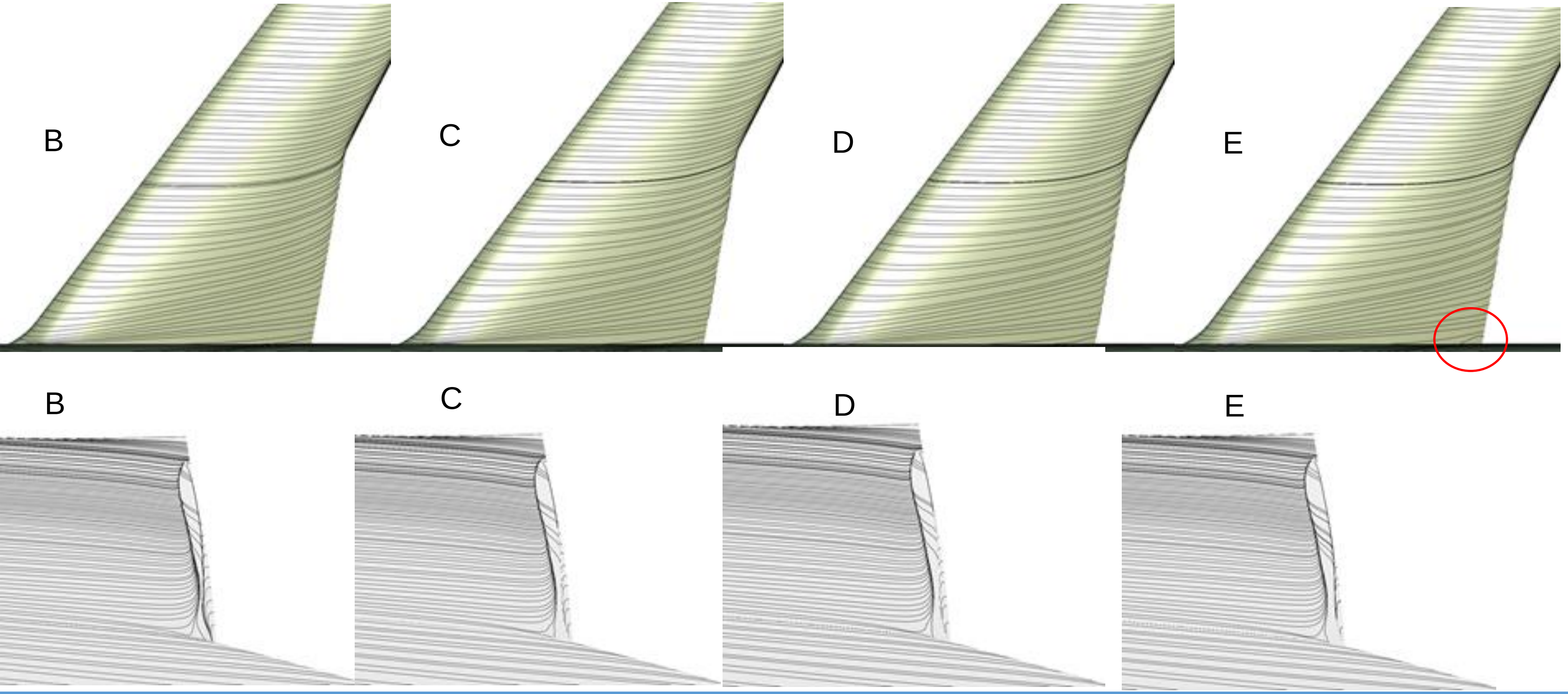


L-001.1 – SA-DDES-low-diss, L-001.2 - SA-DDES, L-001.3 - SA-QCR DDES, L-003.1 – SA-DDES-custom (Custom Pointwise Grid), L004.3 – SA-QCR DDES, L004.4 SA-QCR-DDES-DR, L005.1 – SST-SBES (ANSA Grid)

Case 1 – L004.3 – SA-QCR-DDES



Case 1 – L004.4 –SA-QCR-DDES-DR



Case 1 Conclusions

- **Case 1 (i.e clean wing with no slats/flaps) has exposed an issue previously known (but not observed in HLPW4) of shielding function breakdown for the standard DDES formulation on fine grids**
- Confirmed using two different codes and different DDES formulations (SA-QCR DDES and SA-DDES)
- Initial work to mitigate this with Deck-Renard function, custom DDES formulation and SBES looks promising, but more work needed to confirm (most groups moved to focus on case 2)
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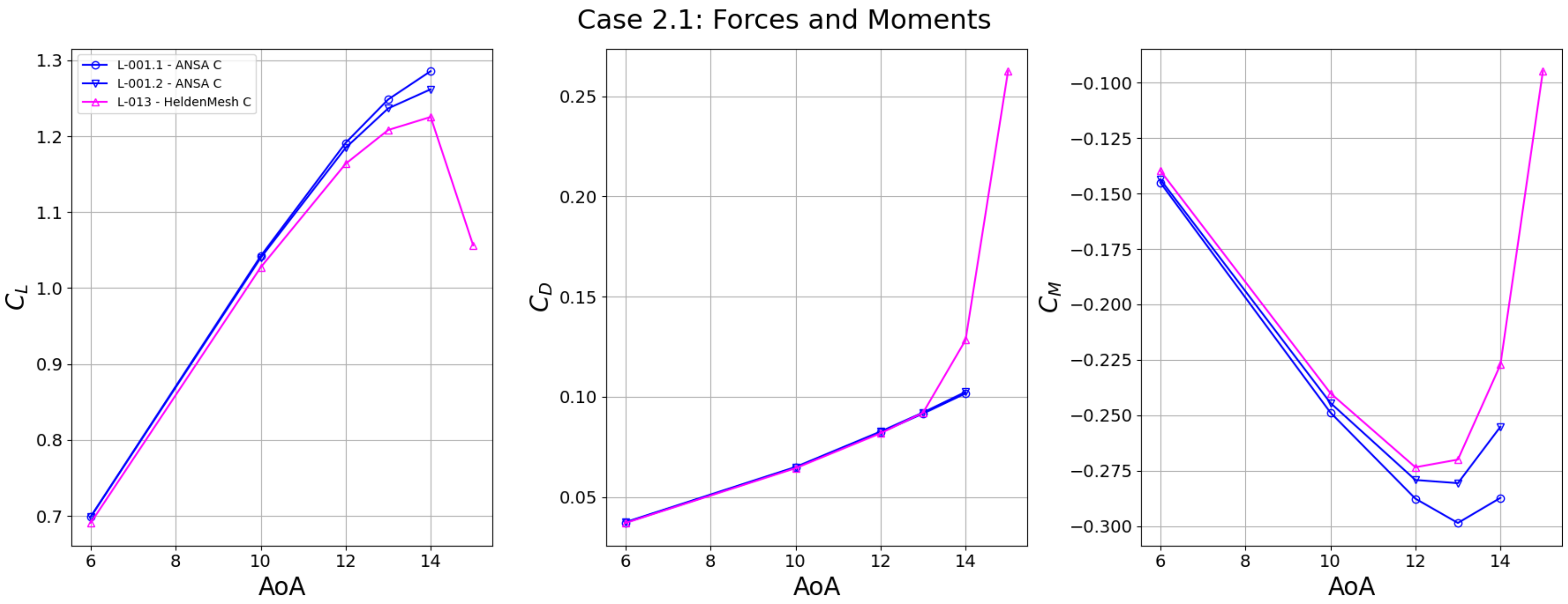
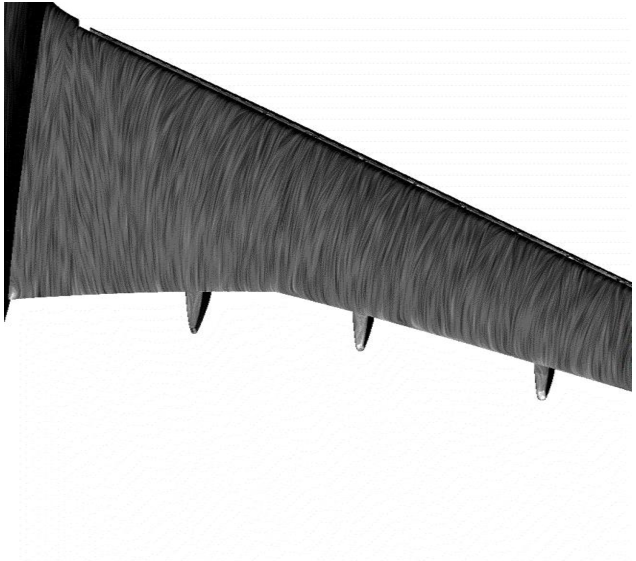
Case 2.1



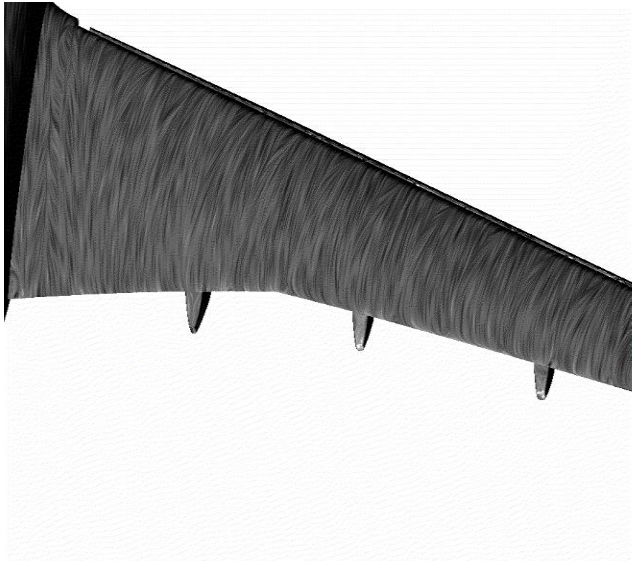
Limited time for analysis – so please see SciTech paper for full details

Case 2.2

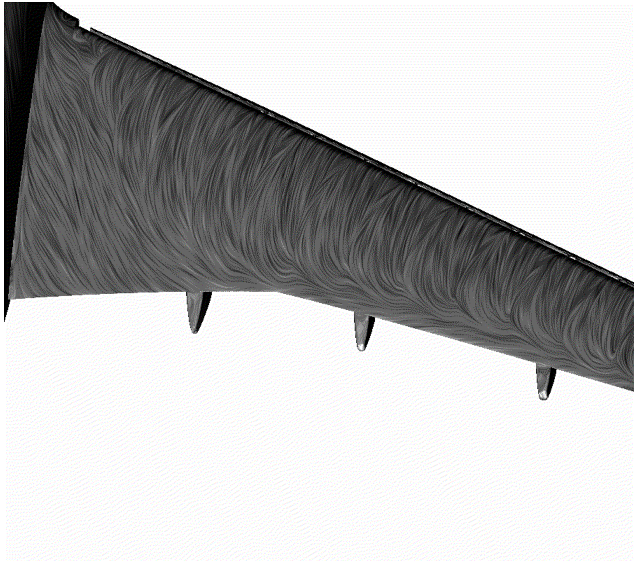
Flow features



Case 2.2 (6º)



Case 2.2 (10º)

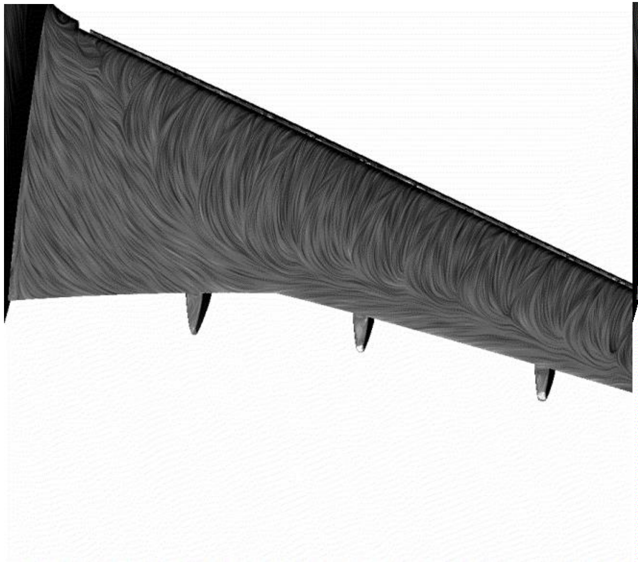


Case 2.2 (20º)

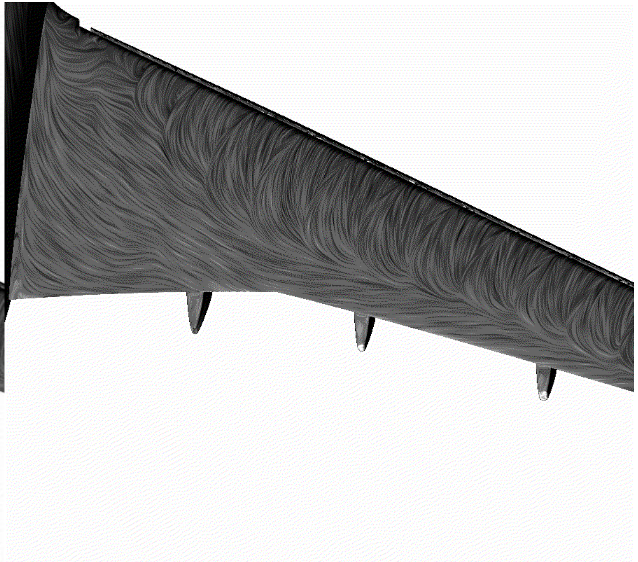
No flap or nacelle

L004 SA-QCR DDES simulation

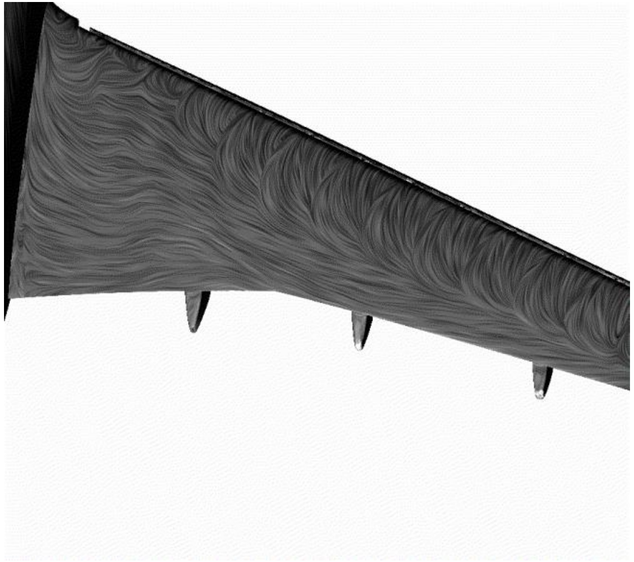
Flow features



Case 2.2 (21.5º)



Case 2.2 (23º)



Case 2.2 (23.8º)

No flap or nacelle

L004 SA-QCR DDES simulation

Case 2 Submission details

PID	Lead	Code	2.1	2.2	2.3	2.4	Notes	Model	Grid
L-001.1	Fitzgibbon	Flow360	x	x	x	x	SA-DDES, low diss cold start, various ANSA (BEST-PRACTICE)	SA-neg-DDES	2.L.01
L-001.2	Fitzgibbon	Flow360	x	x		x	SA-QCR-DDES, cold start, ANSA grids	SA-neg-QCR2000-DDES	2.L.01
L-004.1	Batten	CFD++		x	x	x	SA-QCR-DDES; (BEST-PRACTICE)	SA-QCR-DDES + Deck-Renard	2.L.01
L-004.2	Batten	CFD++		x	x	x	SA-QCR (RANS);	SA-QCR	2.L.01
L-004.3	Batten	CFD++		x	x	x	SST-Langry Menter Transition model	SST-LM-2009	2.L.01
L-009	Powell	FUN3D				x	Custom HeldenMesh grids + lower dissipation + cold start	SA-DDES	self
L-013	Lofthouse	KCFD	x	x	x	x	HeldenMesh grids	SA-QCR DDES	2.L.02
L-015	Riegel	PACEFISH		x			First work in the aerospace field - validating/developing the code	SST-DDES	self

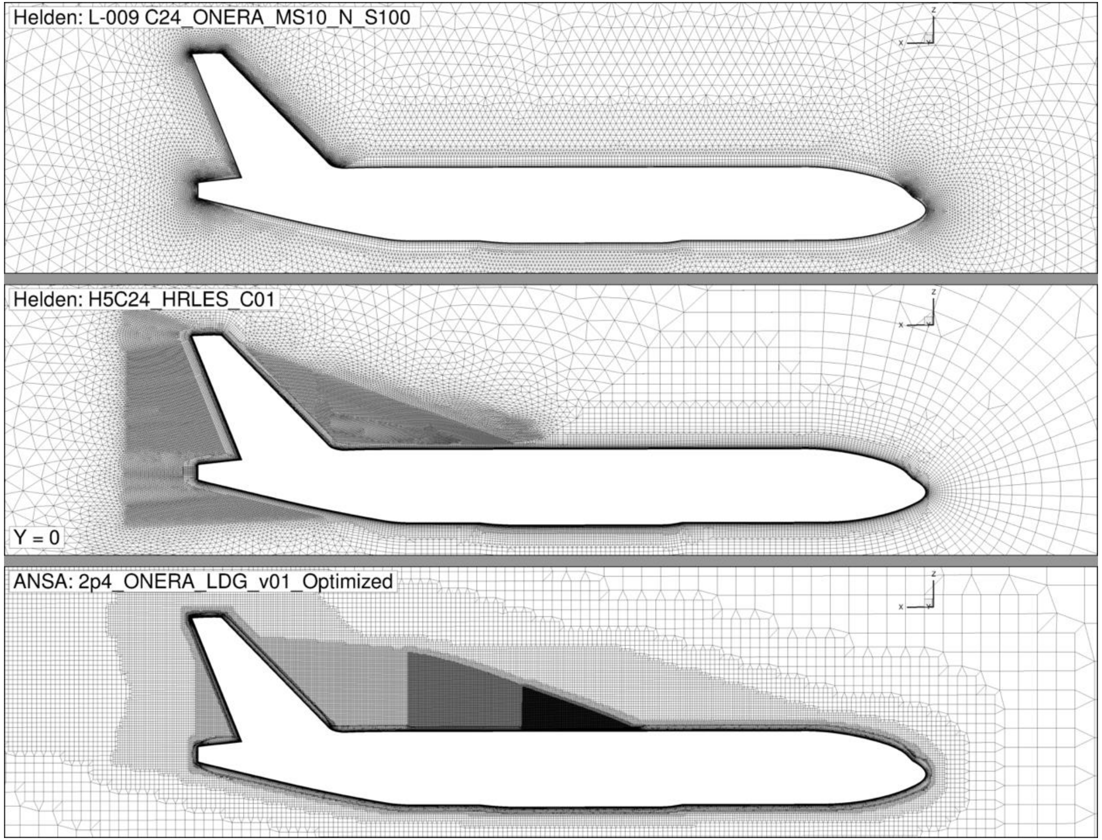
Mesh details (*2p4 but similar for 2.2/2.3*)

Y=0

L-009 built their own heldenMesh grids (**top**)

L-013 used the committee HeldenMesh grids (**middle**)

L-001 and L-004 used ANSA meshes (**bottom**)



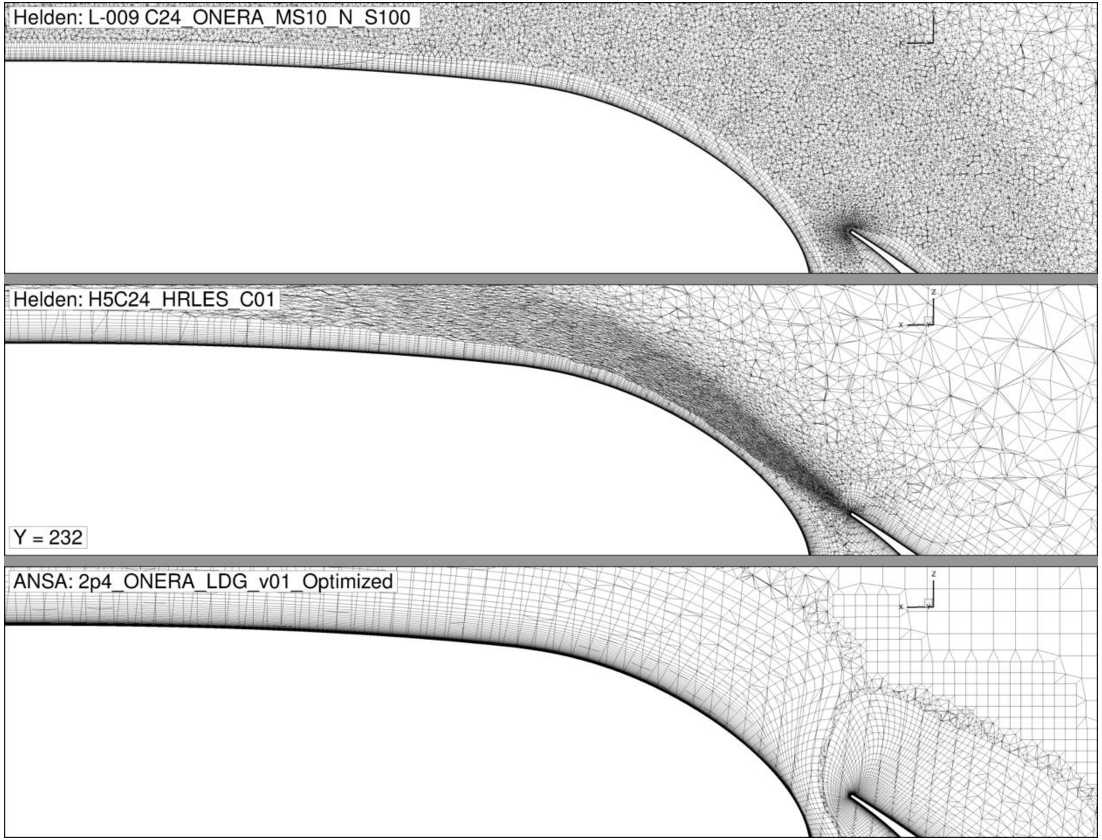
Mesh details (*2p4 but similar for 2.2/2.3*)

Y=232 (slat shear layer)

L-009 built their own heldenMesh grids (**top**)

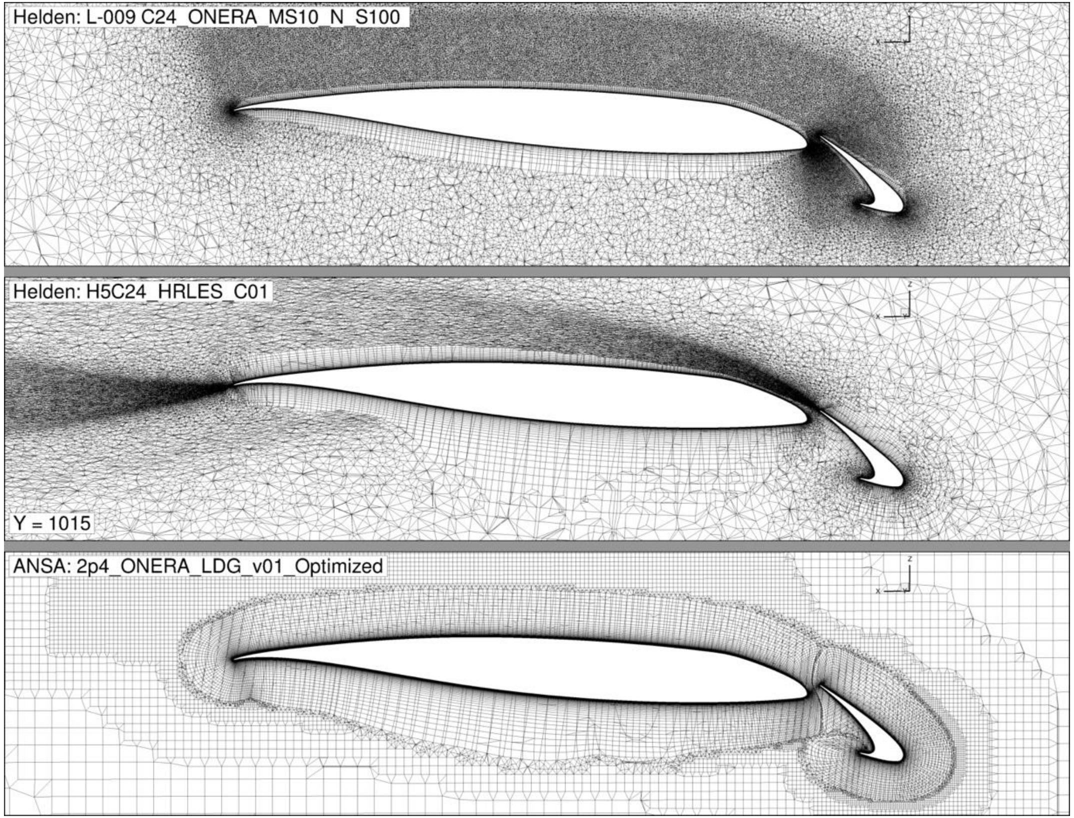
L-013 used the committee HeldenMesh grids (**middle**)

L-001 and L-004 used ANSA meshes (**bottom**)



Mesh details (*2p4 but similar for 2.2/2.3*)

Y=1015



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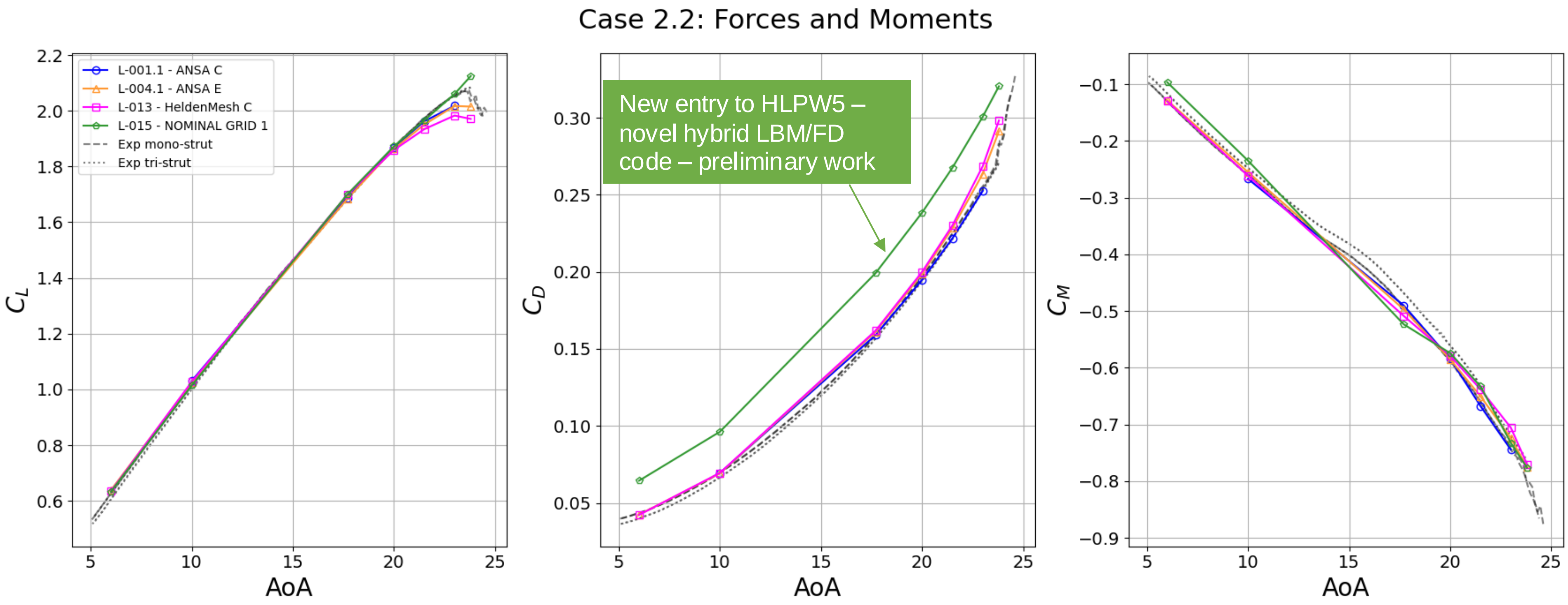
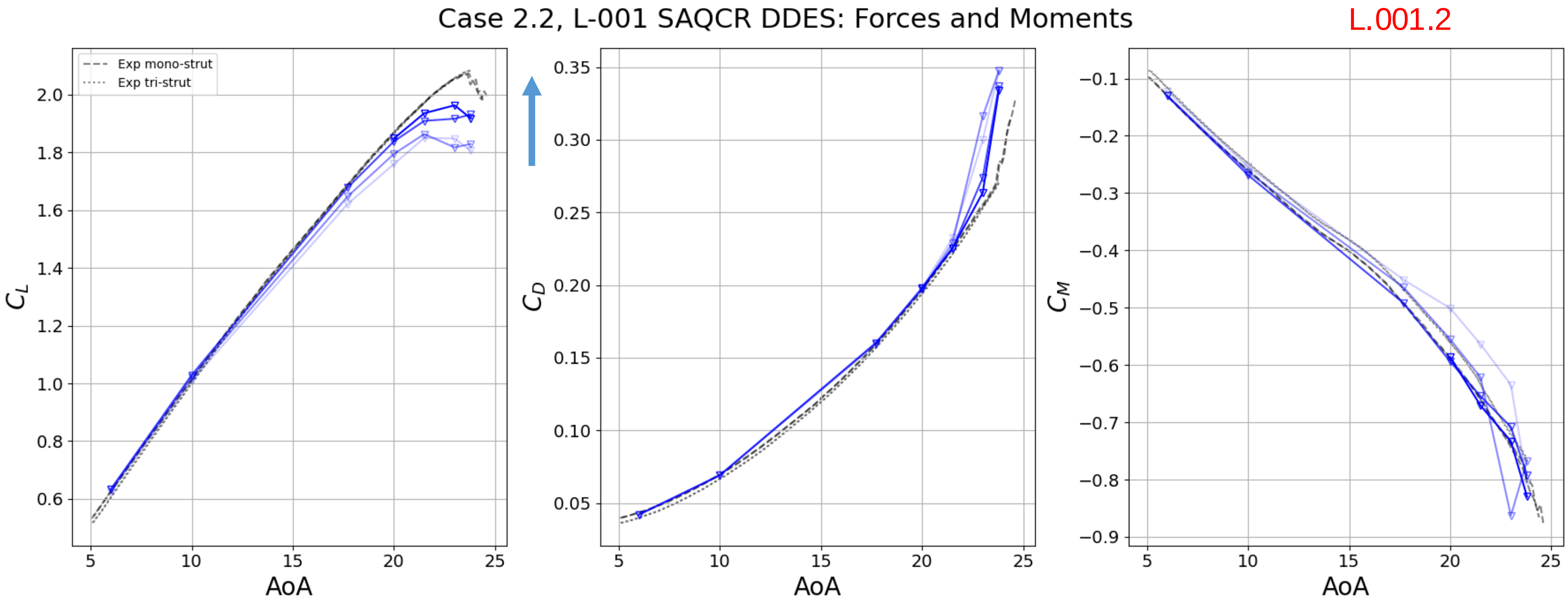
Case 2.2 – All best-practice submissions



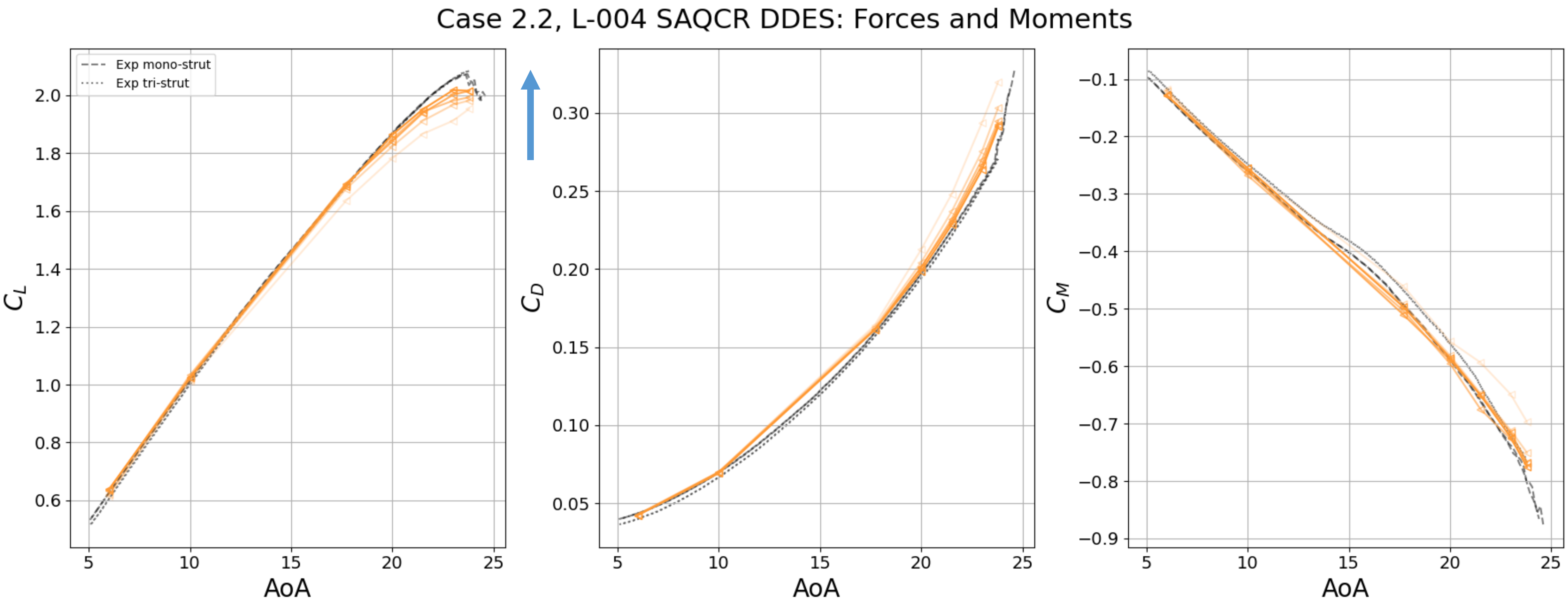
L-015 is an outlier - three other simulations ultimately match closely for their best-practice settings

Case 2.2 - HRLES



As expected, main differences are at higher AoA - clear to see that there is trend of additional mesh refinement moving towards exp. data

Case 2.2 - HRLES



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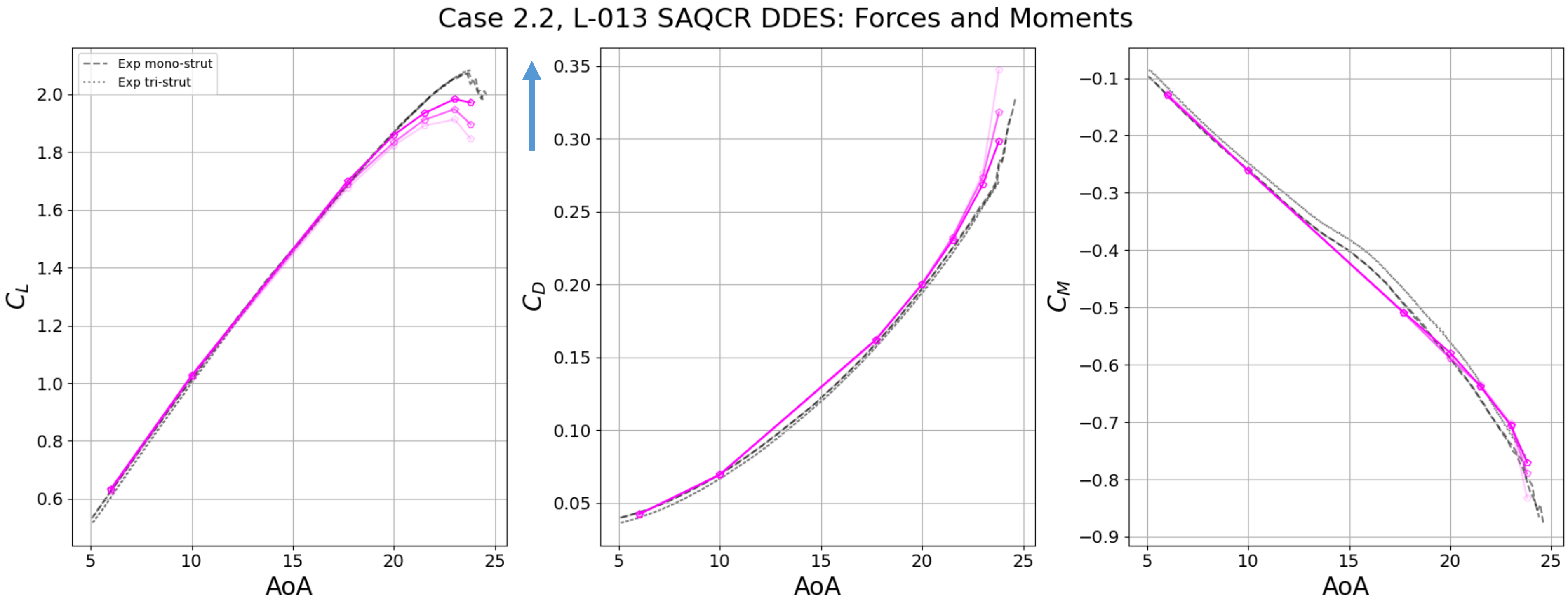
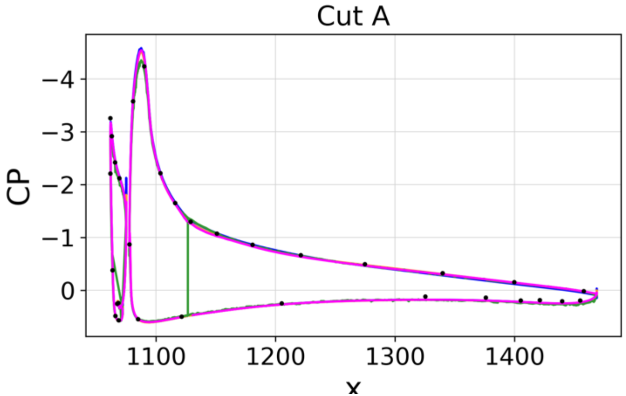
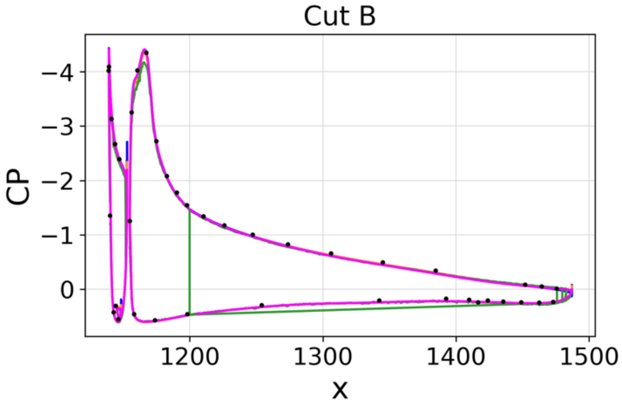


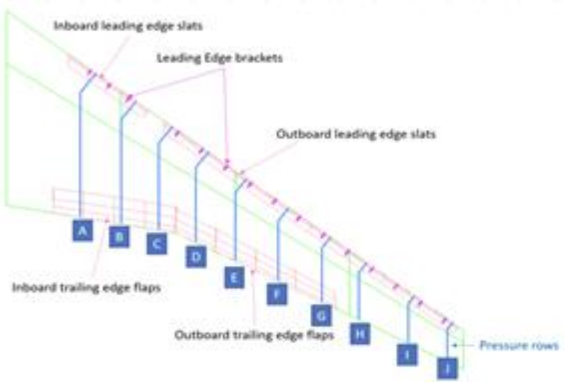
As expected, main differences are at higher AoA - clear to see that there is trend of additional mesh refinement moving towards exp. data

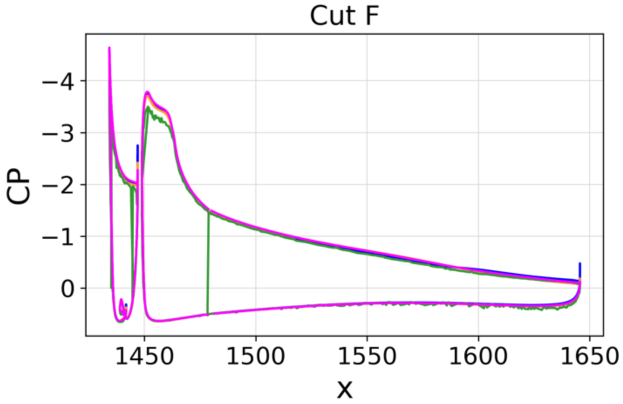
Case 2.2 – 17.7deg AoA –HRLES

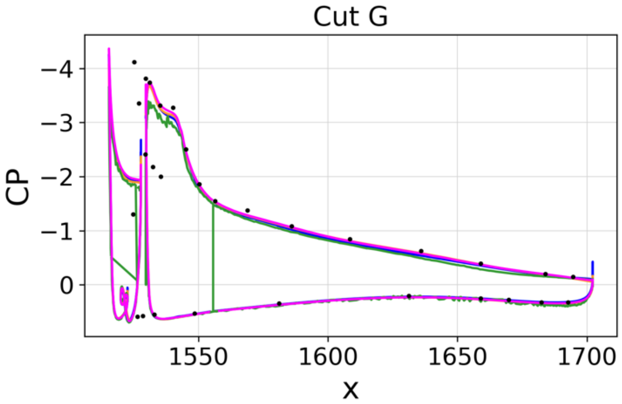
L-001: Blue, L-004: Orange, L-015: Green, L-013: Magenta, Exp: black

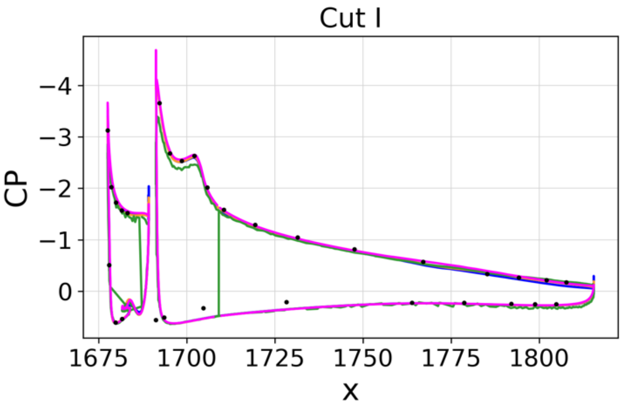








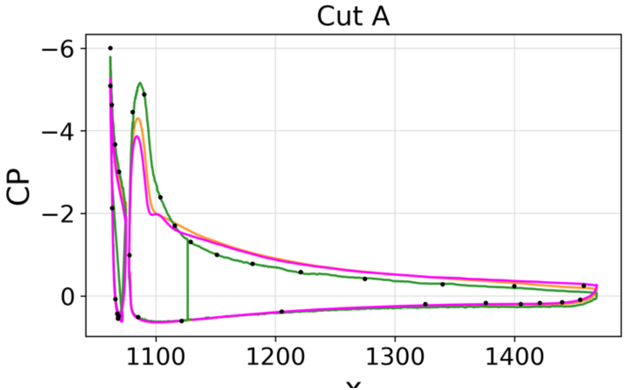


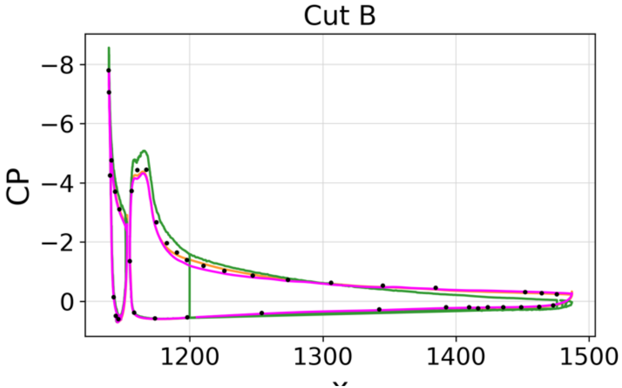


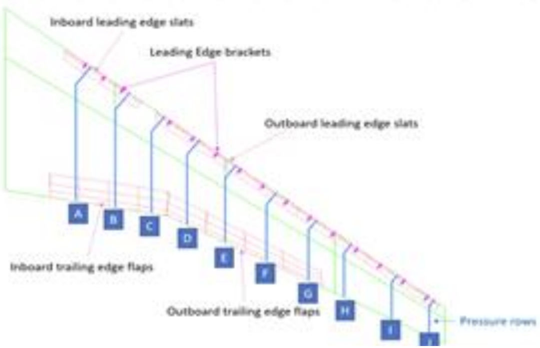
Good correlation reflected in the Cp at 17.7

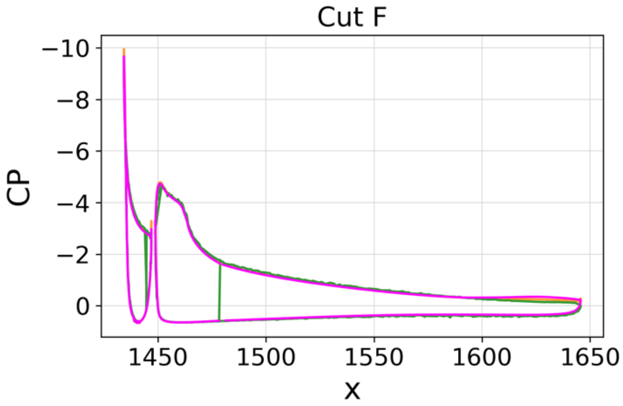
Case 2.2 – 23.8deg AoA –HRLES

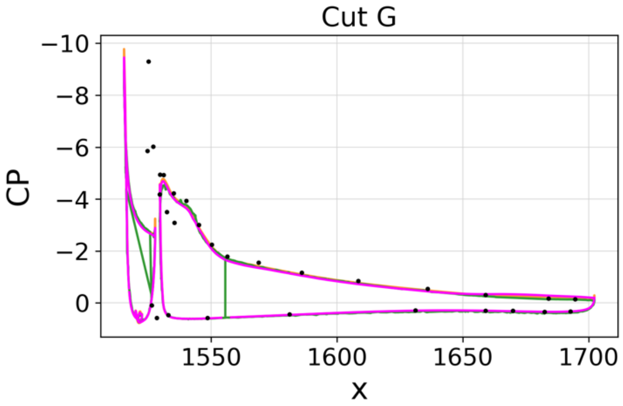
L-001: Blue, L-004: Orange, L-015: Green, L-013: Magenta, Exp: black

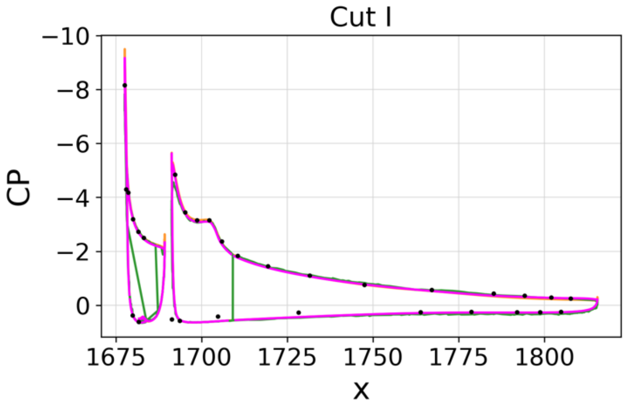






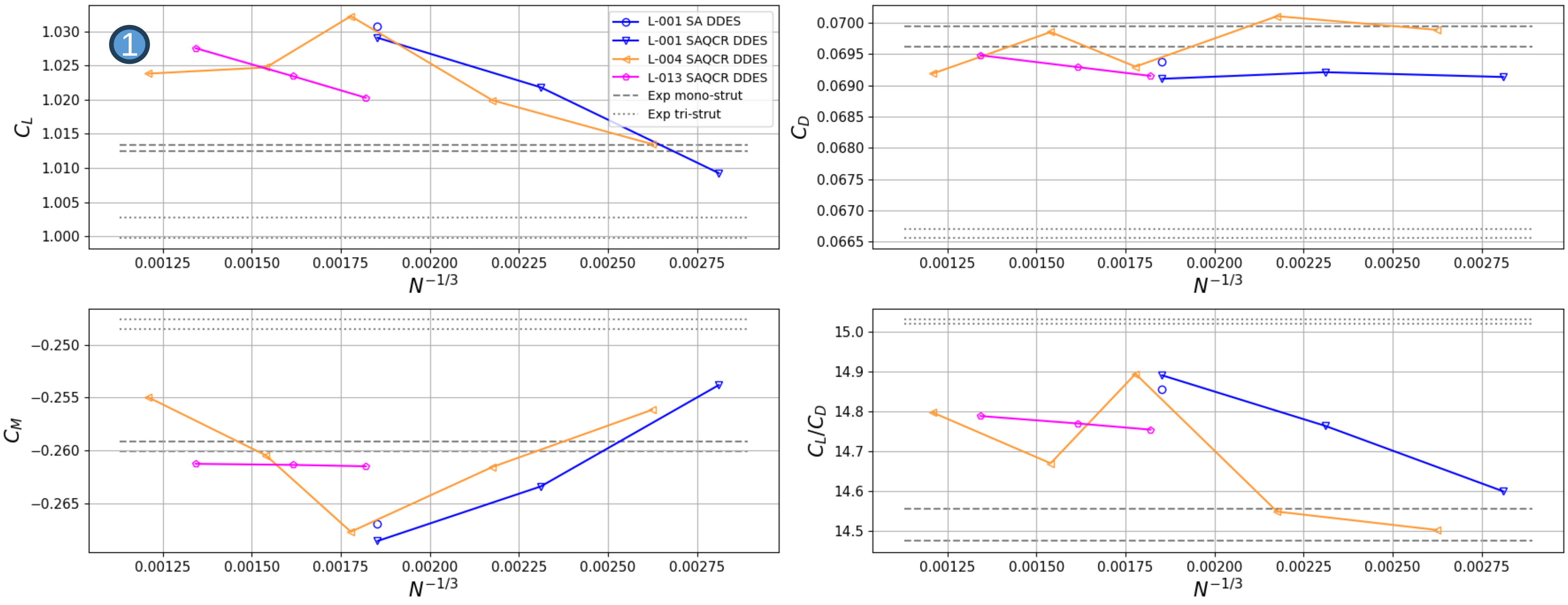






Differences at 23.8 arises from inboard under-prediction of Cp peaks – most obvious at Cut A.

Case 2.2 – 10deg AoA – HRLES (MSD)



1. MSD is less obvious than Case 1 and only L-004 ran grid E. At grid E we do see the signs of what happened to Case 1. However it seems the slat has a delaying influence, given Case 1 showed issues for Mesh D. L-013 used a different grid family and we may need extra grid level to be sure

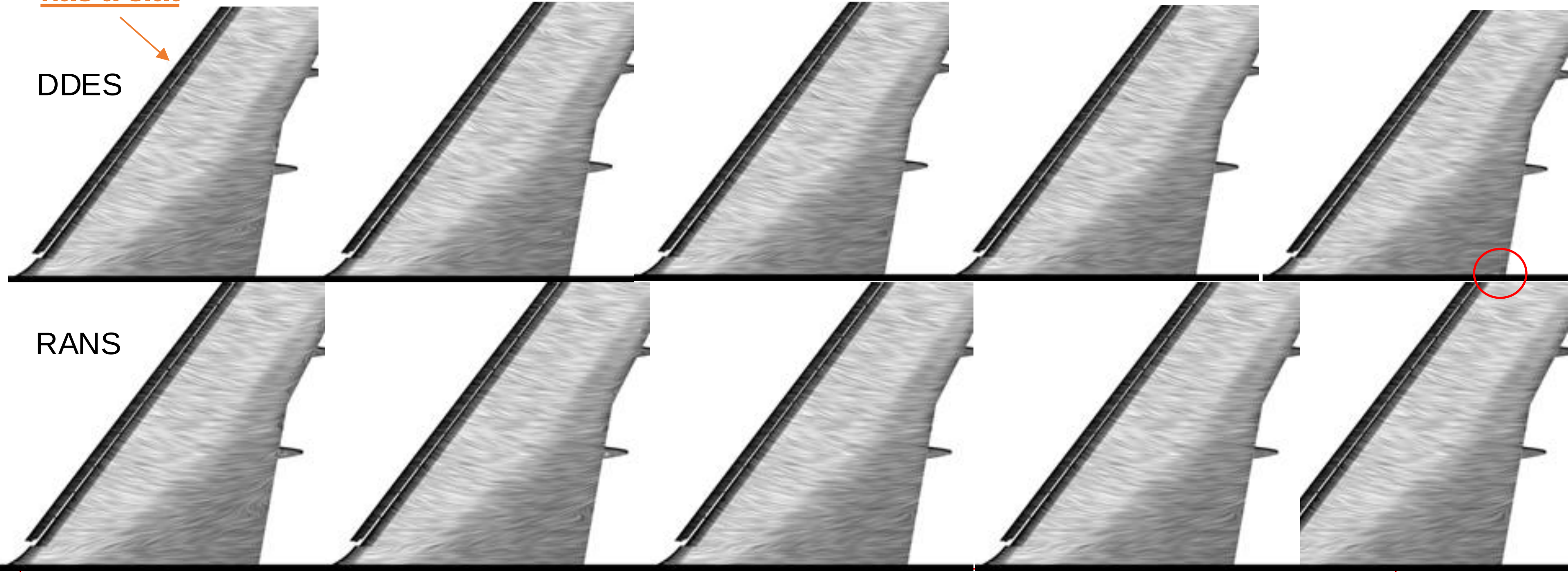
Case 2.2 – 10deg AoA – L.004 – SA-QCR DDES & RANS

Case 2.2 has a slat

Mesh A | Mesh B | Mesh C | Mesh D | Mesh E

DDES

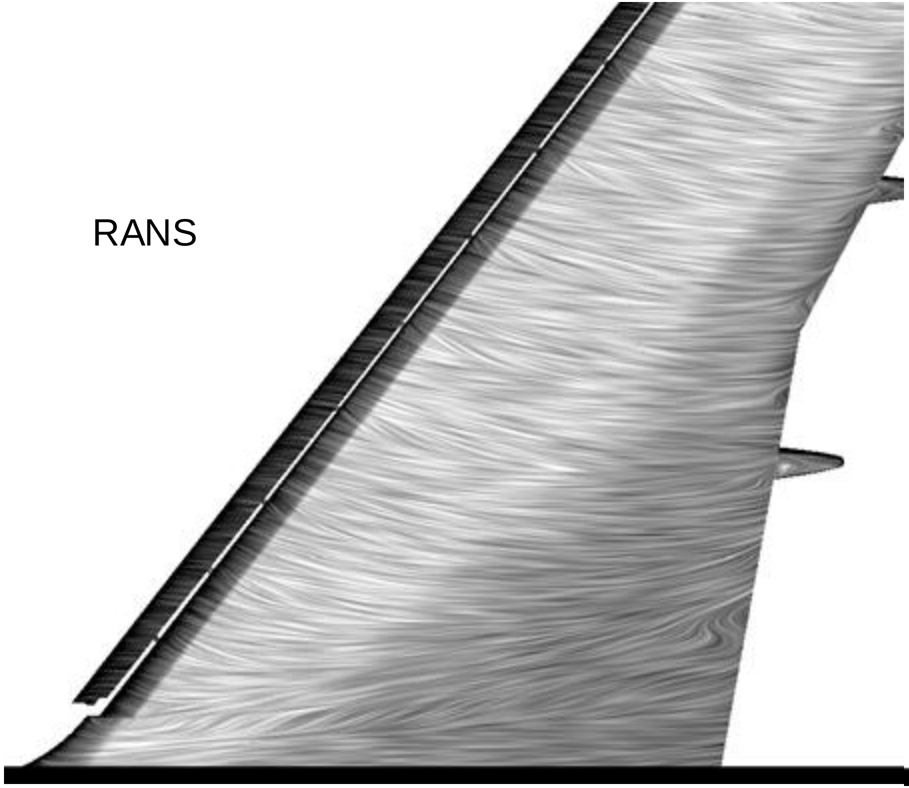
RANS



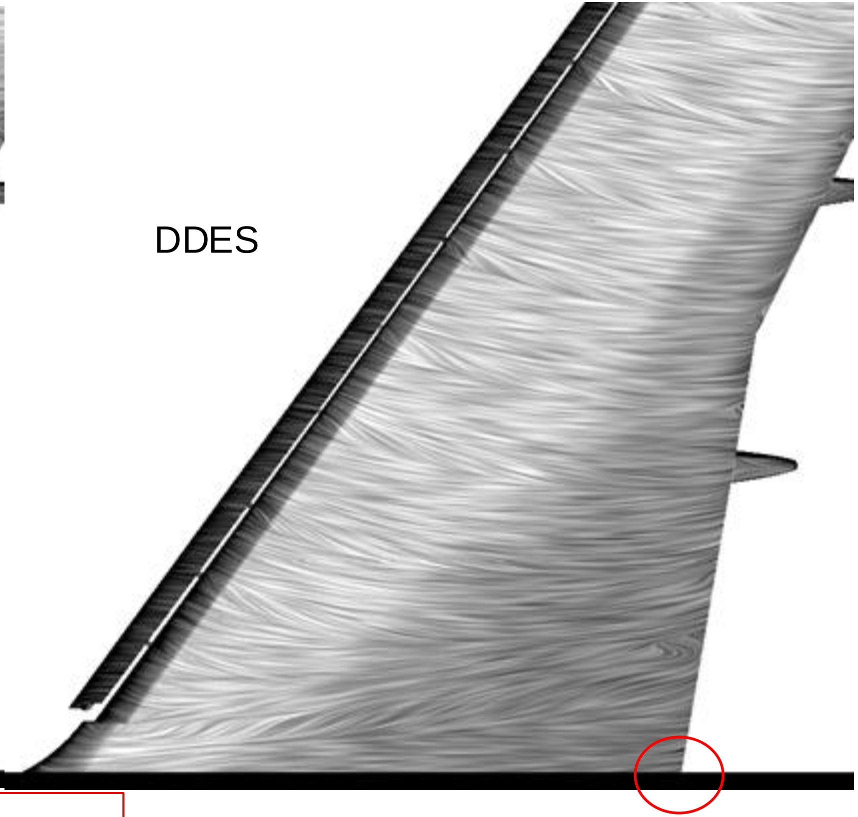
Still need submissions using DR function to better answer

Mesh B

RANS



DDES

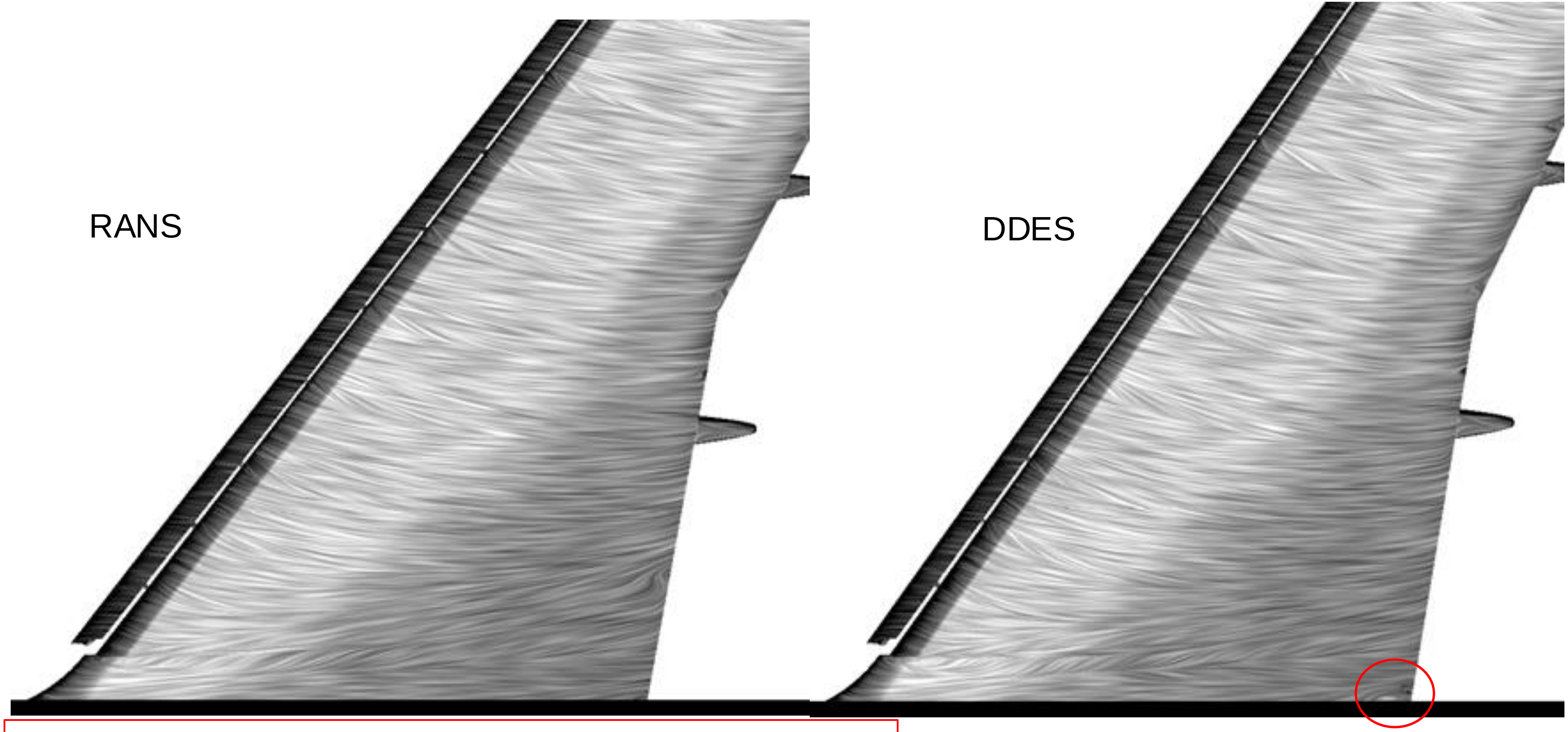


Still need submissions using DR function to better answer

Mesh E

RANS

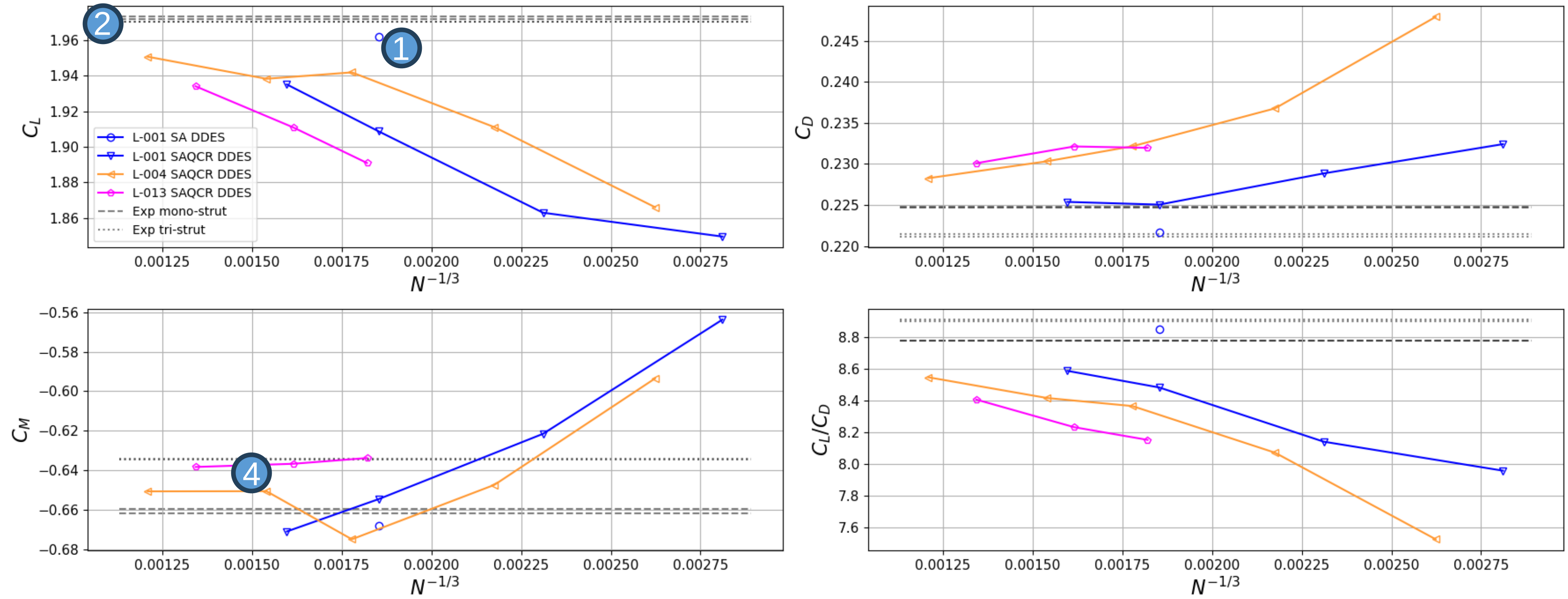
DDES



Still need submissions using DR function to better answer

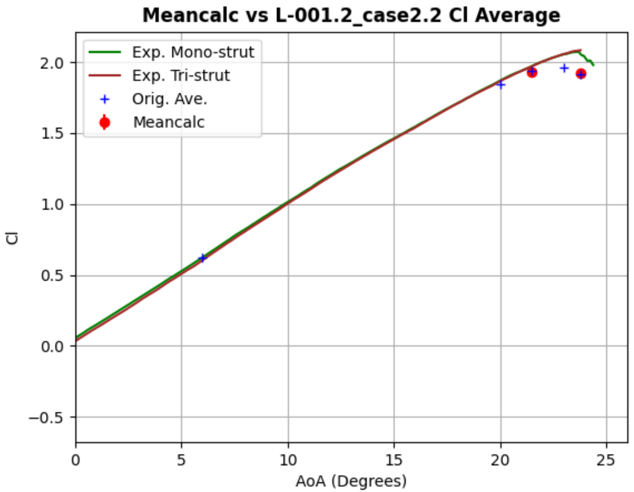
Case 2.2 – 21.5deg AoA - HRLES

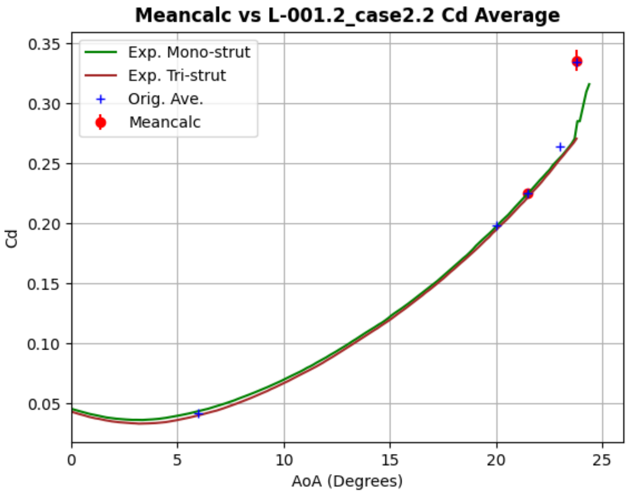
Note: L-001 SA DDES has lower dissipation scheme compared to L-001 SAQCR DDES

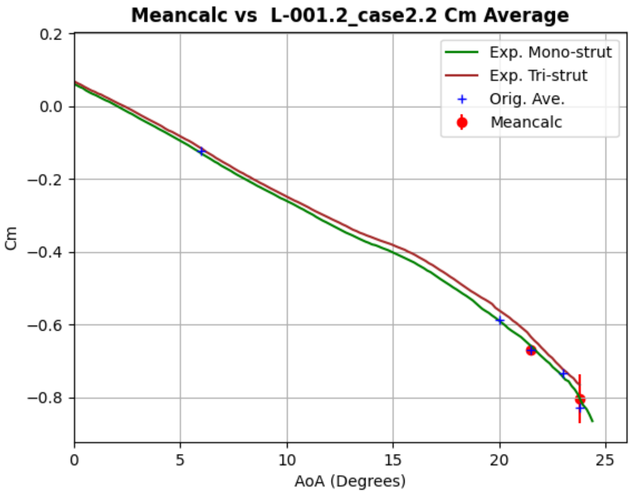


1) Moving to lower dissipation schemes + SA-DDES vs SA-QCR-DDES gave consistent move towards exp. data
2) Majority of submissions are trending towards the exp. Data with increased mesh size, but most likely would need an extra mesh level to be sure (i.e ~500M cells)
3) Pitching moment shows the worst correlation and deviation between methods

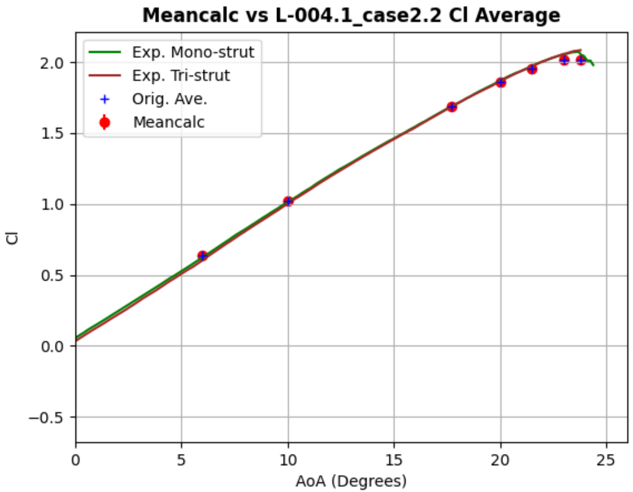
Check on Best-Practice Submission Averages Using Meancalc – Case 2.2

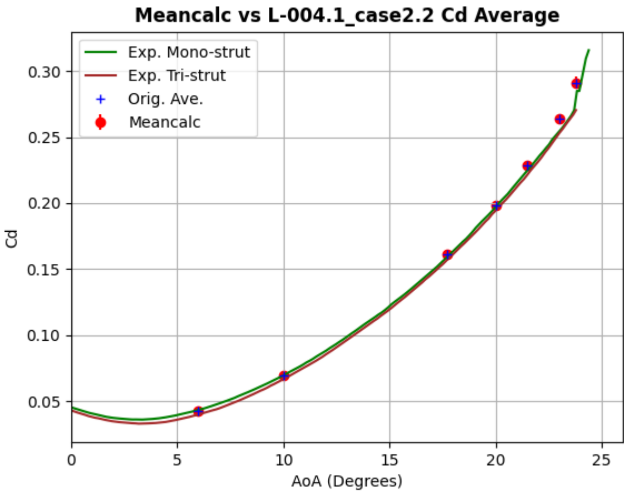


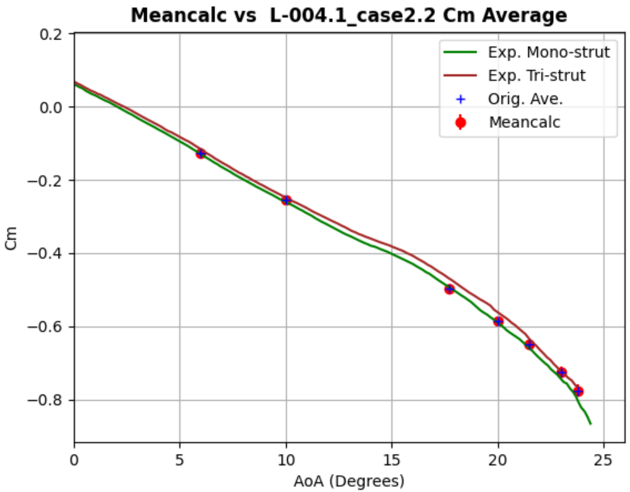




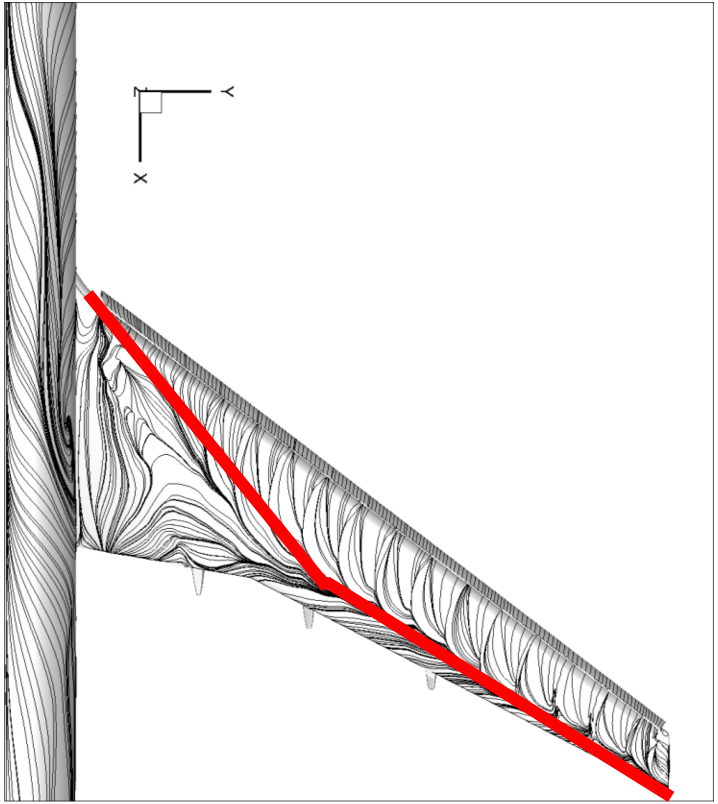
Check on Best-Practice Submission Averages Using Meancalc – Case 2.2



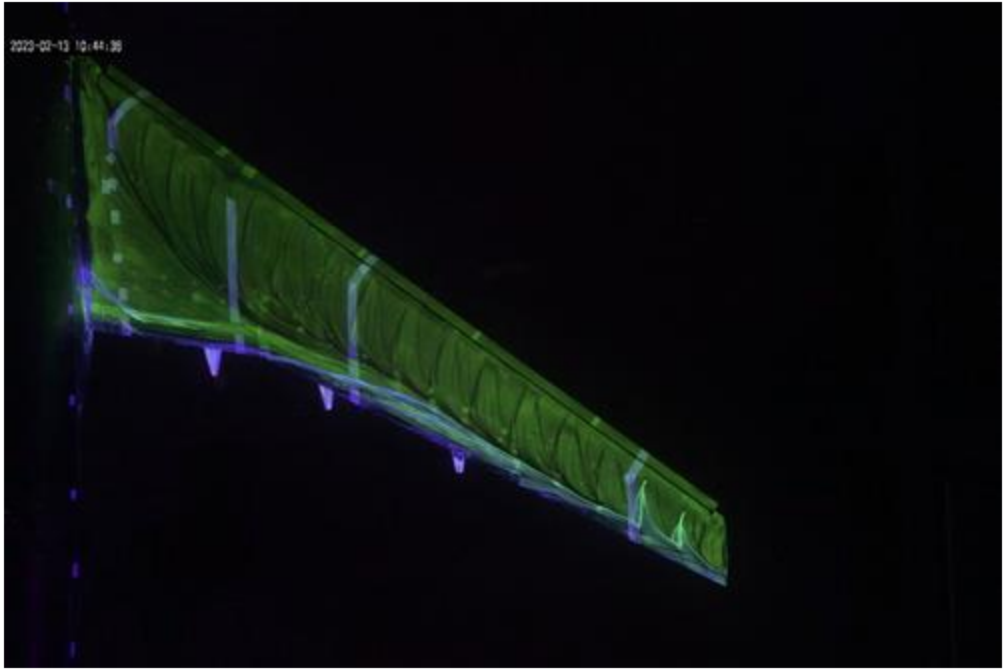




Case 2.2 – L-001 – SA-QCR DDES

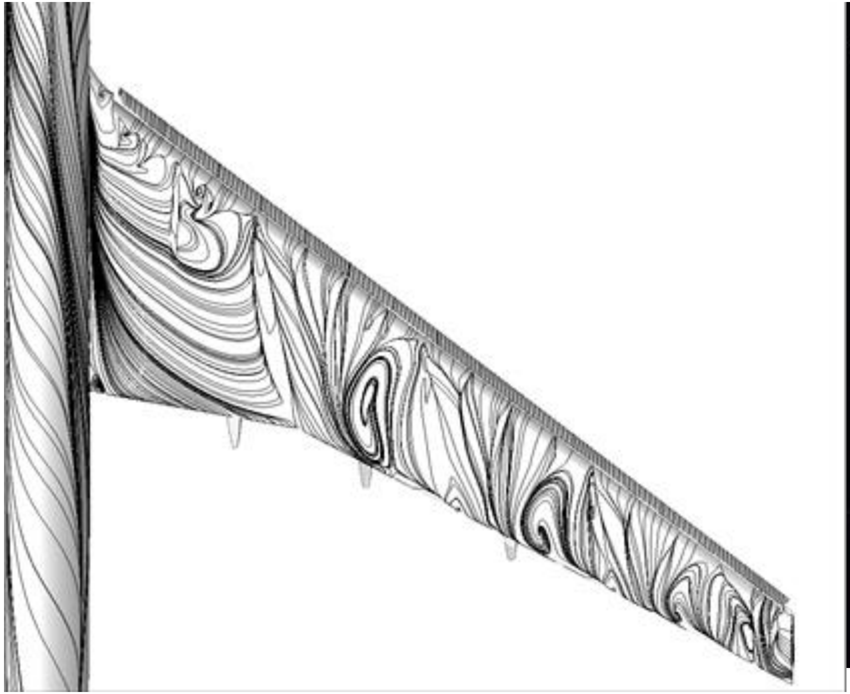


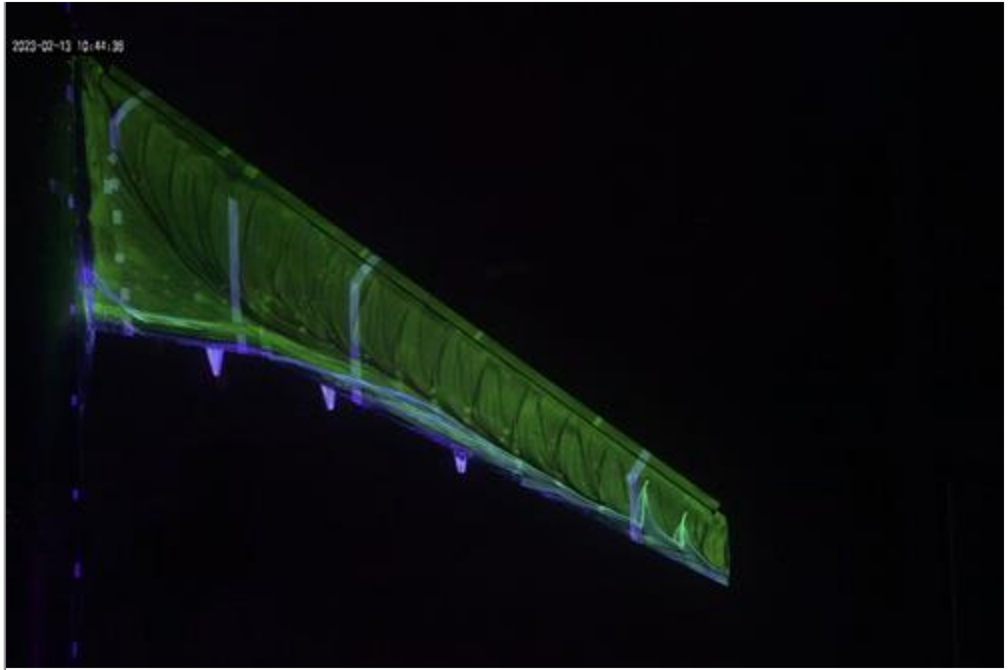
Very strong spanwise flow by 23.8deg AoA



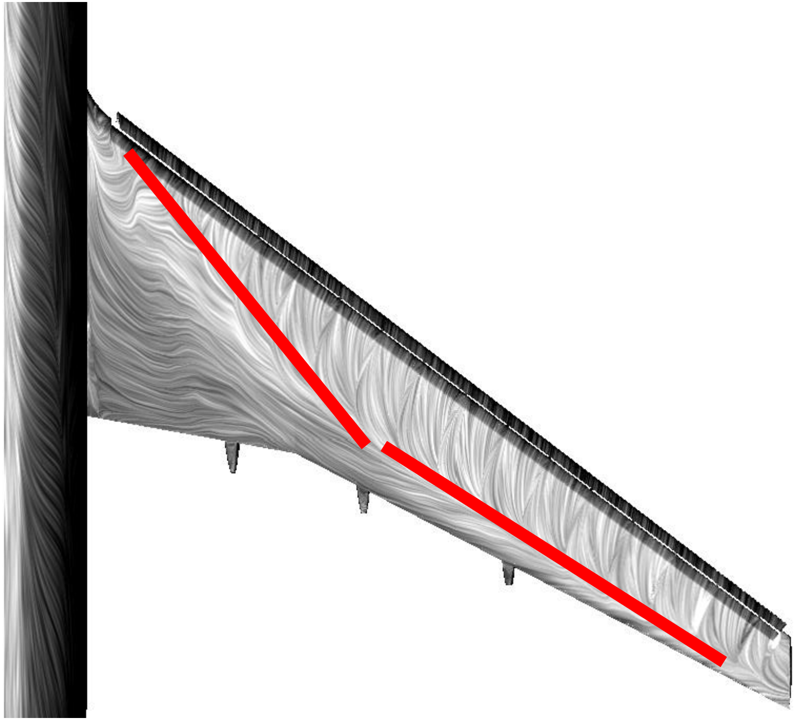
Case 2.2 – L-001 – SA **RANS**

Very different flow predicted by SA **RANS** – much larger separation explains lower C_L at 23.8

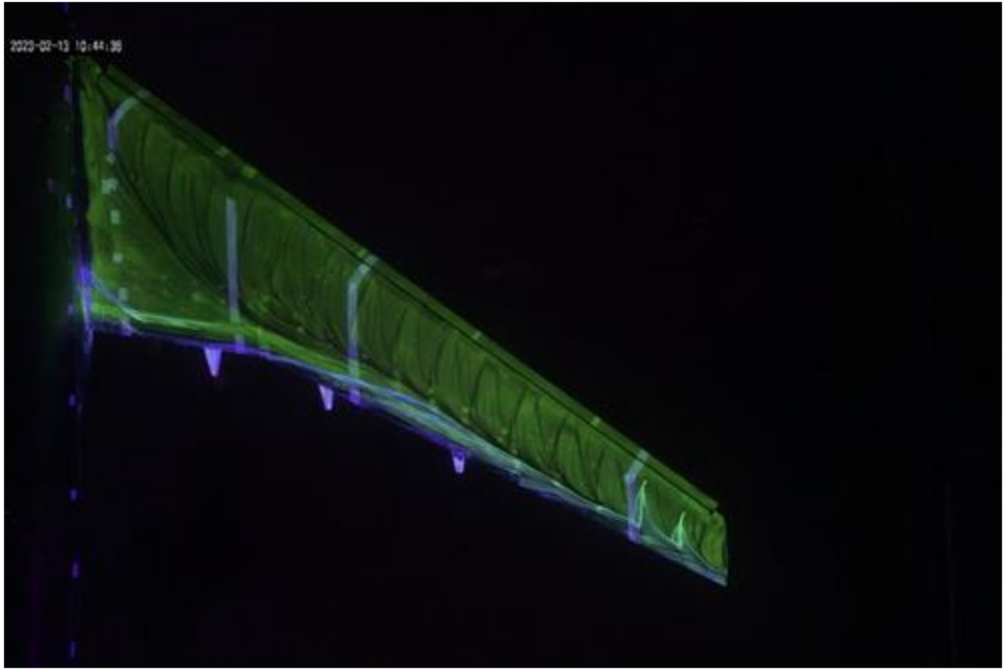




Case 2.2 – L-004 – SA-QCR DDES

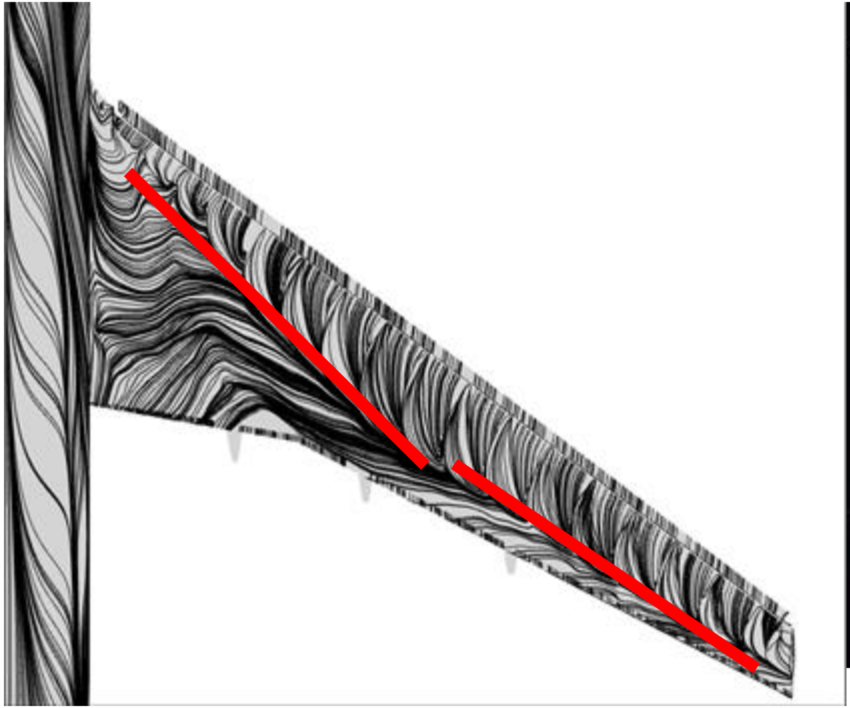


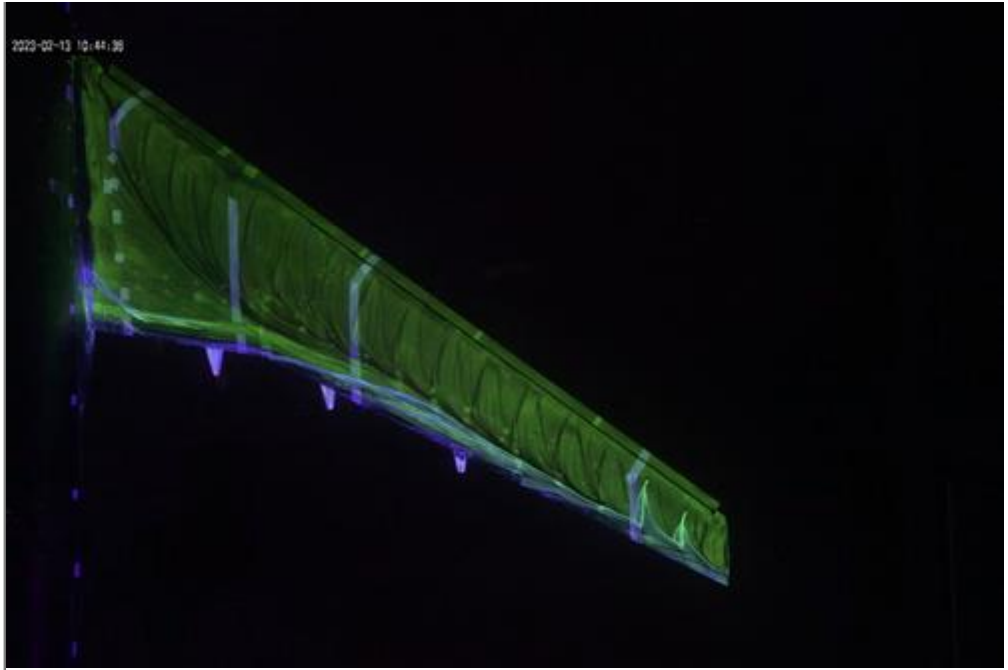
Good agreement



Case 2.2 – L-013 – SA-QCR DDES

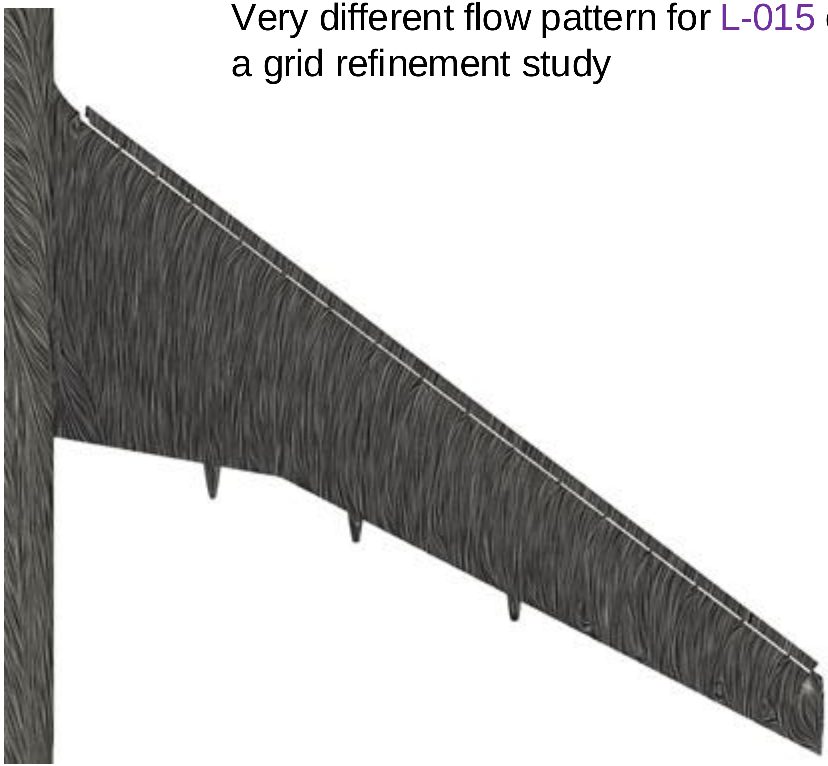
Very strong spanwise flow by 23.8deg AoA

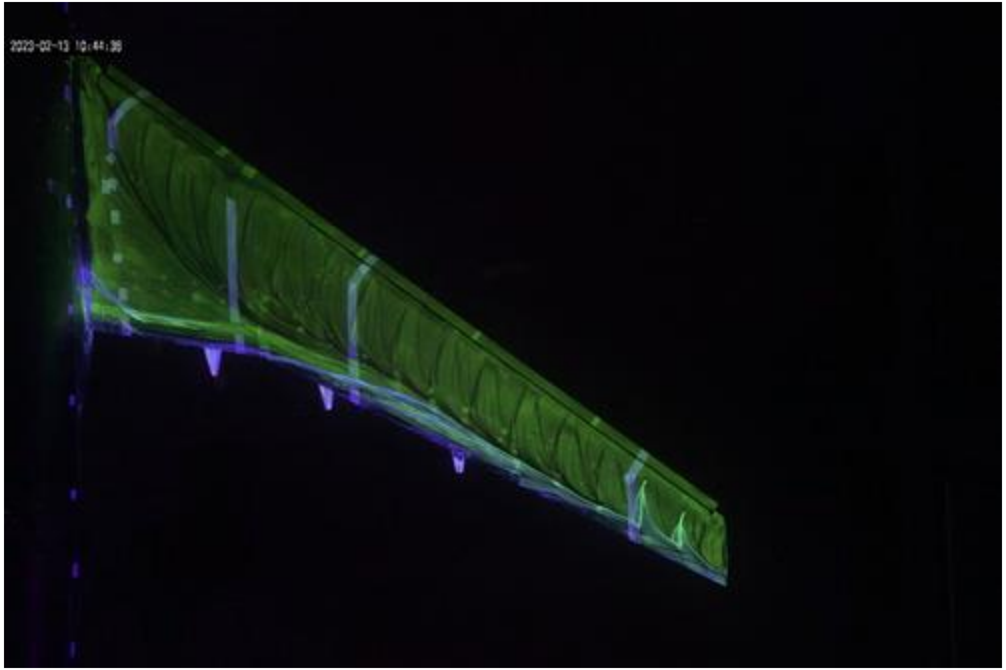




Case 2.2 – L-015 – SST-DDES

Very different flow pattern for L-015 compared to other results – requires deeper analysis and a grid refinement study





Case 2.3

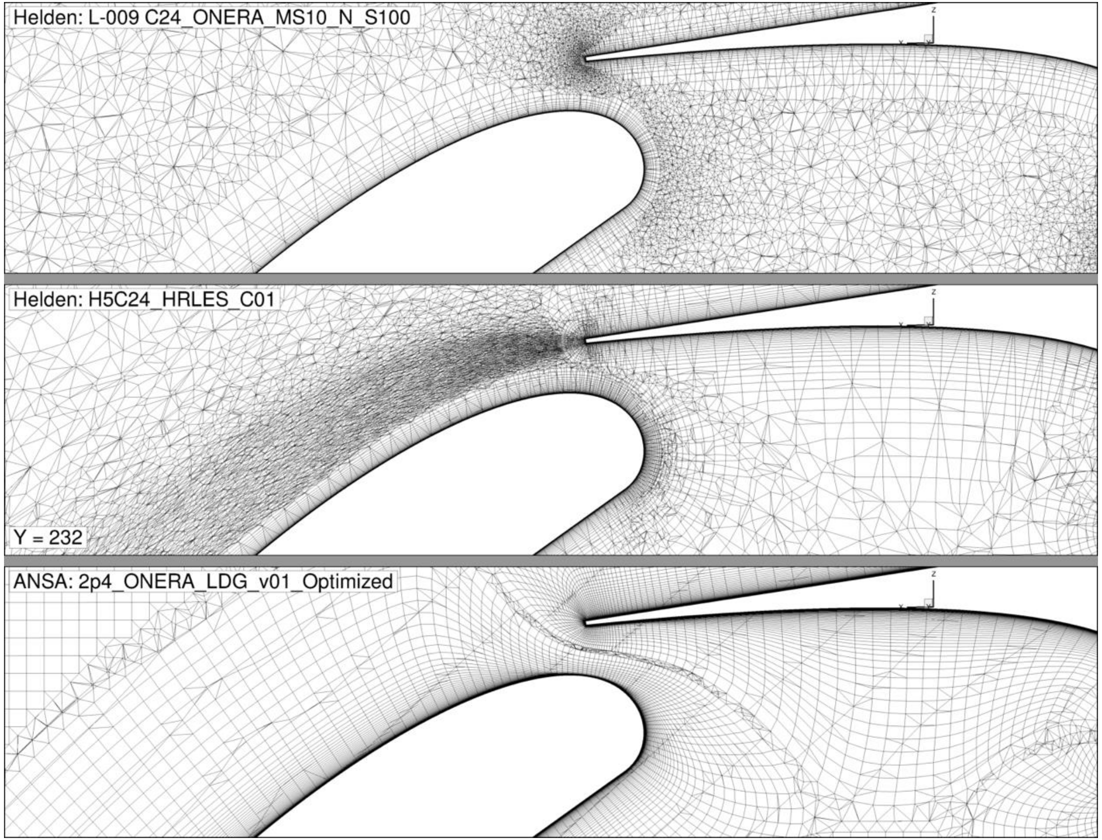
Mesh details (*2p4 but similar for 2.2/2.3*)

L-009 built their own heldenMesh grids (**top**)

L-013 used the committee HeldenMesh grids (**middle**)

L-001 and L-004 used ANSA meshes (**bottom**)

Y=232 (flap shear layer)



“O-level” Mesh - Targeted/Solution-Driven Mesh Refinement – Beyond the C+ Mesh…

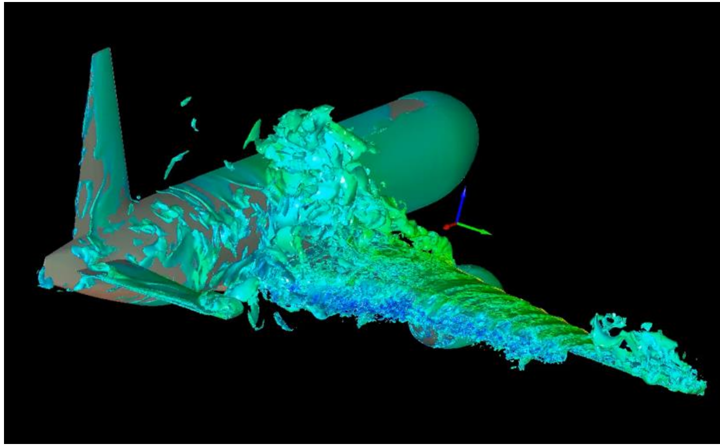
Group effort between multiple groups to create this new grid – not just A-B-C-D-E. (full paper will show differences more clearly)

Mesh C+ mesh solution used to compute a (short) time-averaged solution of total TKE at lowest and highest AoAs (7.6 and 23.6 degrees):

Normalized Total TKE = $\frac{1}{2U_\infty^2}\left[\left(\overline{u_i'u_i'}\right)_{resolved} + \left(\overline{u_i'u_i'}\right)_{modeled}\right]$

With $\left(\overline{u_i'u_i'}\right)_{modeled}$ approximated via trace in QCR terms (Bradshaw’s hypothesis

Two solutions (7.6 and 23.6 degrees) are averaged to produce a metric relevant for requested AoA range

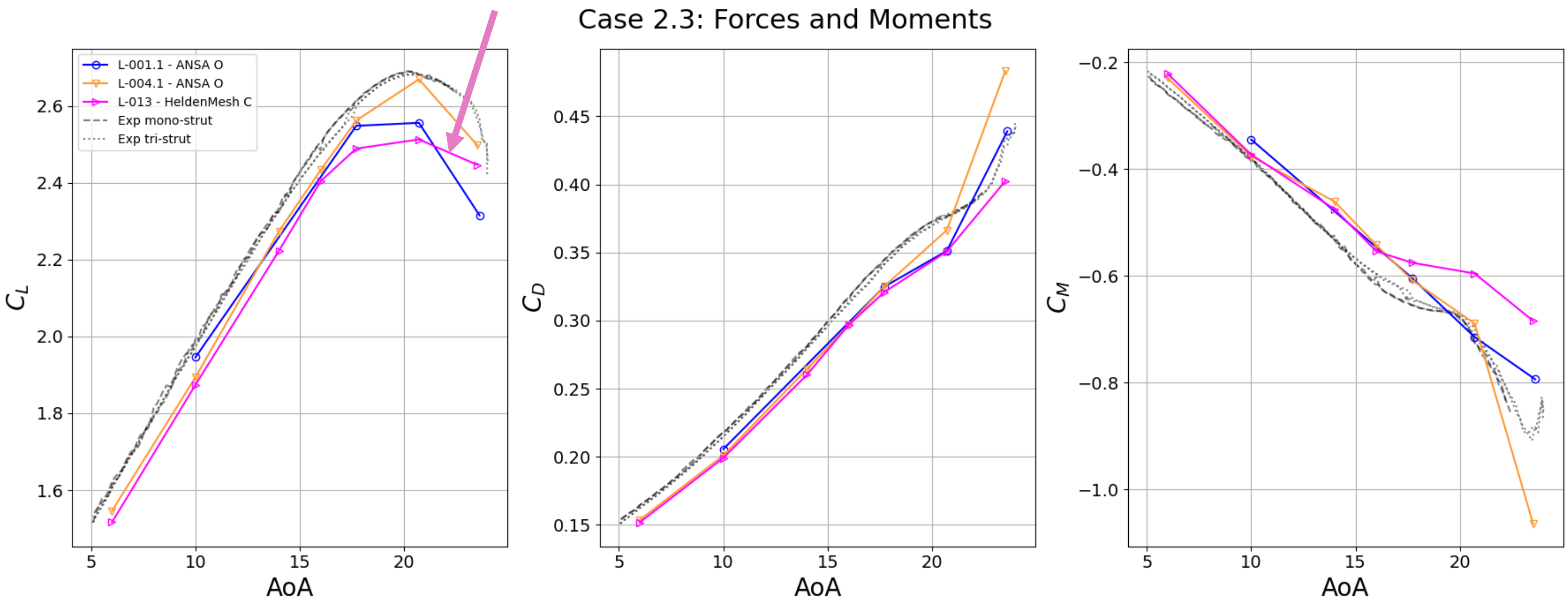


Combined & normalized TKE = 0.005 isosurface

Case 2.3

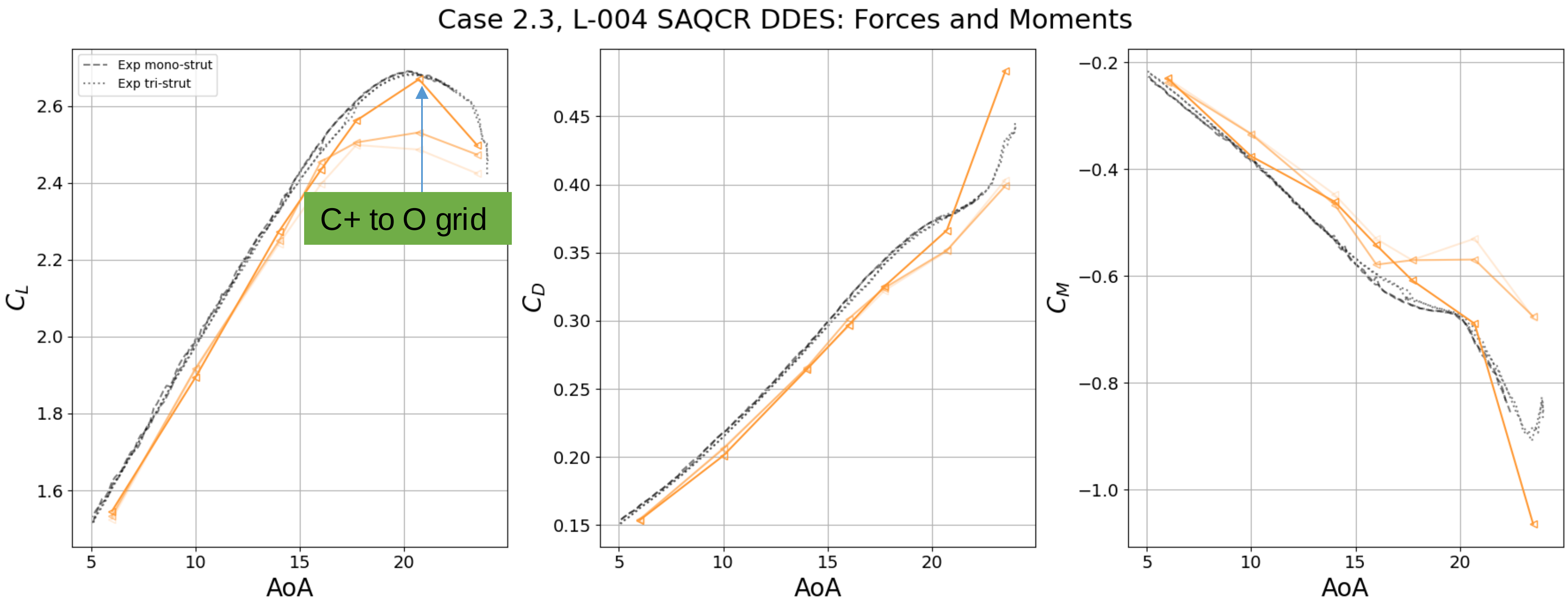
L-013 had less grid resolution than L-004.1 (they focused on 2.4 or had limited HPC resources) – O-level grid made a big difference

Summary paper will have more analysis of the flap prediction issue at low-mid AoA



2.3 much more challenging than 2.2 due to addition of the flap

Case 2.3

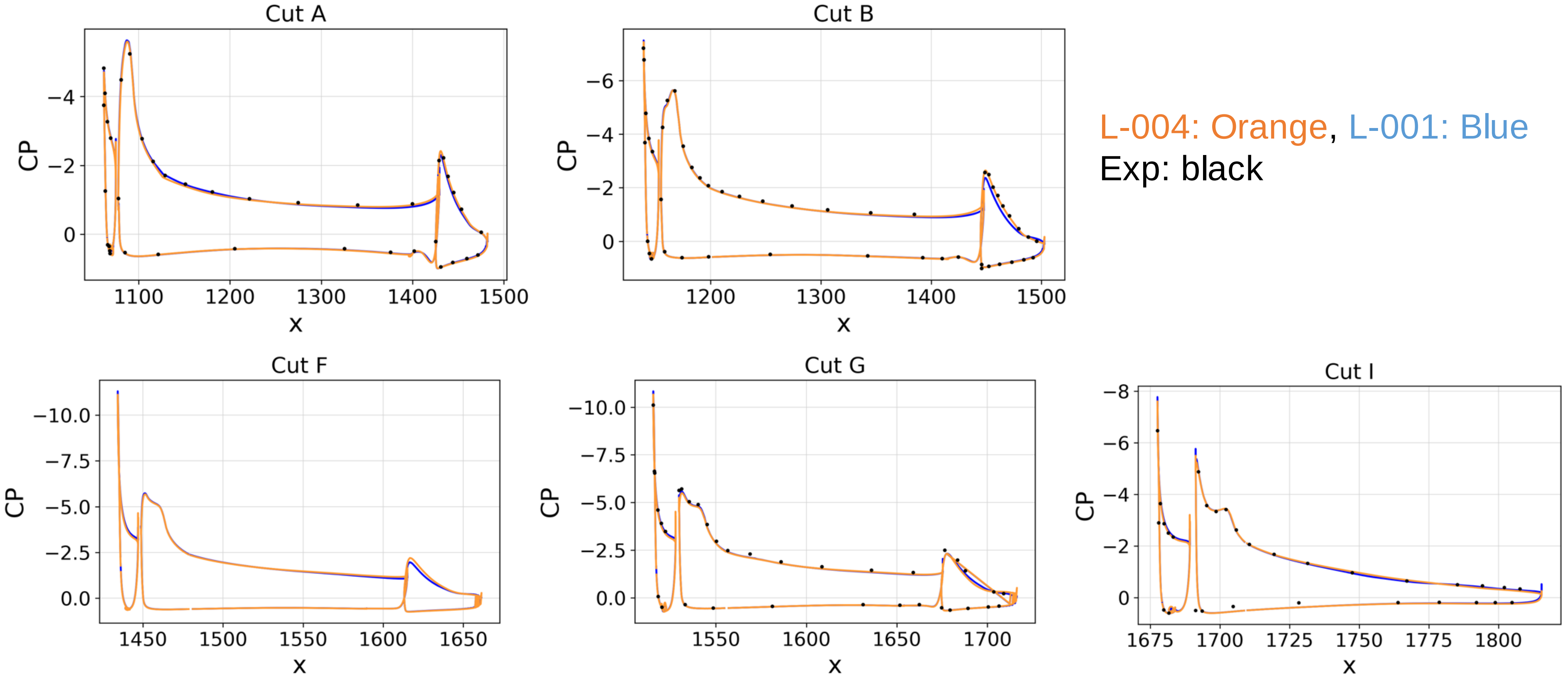


"O-level" grid helped but still more work to focus on mesh topology, not just refinement.

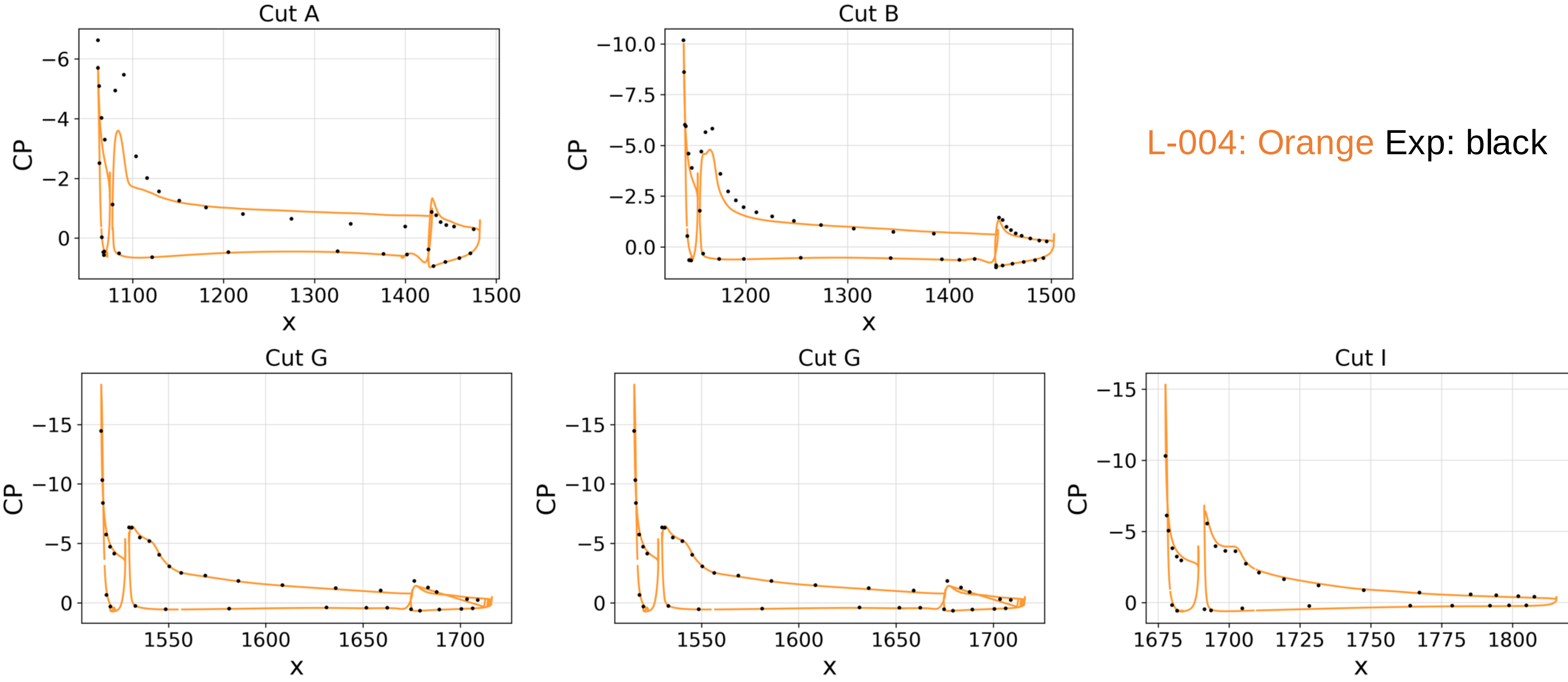
Case 2.3

Clear that additional refinement is still needed

Case 2.3 – 17.7deg AoA –HRLES



Case 2.3 – 23.5deg AoA –HRLES

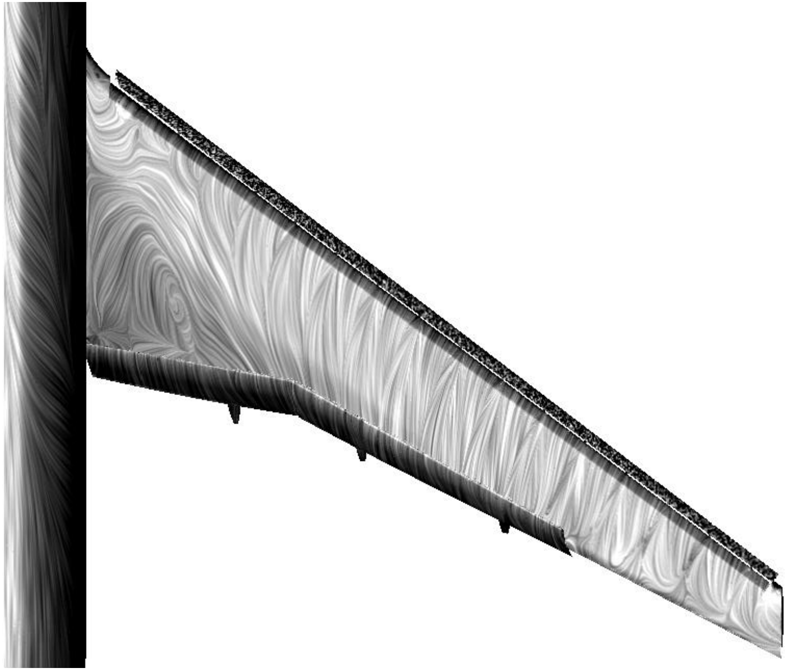


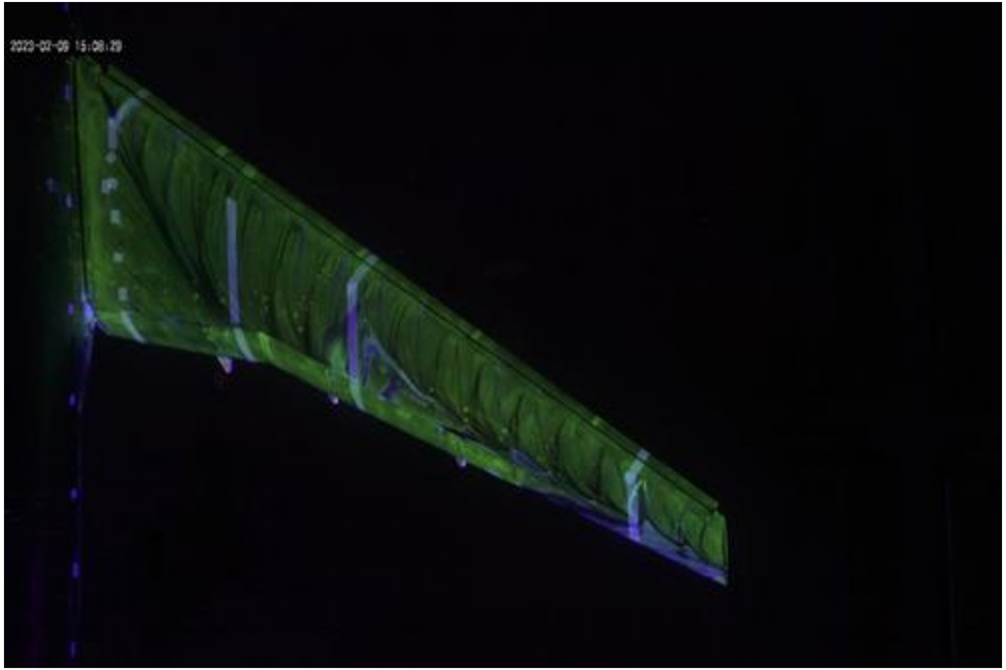
L-004: Orange Exp: black

Similar to 2.2 at highest AoA, inboard cuts show the biggest differences (both A and B)

Case 2.3 – L-004 SA-QCR DDES

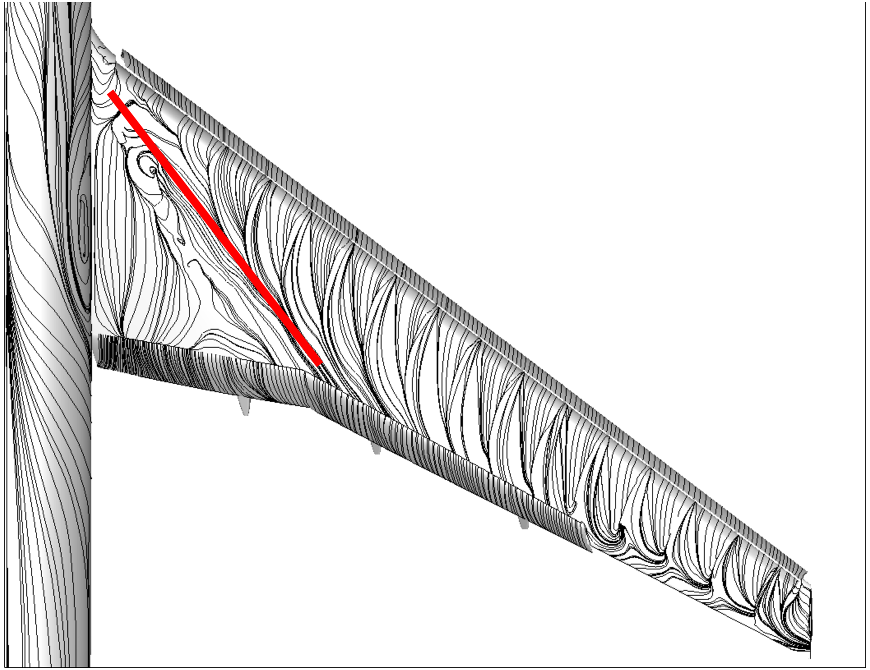
Similar strong spanwise flow at 23.5 as 2.2 but flaps restrict it mainly inboard (exp. and L-004)

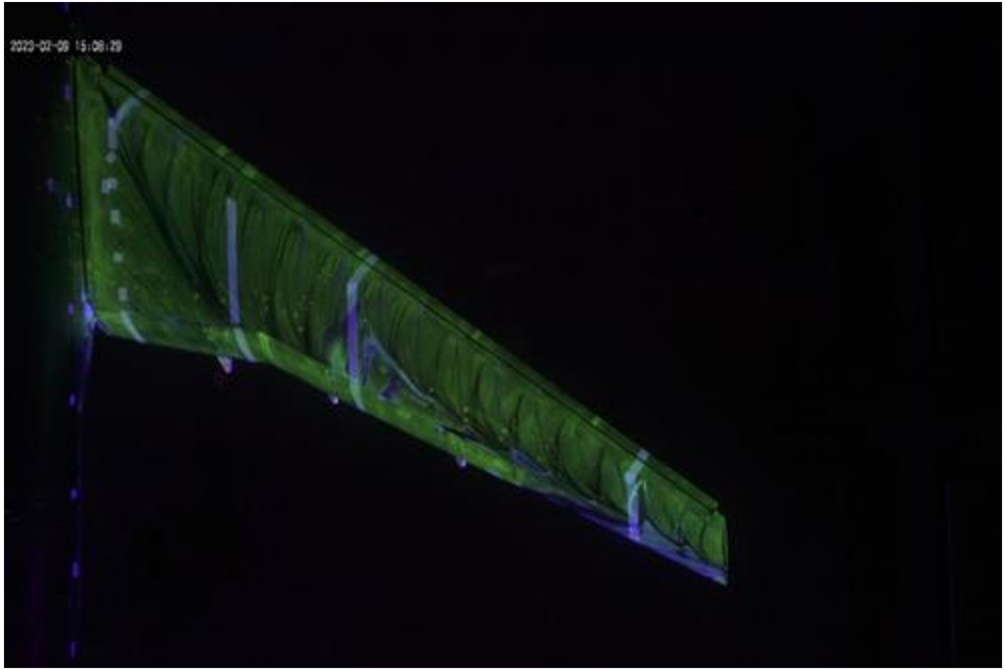




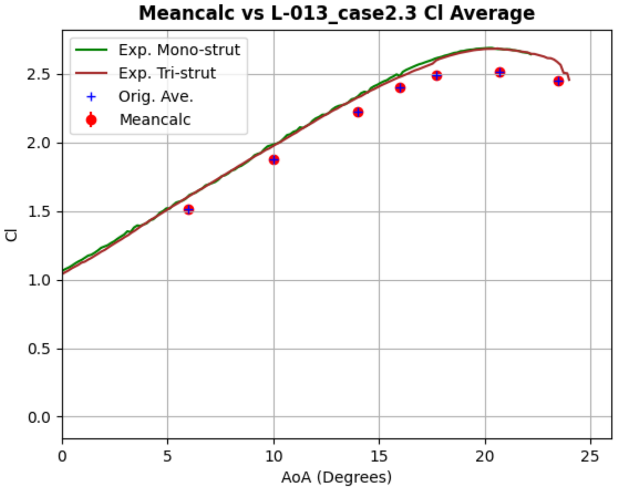
Case 2.3 – L-001 SA DDES (*with low dissipation scheme*)

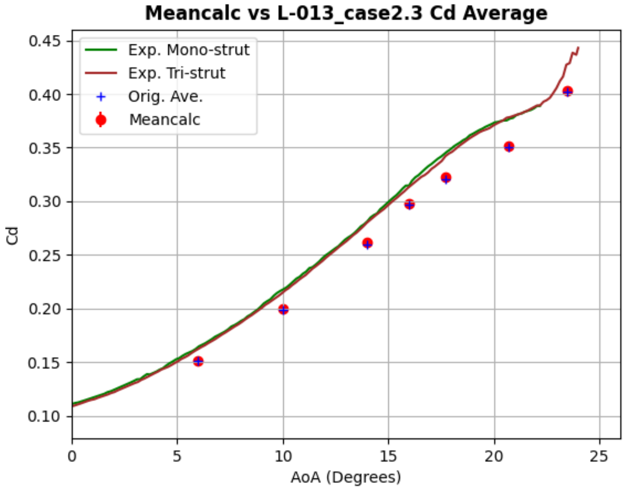
Similar between L-001 and L-004 – capture main features of the flow – slightly larger separation than exp.

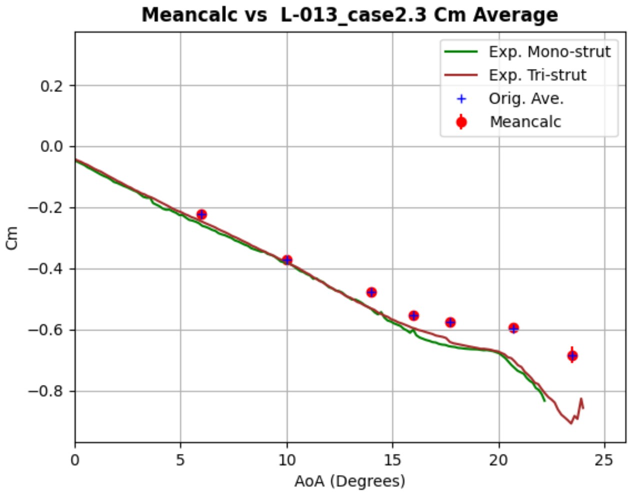




Check on Best-Practice Submission Averages Using Meancalc – Case 2.3



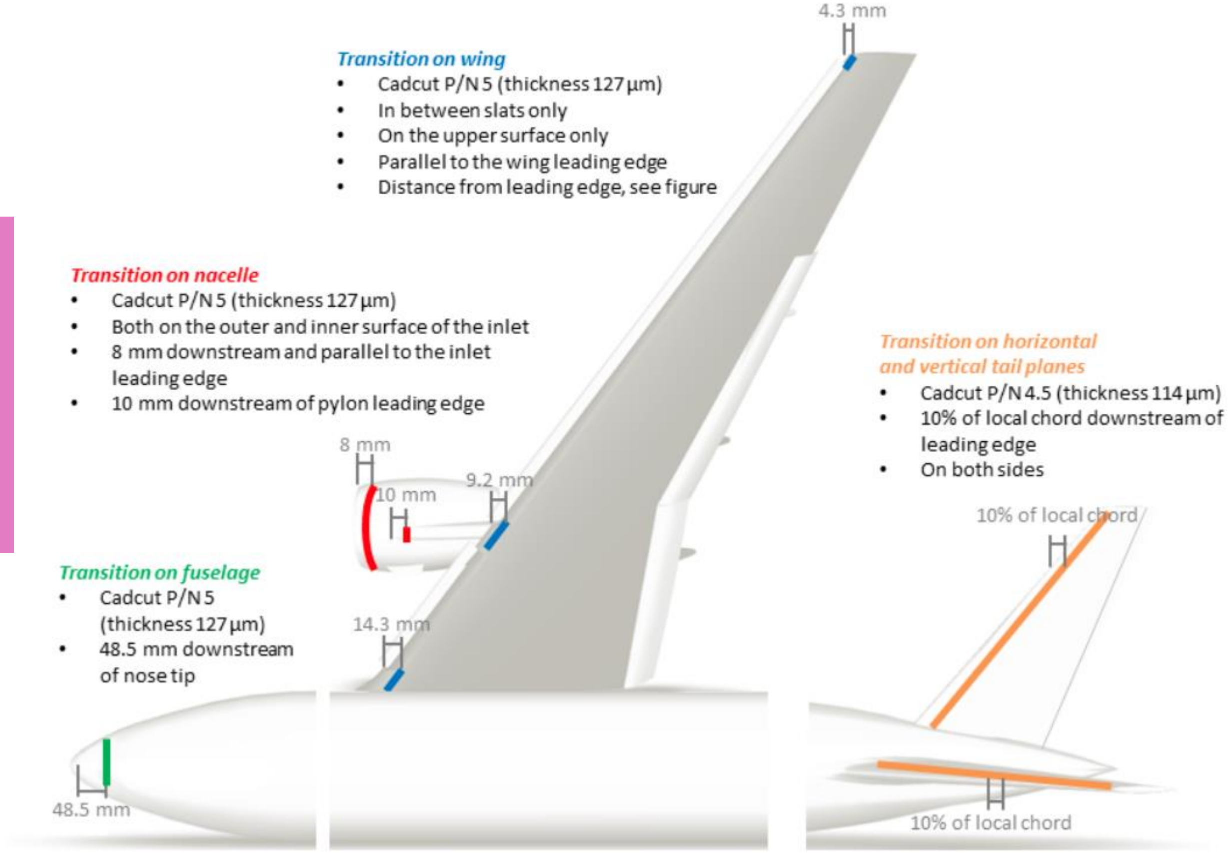




Transitional Studies with Langtry-Menter Model + Experimental Trips

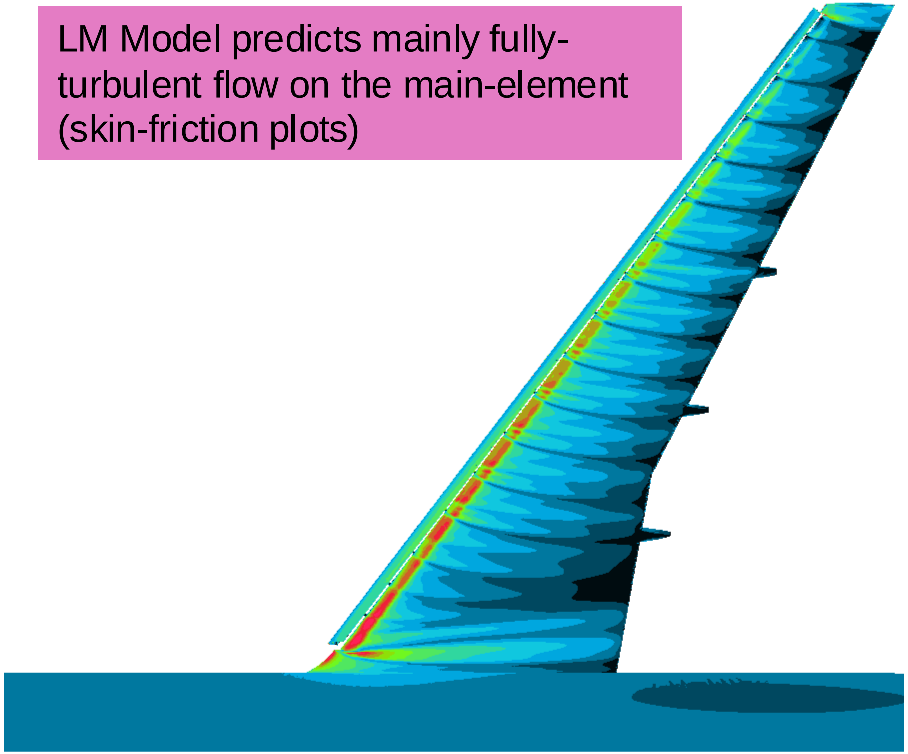
Given Re=5.8M, geometry has select trip points along slot

“No tripping is applied on section of the wings where slats and flaps are present”

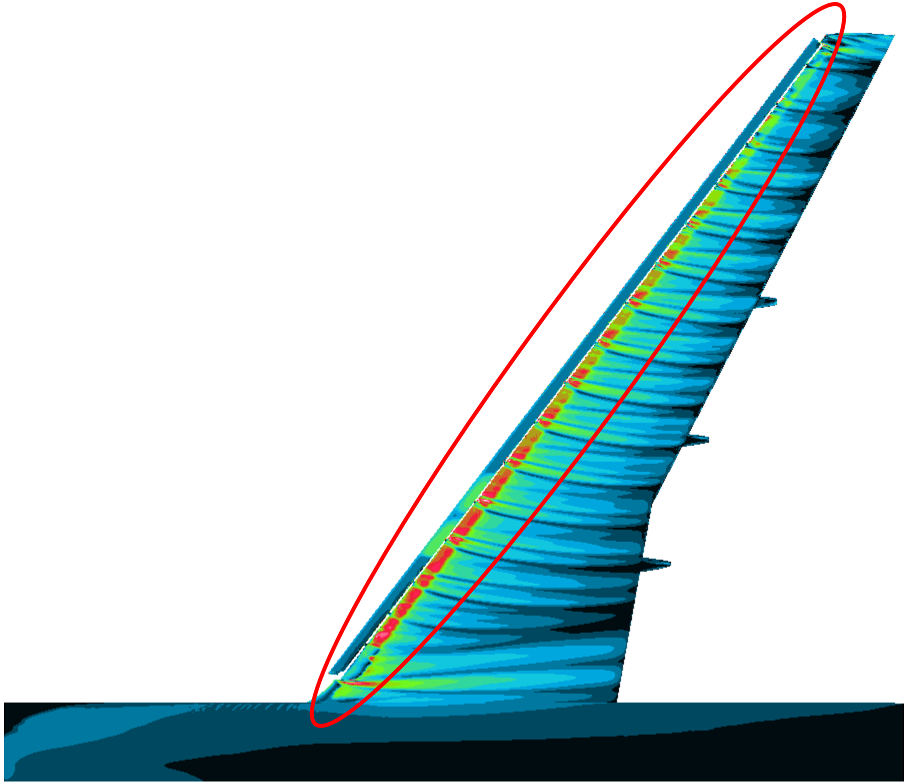


Case 2.2 – L-004 HRLES vs LM+Trips – 6 deg AoA

LM Model predicts mainly fully-turbulent flow on the main-element (skin-friction plots)



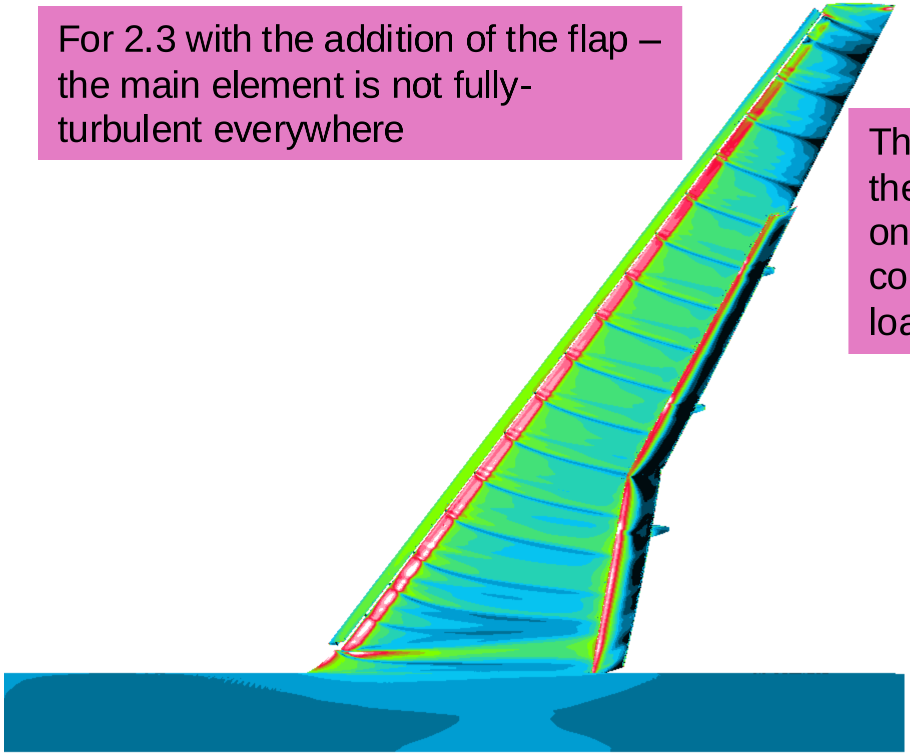
SA-QCR-DDES – Mesh D



RANS- Langtry-Menter+Trips – Mesh D

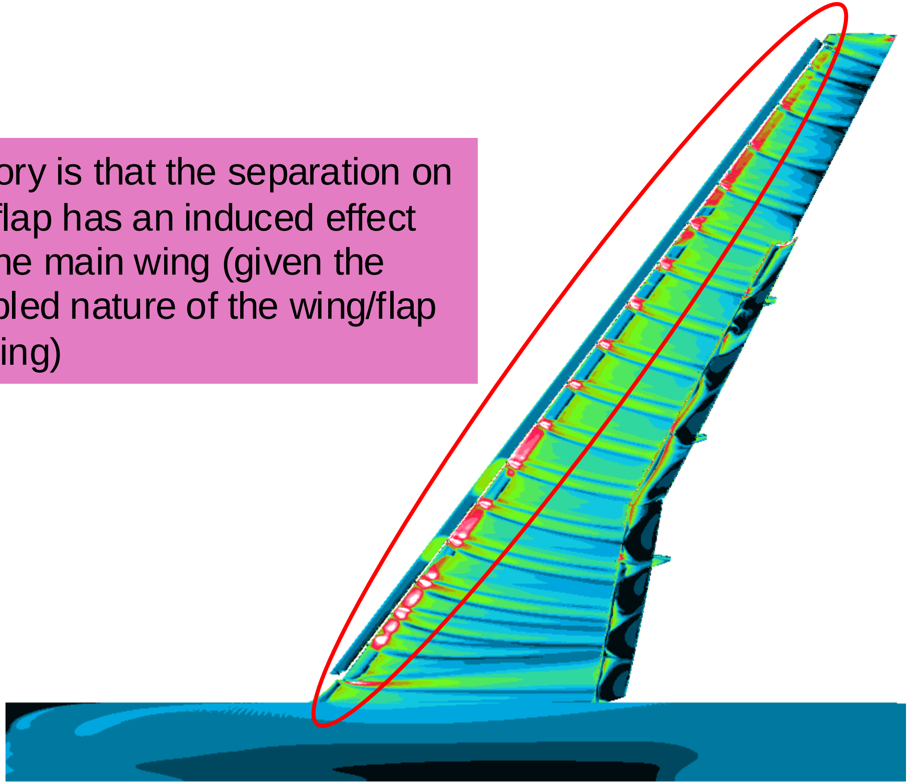
Case 2.3 - HRLES vs LM+Trips – 6 Degree AoA

For 2.3 with the addition of the flap – the main element is not fully-turbulent everywhere



SA-QCR-DDES – Mesh D

Theory is that the separation on the flap has an induced effect on the main wing (given the coupled nature of the wing/flap loading)

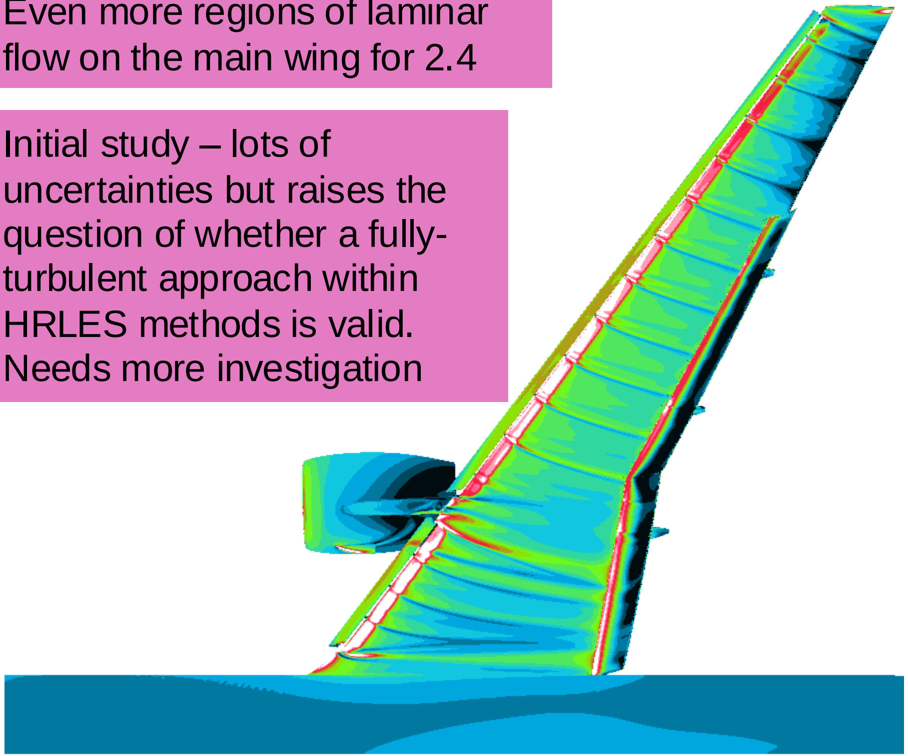


RANS- Langtry-Menter+Trips – Mesh D

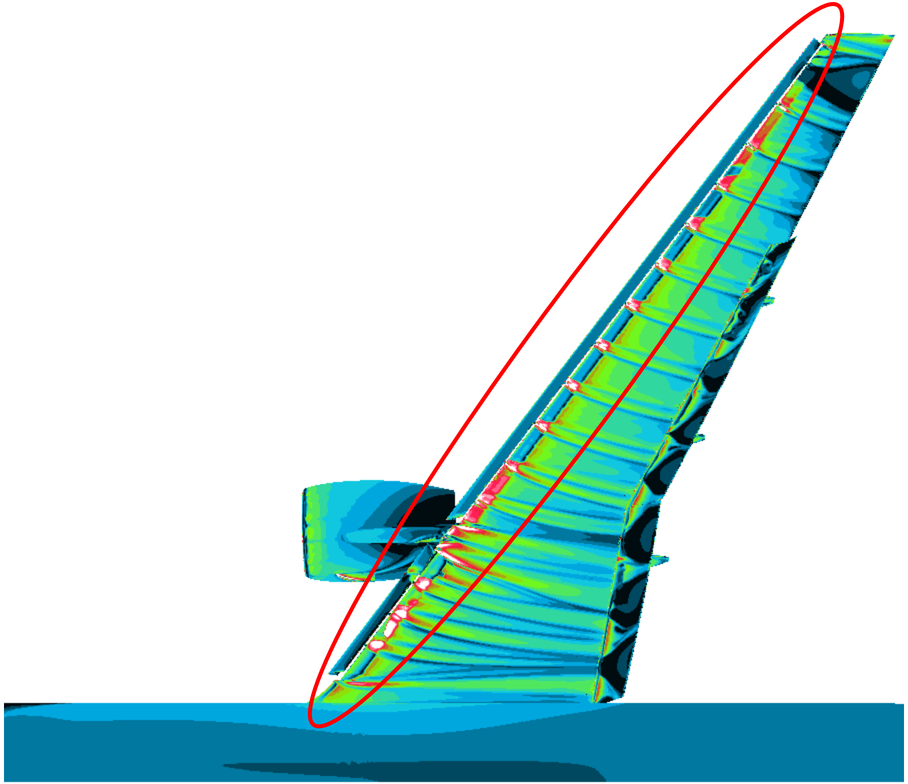
Case 2.4 – HRLES vs LM+Trips – 7.6 Degree AoA

Even more regions of laminar flow on the main wing for 2.4

Initial study – lots of uncertainties but raises the question of whether a fully-turbulent approach within HRLES methods is valid. Needs more investigation



SA-QCR-DDES – Mesh D



RANS- Langtry-Menter+Trips – Mesh D

Case 2.4

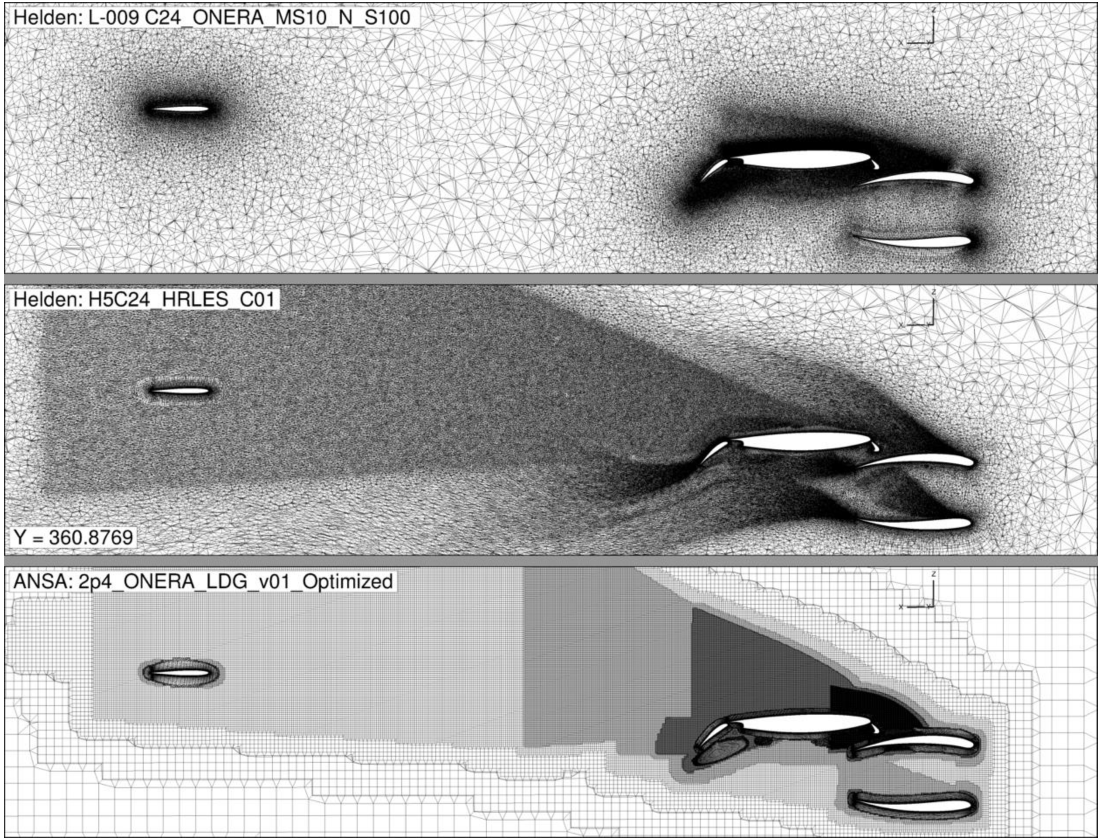
Case 2p4 mesh details

Y=360 (zoomed out)

L-009 built their own heldenMesh grids (**top**)

L-013 used the committee HeldenMesh grids (**middle**)

L-001 and L-004 used ANSA meshes (**bottom**)



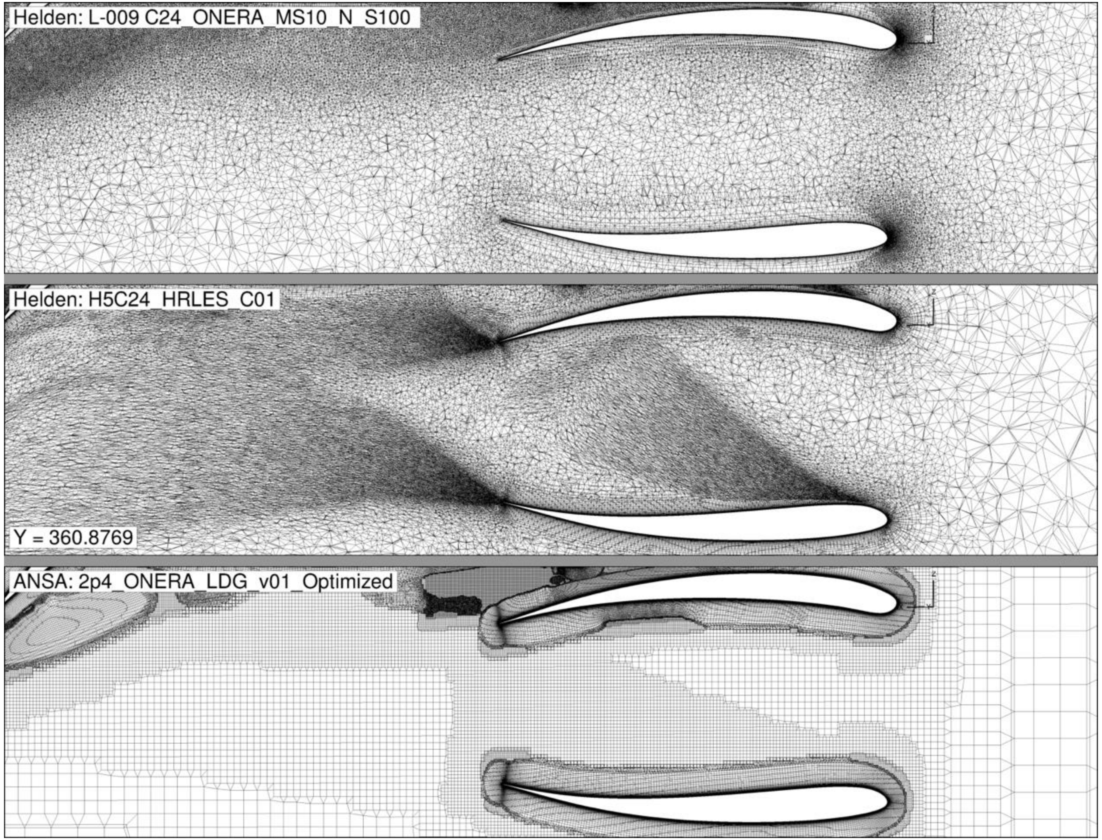
Case 2p4 mesh details

Y=360 (nacelle)

L-009 built their own heldenMesh grids (**top**)

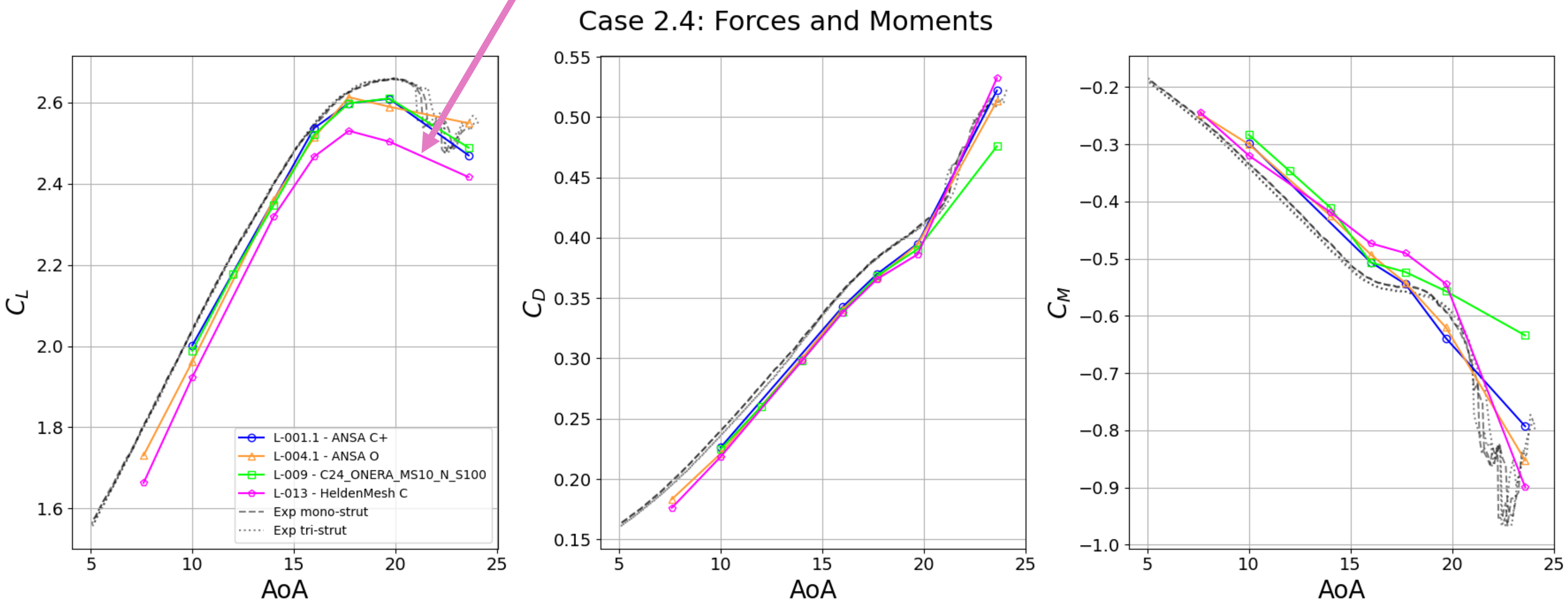
L-013 used the committee HeldenMesh grids (**middle**)

L-001 and L-004 used ANSA meshes (**bottom**)



Case 2.4

L-013 may require further mesh refinement (discussed later)



Better than 2.3 and other than L-013 – close agreement – however further mesh refinement will bring these together

Case 2.4

Still need further mesh refinement for higher AoA

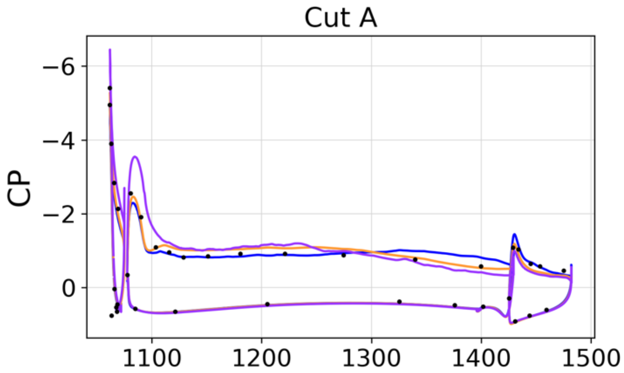
Case 2.4

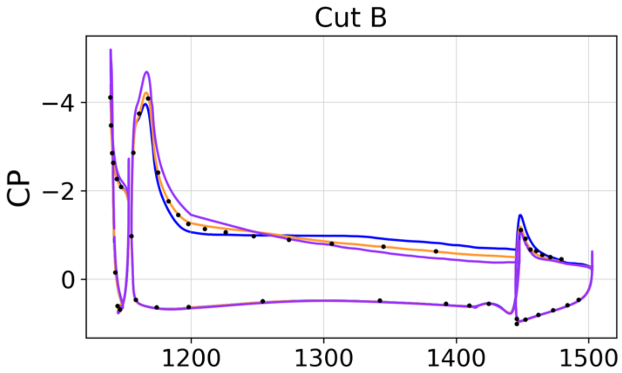
Still need further mesh refinement for higher AoA

Case 2.4 (RANS)

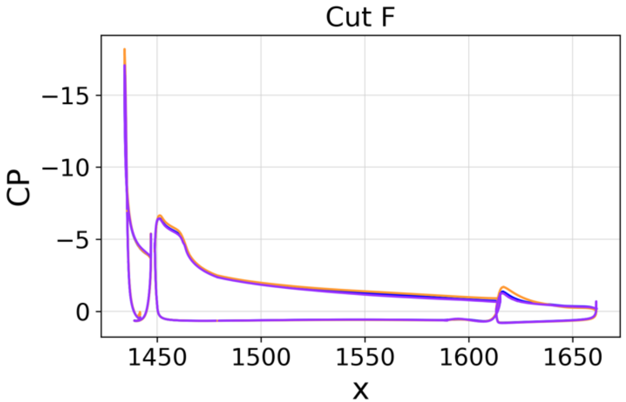
Further mesh refinement doesn't help SA-RANS (but see RANS TFG for more details)

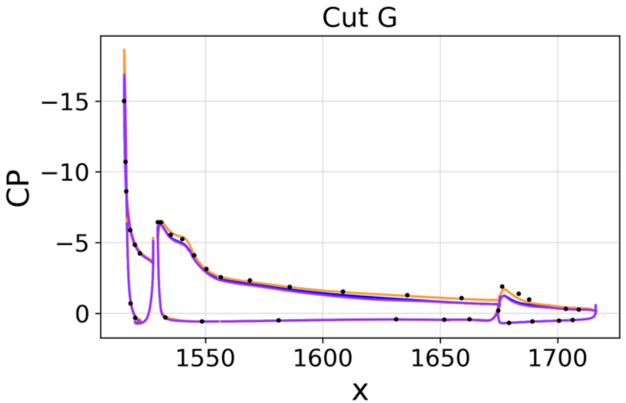
Case 2.4 – 23.6deg AoA –HRLES

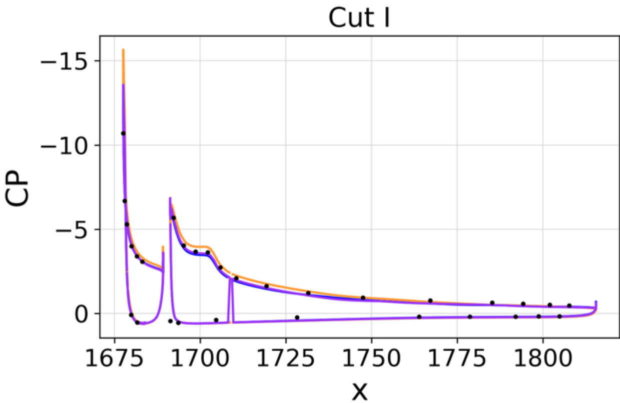




L-001: Blue, L-004: Orange, L-009: Purple, Exp: black

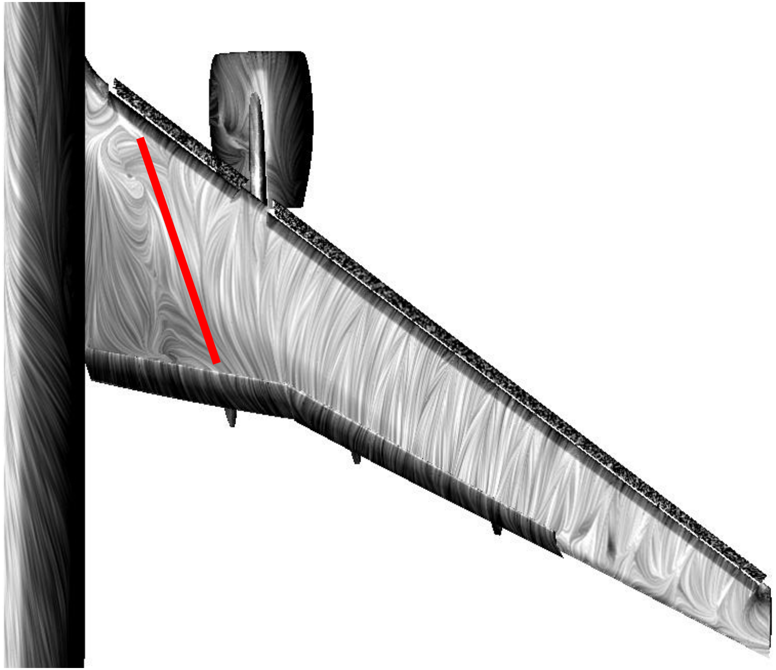


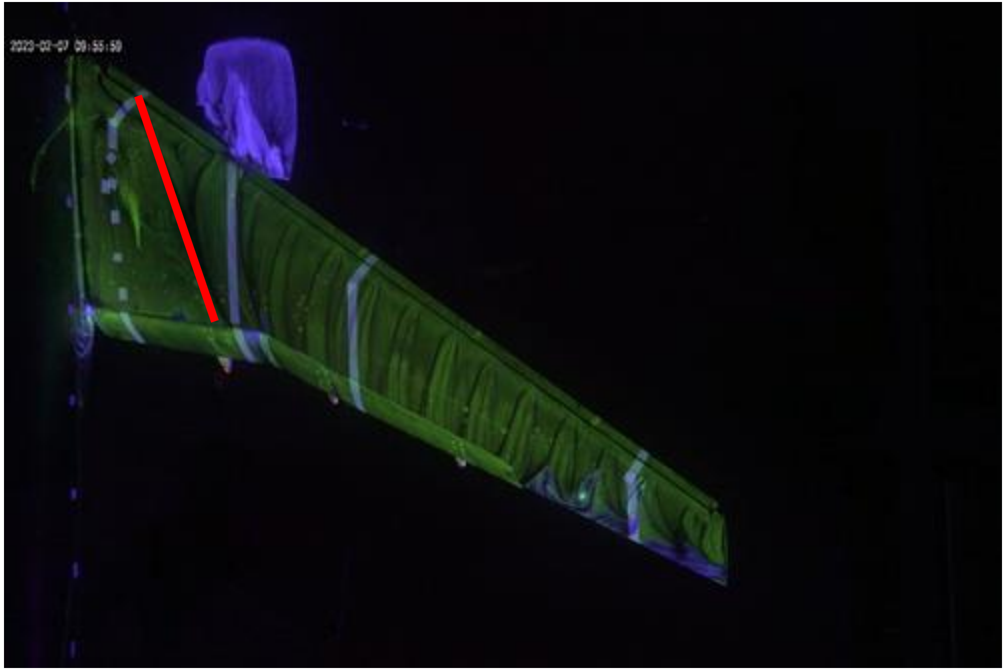




Correlation looks closer for 2.4 than 2.3 for Cp inboard cuts – but now outboard cut is under-predicted – which may be responsible for Cm

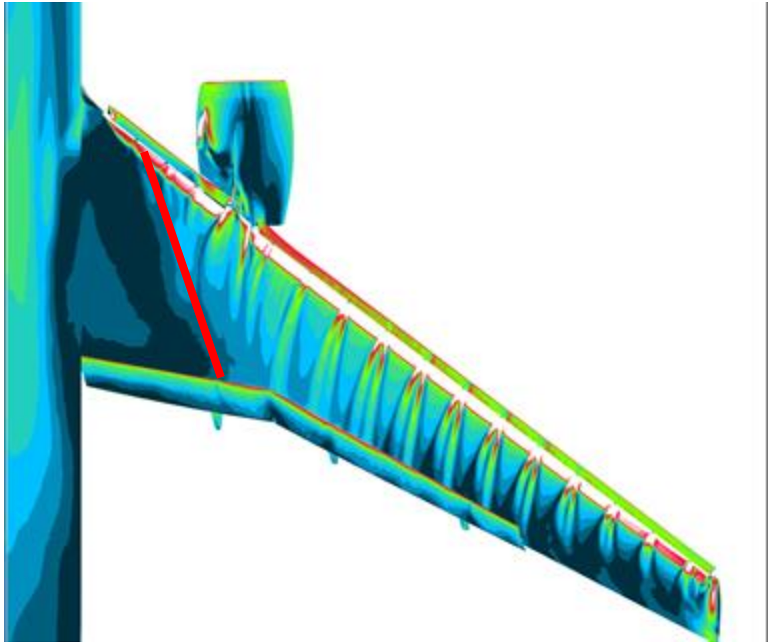
Case 2.4 – L-004

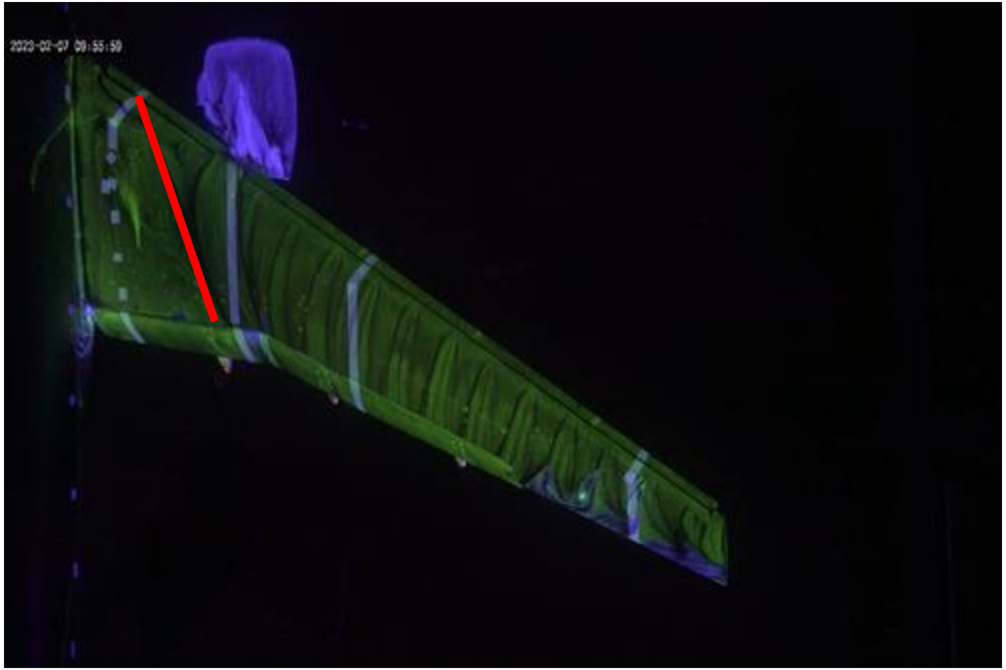




Largely capturing the correct flow at the higher AoA

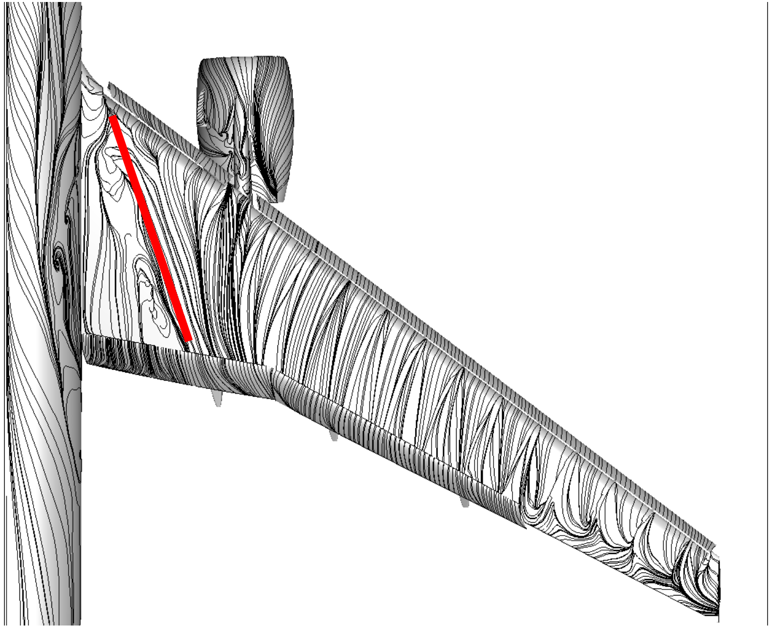
Case 2.4 – L-013

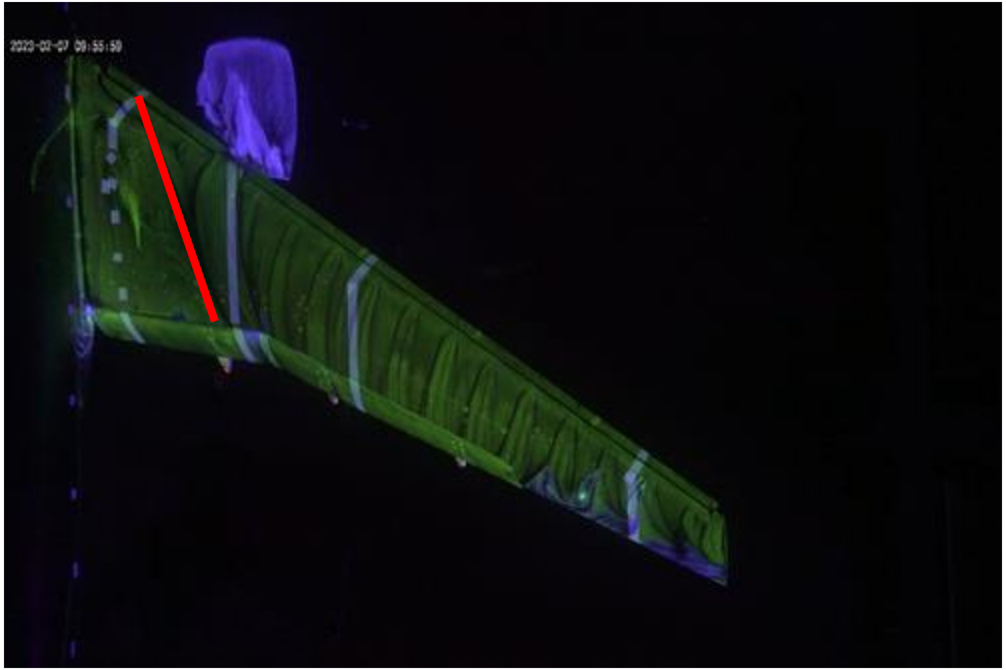




Largely capturing the correct flow patterns at the higher AoA but more separation on the flaps

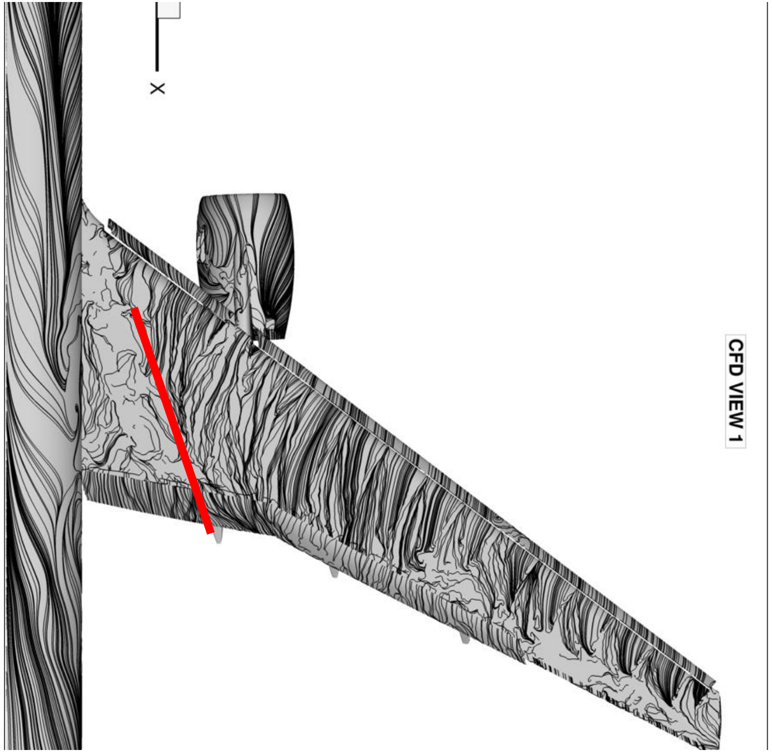
Case 2.4 – L-001



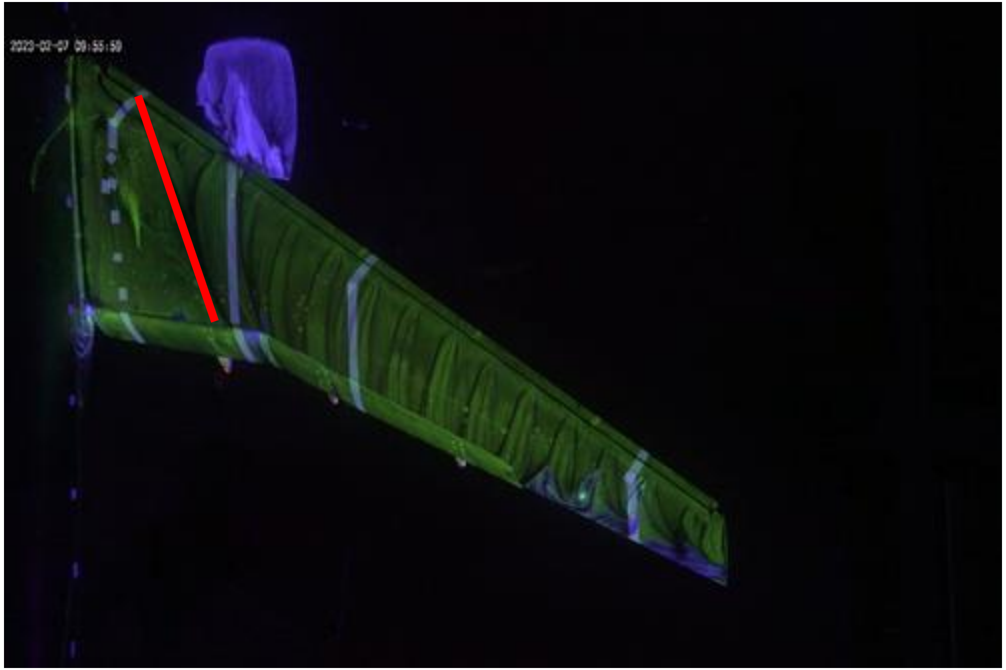


Good capturing of the overall flow patterns

Case 2.4 – L-009

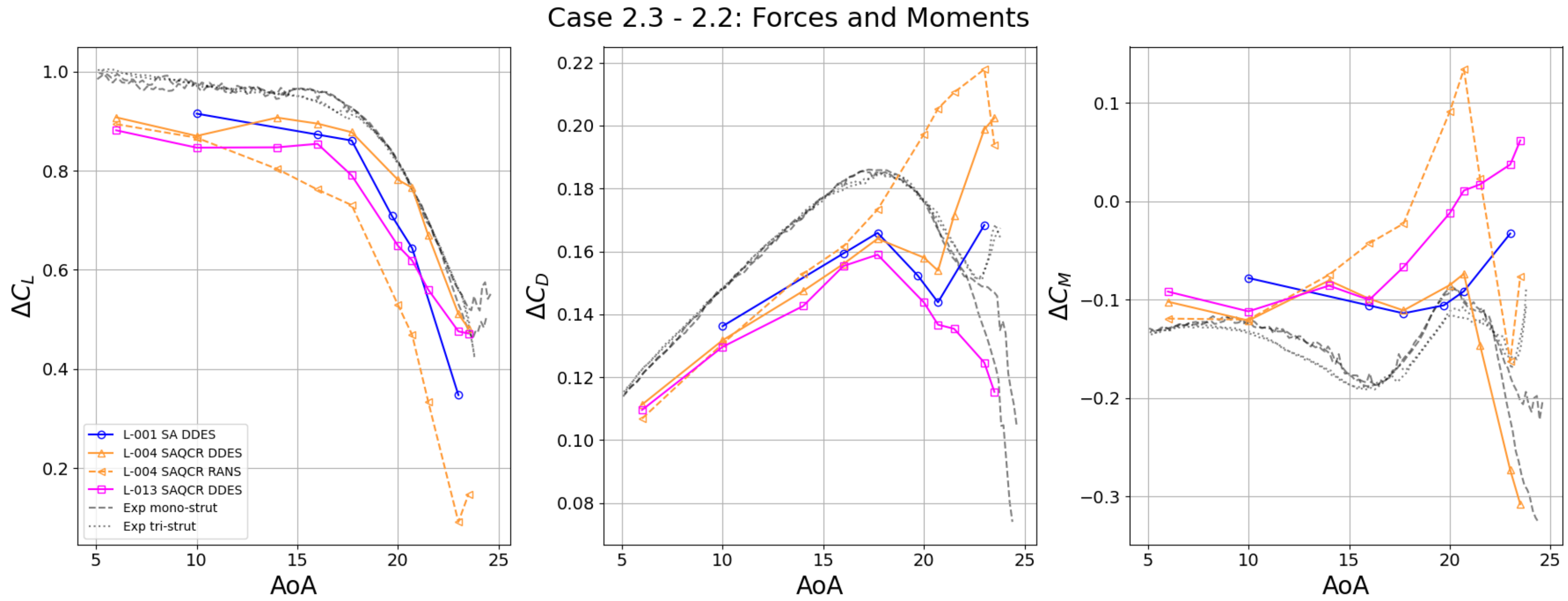


23.6



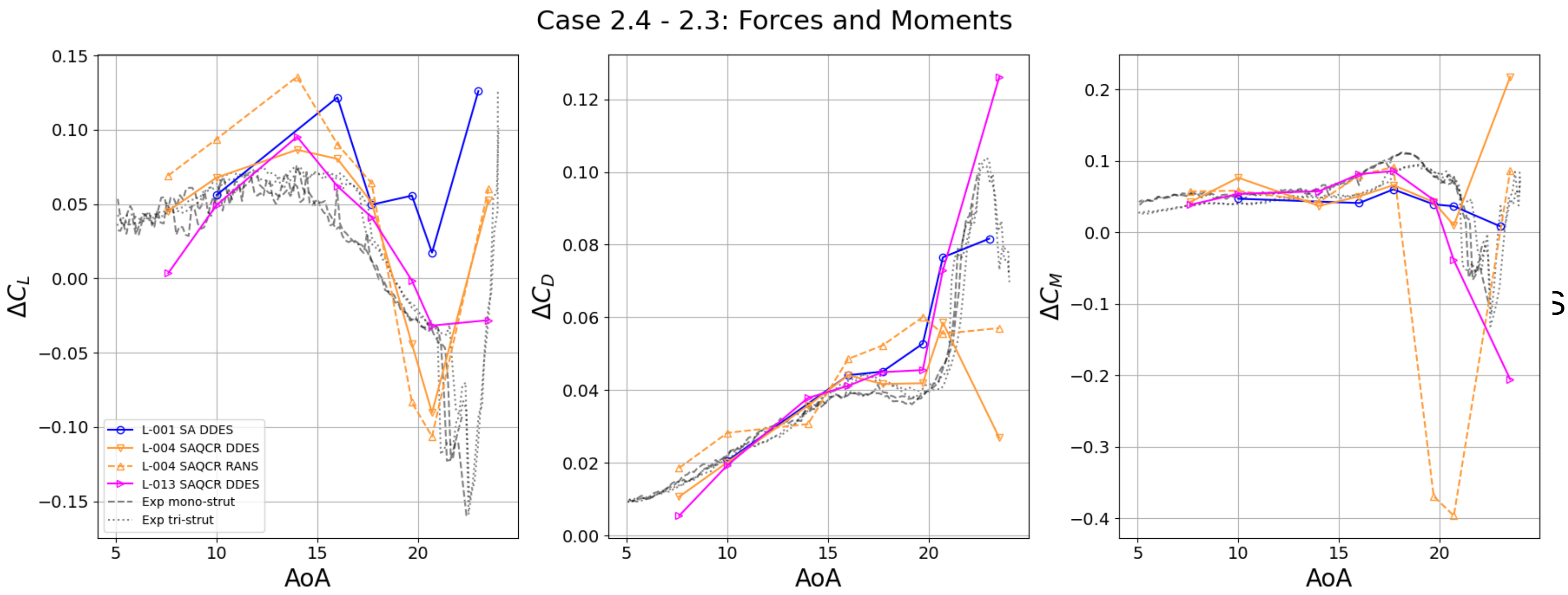
Needs time-averaged streamlines but appears to be correct flow patterns

Delta between 2.3 and 2.2 i.e addition of the flap



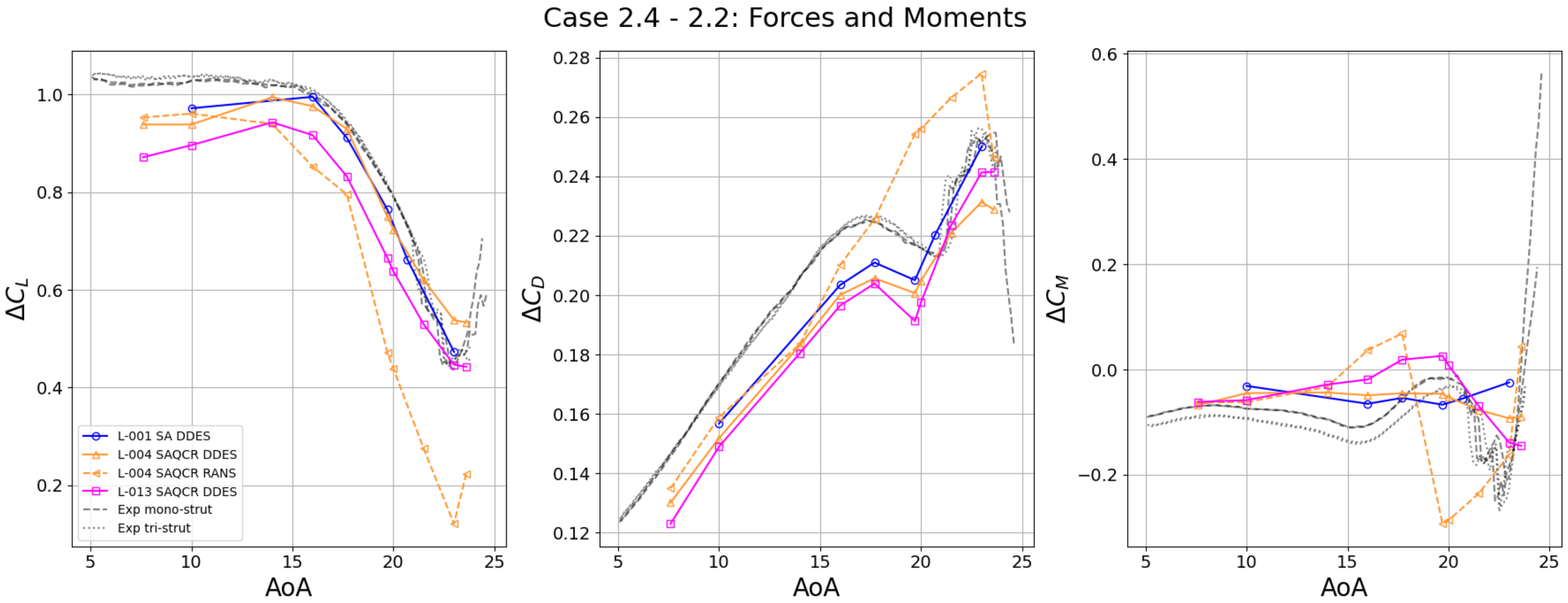
- All submissions found it challenging to predict the delta (not just the absolute 2.3 force and moments)
- Important to note, turbulence models and mesh refinement sometimes differed between 2.2 and 2.3 for a particular submission
- HRLES closer than the SA-based RANS

Delta between 2.4 and 2.3 i.e adding nacelle



- HRLES in general predict closer deltas than RANS (as it does for absolute values)
- May be better still if we held the exact same HRLES CFD setup for each geometry

Delta between 2.4 and 2.2



NS

HRLES in general predict closer deltas than RANS (like absolute values)
May be better still if we held the exact same HRLES CFD setup for each geometry

Computational cost and time

Key factors in Computational cost, time & efficiency

1. **The time it takes to run a simulation is an important factor in the adoption of a specific code or method e.g 4hrs vs 4 days**
2. The time itself is a function of available HPC resources, the type of HPC resources and the scalability of the code and specific setup of the code for the problem itself
3. Simulation time is highly dependent on the amount of HPC resources, but simulation cost is more constant (whilst in the linear range of scalability)
4. Cost is an important factor in whether a method can ultimately be used in production
5. Power/CO_2 is an increasingly important metric in the era of sustainability and climate change concern
6. Accuracy of the method/setup/code must be considered or else a super-fast/cheap method that is poorly correlating could be considered ‘best’

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Challenges

1. **Time itself is not a fair metric because it depends on HPC resources thus traditionally core-hours has been a common metric**
2. Core-hours is misleading because 1) it assumes CPUs 2) it doesn't take into account the wide range of speed 'per core' 3) it can be difficult to put into reality e.g what does 1M core-hours really mean to you as an engineer/researcher?
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5. Hardware costs of CPUs/GPUs are not readily available – other than through cloud computing providers
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Possible methods

1. **In HLPW4 – we took the approach of using AWS public costing and translating each run to a related AWS GPU/CPU and then multiplying by the simulation time.**
2. Positives – consistent metric to balance out the large difference in per-node costs of GPUs and CPUs
3. Negatives – 1) didn't take into account accuracy of the method. 2) doesn't include power numbers 3) doesn't reflect the cost that an end-user would pay (differing discounts by cloud/on-prem) or the particular node type being different
4. One particular comment was that some approaches were not optimized for HPC i.e either the code was running in debug mode, running on old hardware, had lots of extra reporting. Were based upon a very large mesh that only made 1% difference etc
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Recommendations

1. **It's clear that cost/time are important, but we need to have an agreed way to report this and include accuracy**
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Conclusions and next steps

Executive Summary

Full configuration of HLPW5 has ultimately been a more difficult test-case to predict than HLPW4 (*although new insights from Onera HLPW4 WT may challenge this*). There is still positive news:

1. HRLES still shows the same overall improvements over SA-based RANS (i.e better C_{Lmax} prediction) and better flow-field correlation
2. Addition of the flaps (2.3 and 2.4) has been challenging for all groups (including other TFGs) and there remains many unanswered questions around transition & mesh refinement requirements i.e. issues not unique to HRLES
3. When sufficient mesh resolution and a low dissipation scheme is used, there is good agreement between different codes for HRLES (SA DDES variants) which suggests a maturity of the method for industry. **However all submissions need further mesh refinement.**
4. Low AoA configurations with flaps remains a challenge (absolute and deltas) – as seen with HLPW4 flap deflection study.
5. Open question of transition for case 2 given Re=5.8M. All the HRLES methods assume fully-turbulent flow, yet experimental tripping is challenging and fully turbulent flow may not be realized. Thus is it even possible for HRLES to match the exp. data if transition is not accurately modelled for all AoAs? Still remains a source of uncertainty.
6. More work to do to address the unknowns related to HLPW5 and more analysis by the TFG – which will be shown in the SciTech summary paper.

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Q & A