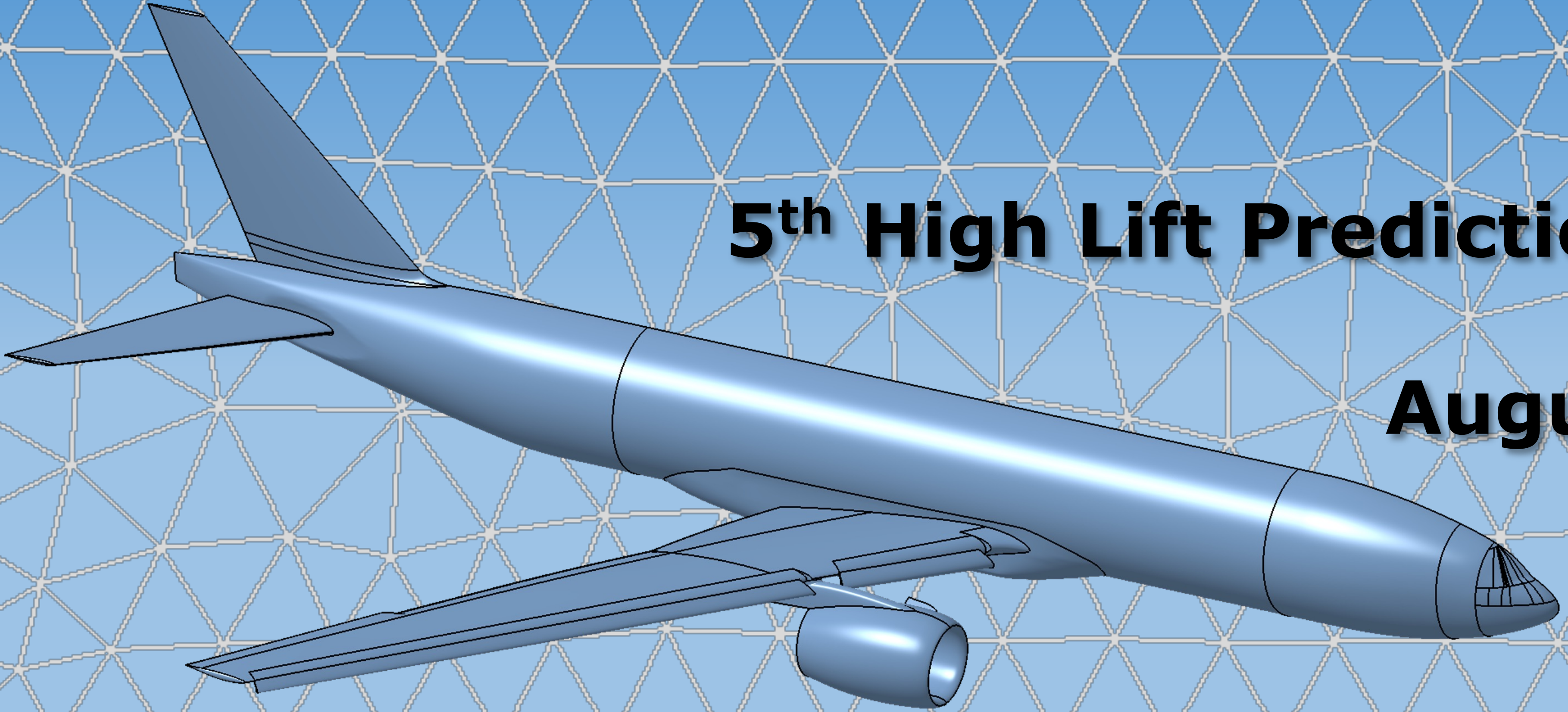


5th High Lift Prediction Workshop

August 2-3, 2024

Committee Summary

HLPW Leadership Team

Introduction

- Findings and lessons learned reflect consideration of all submitted results, somewhat independently from results and analysis considered within TFGs
  - Addressing **original key questions** using submitted data
  - Attempting to be **objective** to the extent possible
  - Generally emphasizing **verified** and **“best practice”** solutions
  - Looking for **overall trends**
  - Identifying **gaps, shortcomings, areas for additional research, and need for additional experimental data**
- Analysis is preliminary – Final analysis will be presented as a summary paper for AIAA SciTech 2025

Test Case 1
Wing-Body Configuration

Test Case 1 – CRM-HL Wing-Body Verification

The verification problem for this workshop is based on the simplified CRM-HL Wing Body (CRM-HL-WB) configuration. The verification problem for this test case will be the same as the one initially introduced and utilized for the **High Fidelity CFD Verification Workshop (HFCFDVW),** planned for SciTech 2024. The target characteristics of this study are grid convergence of lift, drag, and moment coefficients (HFCFDVW does not require moment coefficient, but we require it here).

Geometry

- CRM-HL wing/body* (CRM-HL-WB)

Experimental Data

- None (for code-to-code Verification)

Computational Domain

- Rectangular cuboid computational domain with dimensions $-65{,}000 \le x \le 65{,}000$, $0 \le y \le 65{,}000$, $-65{,}000 \le z \le 65{,}000$
- Symmetry at y=0

Run Conditions

Mach Number	0.20
Chord Reynolds Number	5.6×10^6
Angle of Attack	11°
Reference Static Temperature	521 °R

* Reference configuration

Sample Key Questions

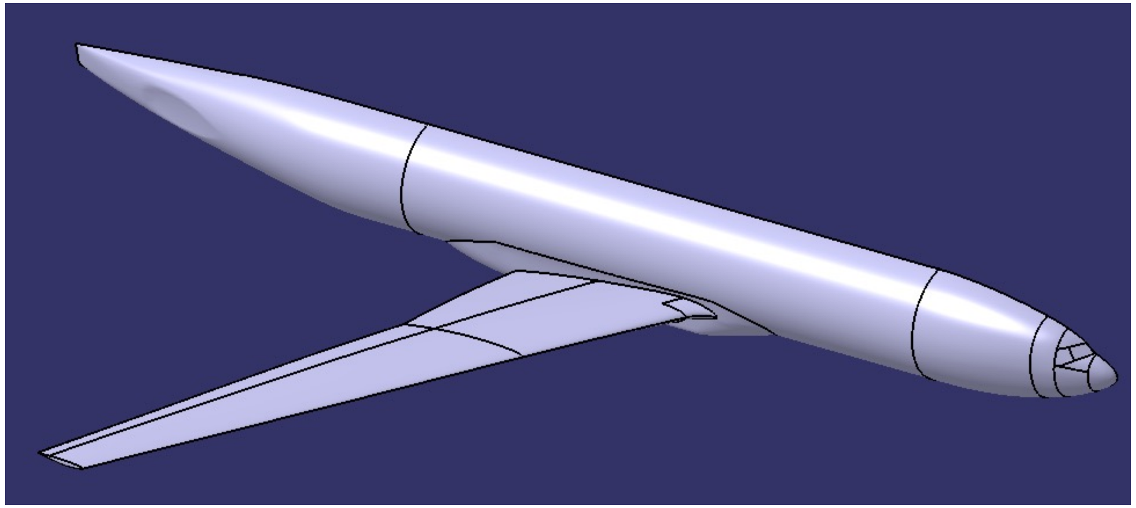
- Are RANS solvers able to demonstrate convergence to the same solution for a given turbulence model in grid refinement using families of fixed and adapted grids?
- For Non-RANS solvers, what is the most consistent approach to grid families that can demonstrate a trend towards grid independence on this problem?
- Is there enough consistency amongst non-RANS approaches that there is reasonable agreement on a grid independent solution?
- Does the ensemble of answers amongst modelling approaches compared to the experimental free air corrected data tell us anything useful about uncertainty?

Details

- Geometry is provided in full-scale inches
- When using a dimensional code, it is recommended to adjust viscosity to a non-physical value to match requested Reynolds number
- SA-neg-QCR2000-R is highly recommended, run fully turbulent (for RANS solvers)
  - Strongly recommended that RANS participants utilize grids from Verification Workshop, but alternate gridding strategies are encouraged, if appropriate
- Participants using non-RANS solvers are encouraged to demonstrate grid convergence on this problem using multiple grid levels along with their best practice solver settings, looking at convergence of the lift, drag, and moment coefficients. The gridding requirements in this section are purposefully left vague. Discussions within TFGs are expected to provide further guidance on how to best family grid sequences for these approaches.

Test Case 1 Configuration – Motivation

- Uses simplest wing/body configuration defined for CRM-HL reference geometry
  - NOT based on DPW CRM
- Angle-of-attack chosen to be near CLmax based on preliminary RANS simulations
- Simulations envisioned to:
  - Complement HFCFD-VW verification learnings
  - Demonstrate grid convergence
  - Probe uncertainties between methods and modeling techniques using a greatly simplified configuration



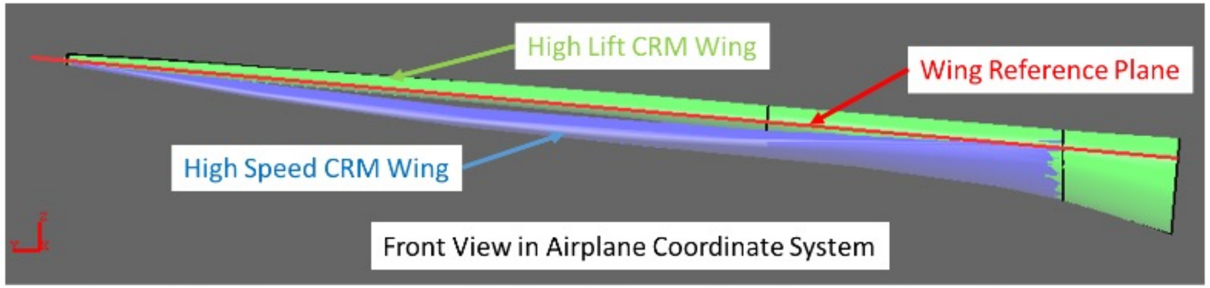


Figure 3 Front view comparison of high speed (blue) and high lift (green) wing surfaces. Wing Reference Plane is shown in red for reference.

Test Case 1 Key Questions

#	Key Question
1	Are RANS solvers able to demonstrate verification on this problem and series of grids?
2	For Non-RANS solvers, what is the most consistent approach to grid families that can demonstrate a trend towards grid independence on this problem?
3	Is there enough consistency amongst non-RANS approaches that there is reasonable agreement on a grid independent solution?
4	Does the ensemble of answers amongst modelling approaches compared to the experimental free air corrected data tell us anything useful about uncertainty?

Test Case 1 – Key Question 1

1	Are RANS solvers able to demonstrate verification on this problem and series of grids?

- Yes, with three main requirements:
  - Iteratively converged
  - Consistently gridded
  - Verified & consistent modelling approaches (turbulence)
- Different grid families may display different grid convergence trajectories, but point towards same consistent answer

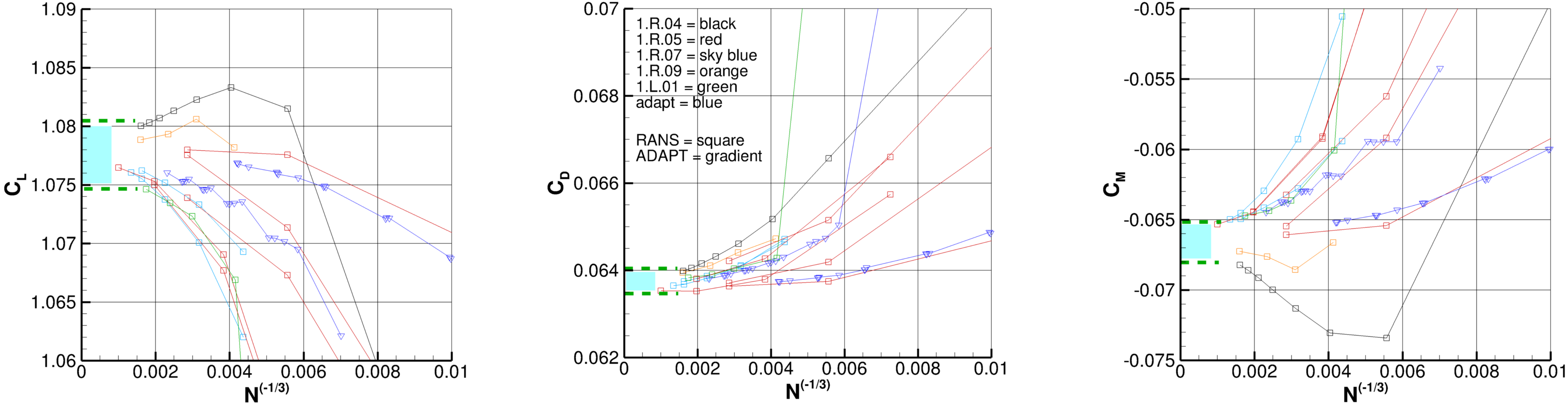
- Note that this approach did little to compare to truth so far (No experimental data yet)
  - Yes, solvers can demonstrate consistency, but are they matching the right separation pattern? Is one turbulence model approach better than another?
  - Spread between turbulence models is also large and points to different answers

- Note that this problem had minimal separation present – if it had more separation, it's likely the answer to this question would likely be 'No'

Test Case 1 – Key Question 1

1	Are RANS solvers able to demonstrate verification on this problem and series of grids?

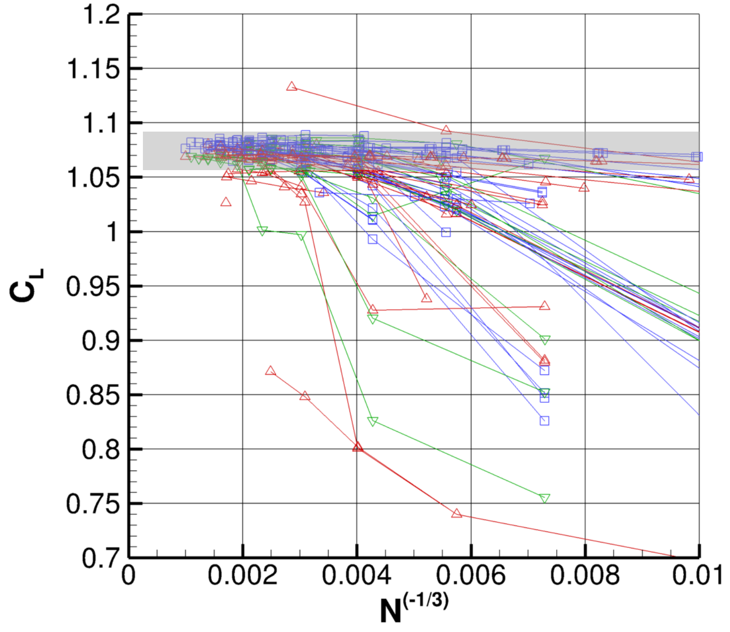
- Selected RANS plots of mesh convergence, including adaptive (SA Model) demonstrate verification is achievable for a given turbulence model
  - △C_L: 0.004 [1.076, 1.08] (shaded)
  - △C_D: 0.0005 [0.0635, 0.0640] (shaded)
  - △C_M: 0.003 [-0.068, -0.065] (shaded)

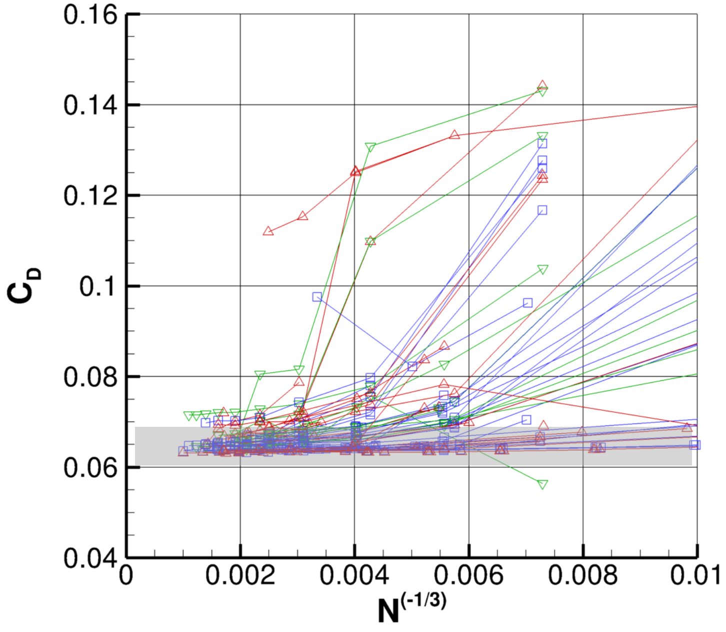


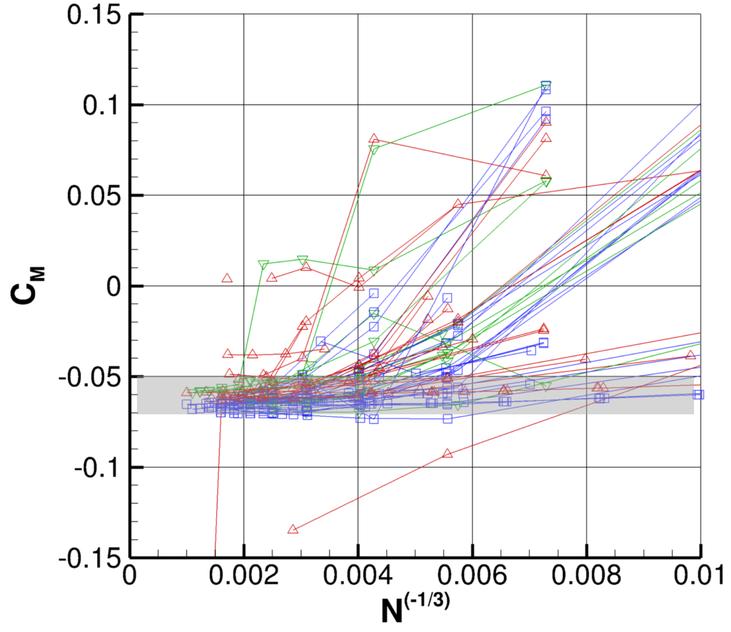
Test Case 1 – Key Question 1

1	Are RANS solvers able to demonstrate verification on this problem and series of grids?

- When including all results (other turbulence models or model variants, insufficient verification, results with inadequate grids, and/or results with insufficient iterative convergence), the spread increases considerably
  - ΔC_L: 0.02 [1.065, 1.085] (shaded)
  - ΔC_D: 0.0040 [0.063, 0.067] (shaded)
  - ΔC_M: 0.022 [-0.070, -0.058] (shaded)



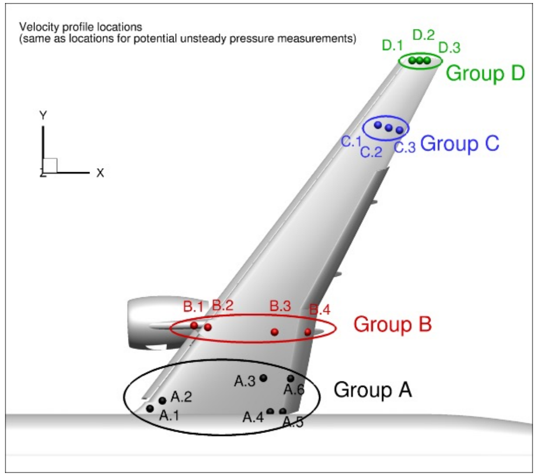


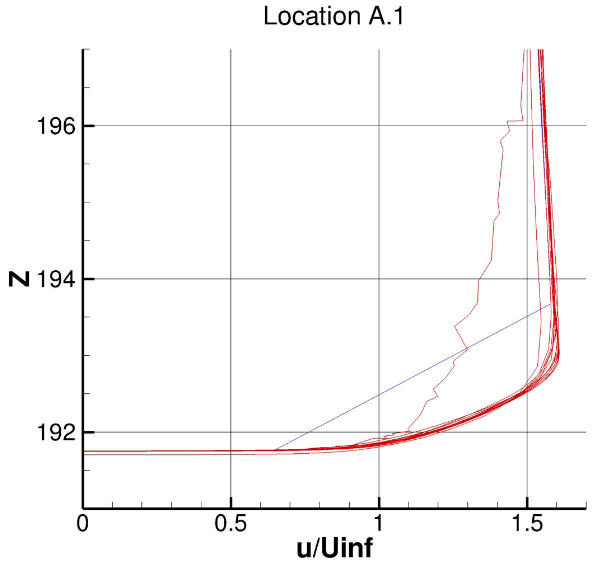


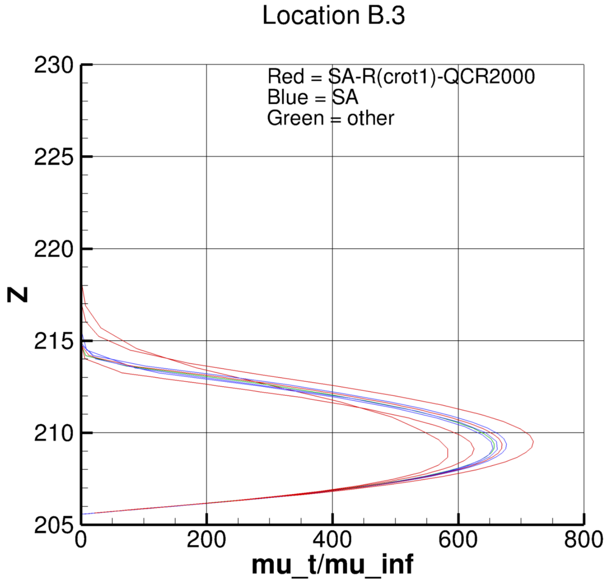
Test Case 1 – Key Question 1

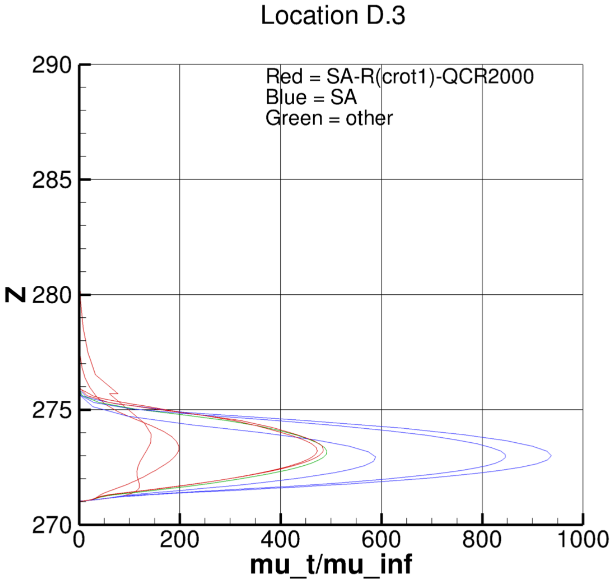
1	Are RANS solvers able to demonstrate verification on this problem and series of grids?

- Velocity profiles at probe points generally agree well
- Eddy viscosity in some cases agree, but in areas closer to separation, diverge from each other
    - Highlights sensitivity of RANS models to separated flow – this is still quite challenging to get agreement on!









Test Case 1 – Key Question 2

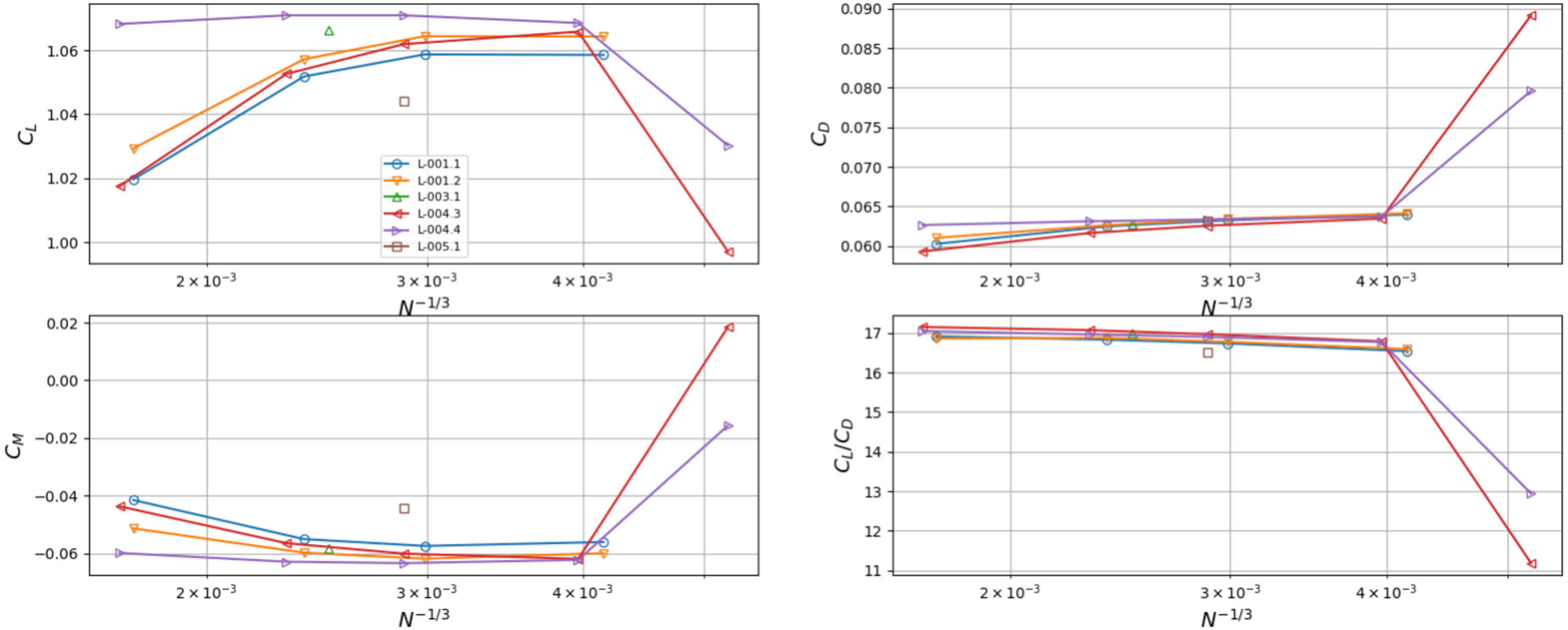
2	For Non-RANS solvers, what is the most consistent approach to grid families that can demonstrate a trend towards grid independence on this problem?

- Many approaches to grid families demonstrated in HLPW 5:
  - Uniform global refinement / scale factor
  - Uniform refinement, but with keeping first cell wall-normal spacing constant (e.g., Y+ = 1)
  - Automated adaptive refinement approaches
  - Expert-in-the-loop refinement in areas of ‘key interest’
- Approaches predominantly affect the convergence trajectory and/or computational efficiency of the grid convergence process
- Wall-modeling presents unique challenges – it’s not obvious that as the first cell is refined, you *should* expect monotonic convergence

Test Case 1 – Key Question 2

2	For Non-RANS solvers, what is the most consistent approach to grid families that can demonstrate a trend towards grid independence on this problem?

- HRLES is not demonstrating grid convergence on this problem – though Deck-Renard could improve this. Potentially interesting to revisit.

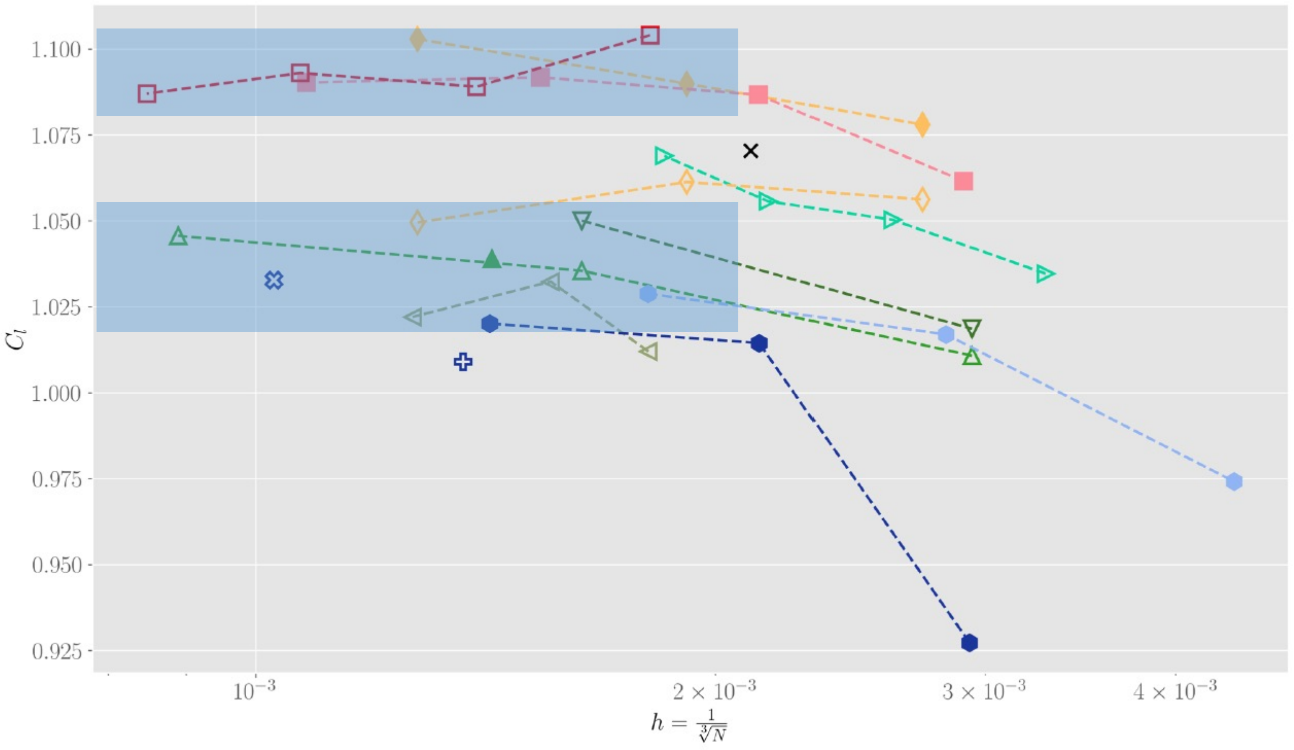


L-001.1 – SA-QCR-DDES (ANSA grids), L-001.2 - SA-DDES (ANSA Grids), L-003.1 – SA-DDES-custom (Custom Pointwise Grid), L004.3 – SA-QCR DDES (ANSA Grid), L004.4 SA-QCR-DDES-DR (ANSA Grid), L005.1 – SST-SBES (ANSA Grid)

Test Case 1 – Key Question 2

2	For Non-RANS solvers, what is the most consistent approach to grid families that can demonstrate a trend towards grid independence on this problem?

- WMLES shows some tendencies towards grid convergence, but is not nearly as convincing as RANS results
- Convergence appears to trend towards two separate solutions
- Includes many different gridding approaches & methodologies
  - Unstructured
  - Cartesian
  - Voronoi
- No one approach appears more consistent than others

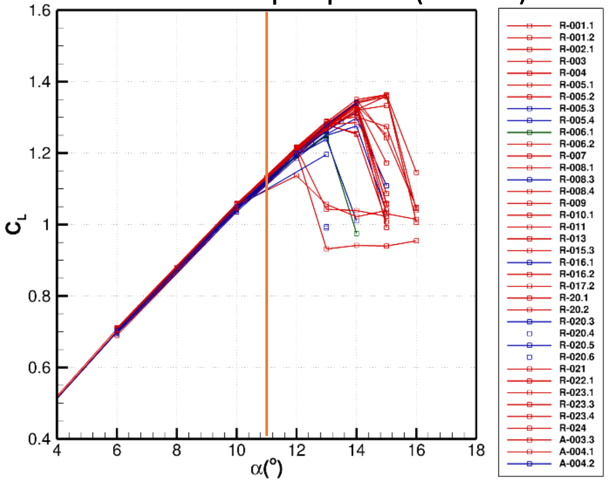


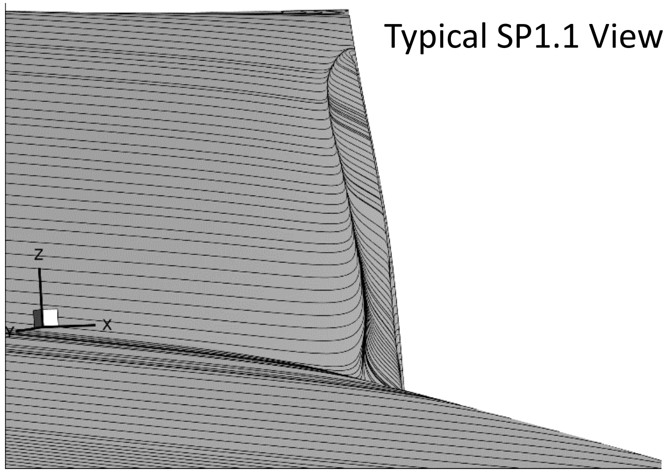
Test Case 1 – Key Question 3

3	Is there enough consistency amongst non-RANS approaches that there is reasonable agreement on a grid independent solution?

- AoA = 11º is where RANS solutions begin diverging – a challenging problem to begin with.
- Spread of seemingly valid solutions across methods is around 0.03 CL for HRLES and 0.1 CL for WMLES.
  - Would reasonably expect tunnel to tunnel experimental results to repeat within 0.01 based on experience.
  - For HRLES, tighter grouping suggests robust mesh convergence, but outliers skew results and likely not enough samples to draw conclusions.
  - For WMLES, arguments could selectively be made about achieving something resembling grid convergence, but there is currently a lack of consistency in modeling approaches (like community consensus on a RANS turbulence model).
- Predominant difference amongst solutions is the extent of trailing edge separation.
  - No test data available as planned
  - Both HRLES and WMLES show significant scatter in pressure distributions

Example polar (TC 2.1)



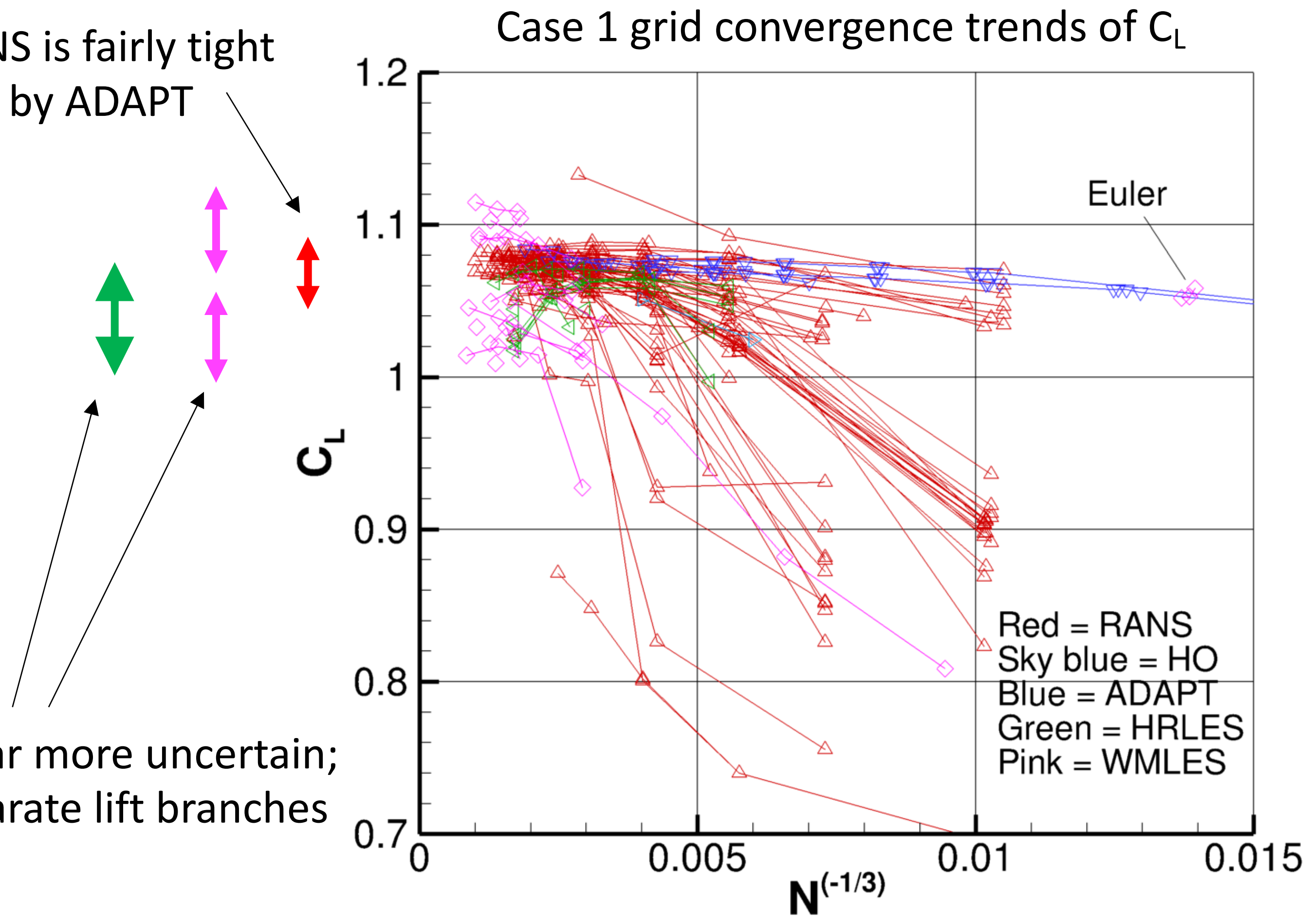


Typical SP1.1 View

Test Case 1 – Key Question 3

3	Is there enough consistency amongst non-RANS approaches that there is reasonable agreement on a grid independent solution?

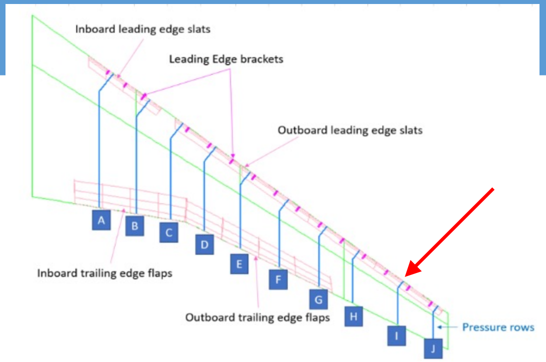
General trend of RANS is fairly tight (and is substantiated by ADAPT solution trend)



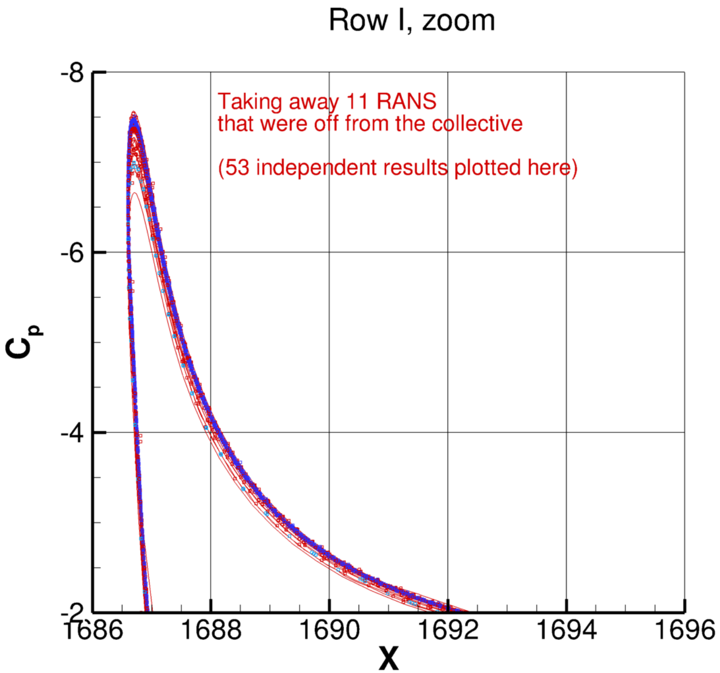
General trends of HRLES and WMLES are far more uncertain; convergence heading to separate lift branches

Test Case 1 – Key Question 3

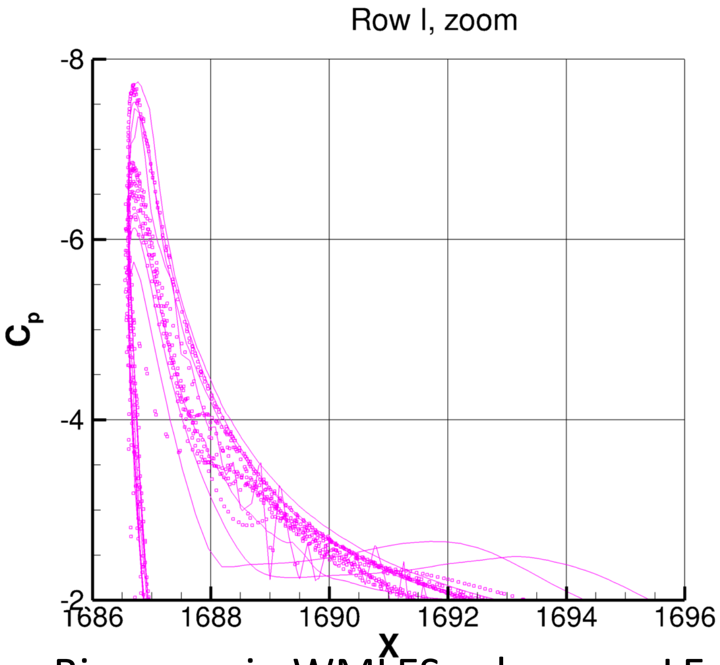
3	Is there enough consistency amongst non-RANS approaches that there is reasonable agreement on a grid independent solution?



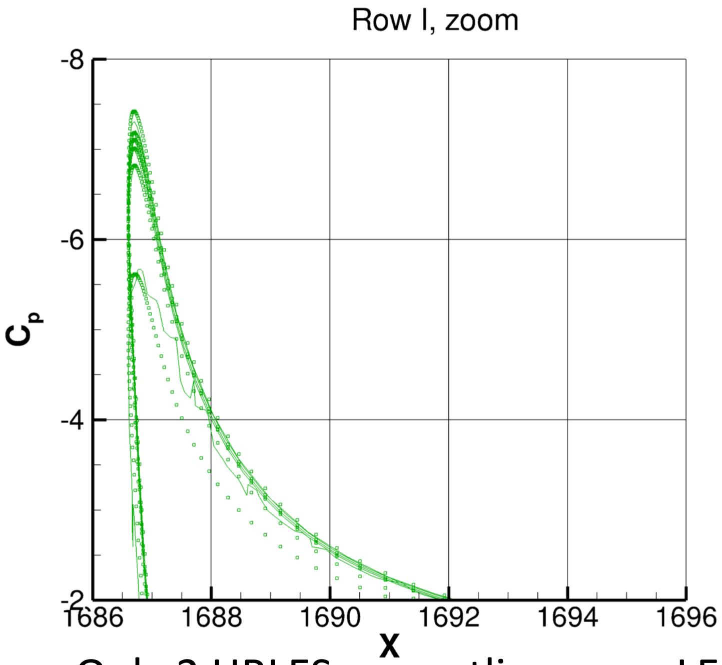
- Pressure peaks near Leading Edge
- WMLES treatment of transition plays a large role in extent of separation predicted



Fairly uniform collective RANS results near LE



Big range in WMLES solns near LE

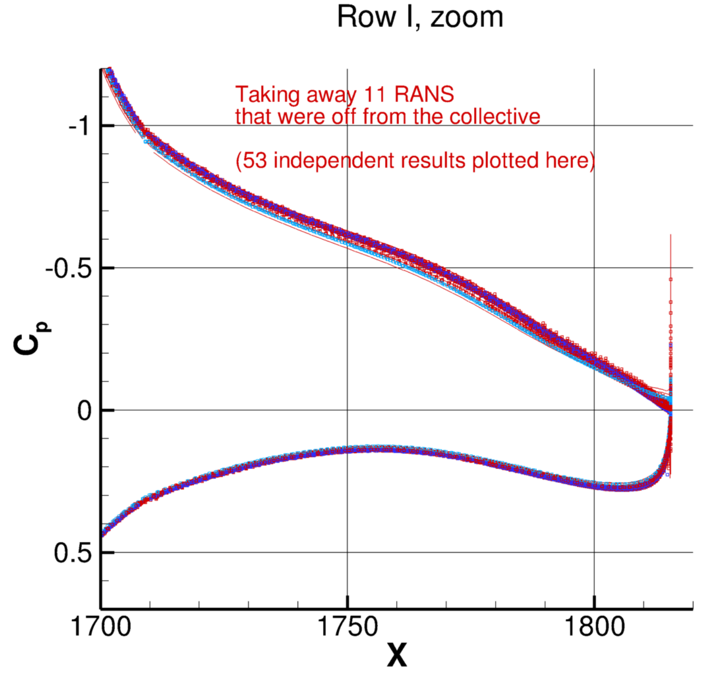


Only 2 HRLES are outliers near LE; otherwise trend looks like RANS

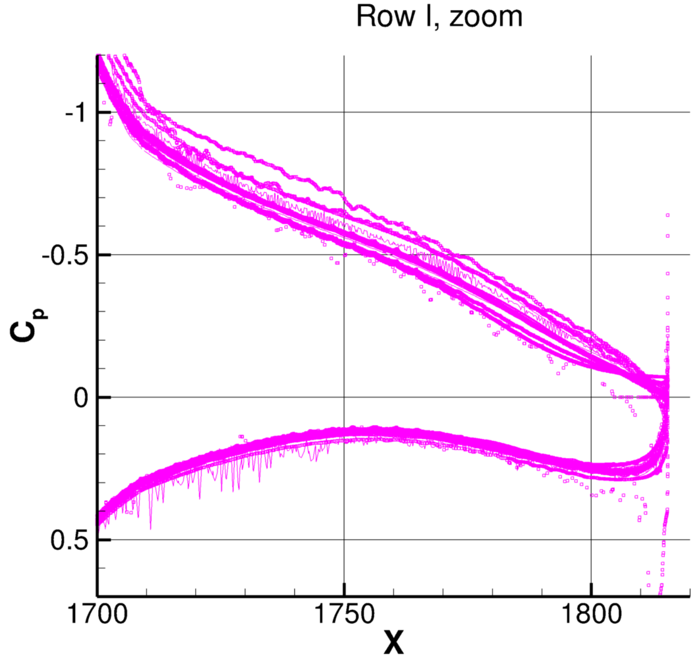
Test Case 1 – Key Question 3

3	Is there enough consistency amongst non-RANS approaches that there is reasonable agreement on a grid independent solution?

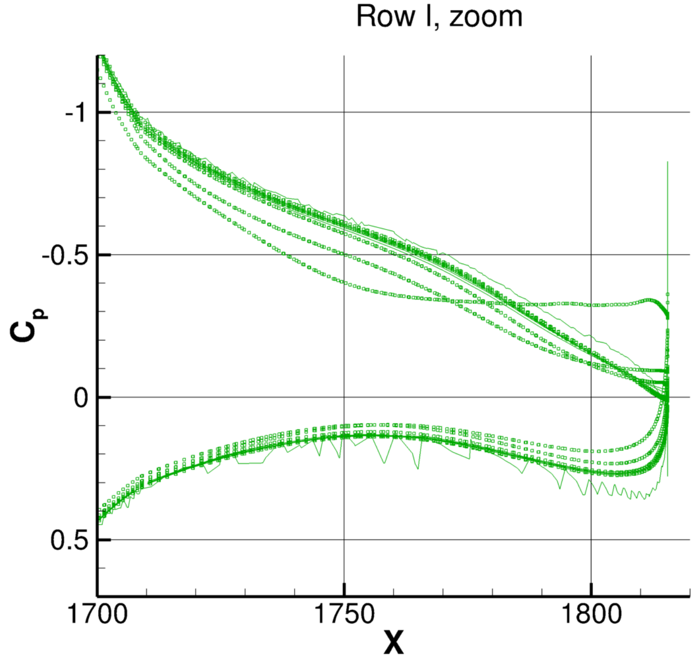
- Over back portion of airfoil for typical row, Cp evidence still points to "No" for WMLES; and also points to "No" for HRLES.



Fairly uniform collective RANS results over bulk of wing section



Big range in WMLES solutions

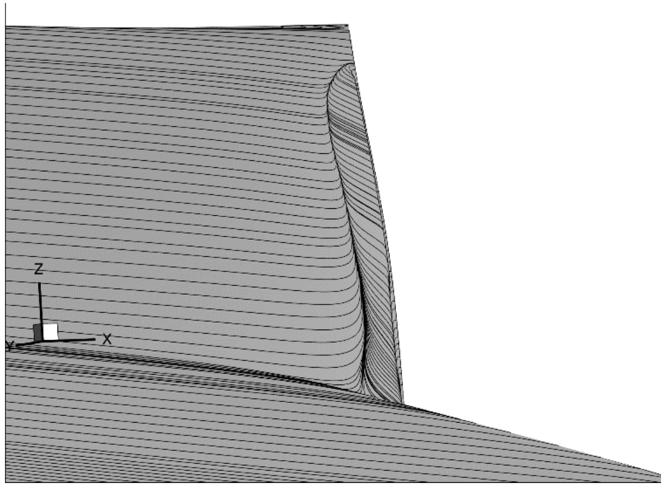


Big range in HRLES solutions

Test Case 1 – Key Question 4

4	Does the ensemble of answers amongst modelling approaches compared to the experimental free air corrected data tell us anything useful about uncertainty?

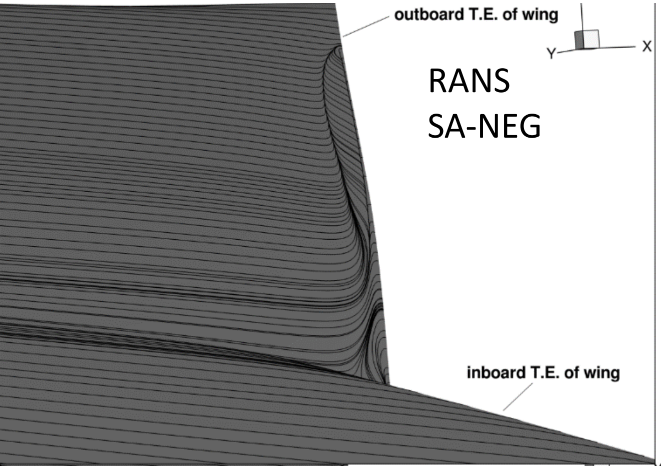
- Inconclusive; Lack of experimental data forced a focus on grid convergence, instead of modelling parameter accuracy
- Ensemble of data highlights significant computational uncertainty
- Beyond integrated forces and moments and surface pressures, need additional test data to characterize flow physics:
  - Experimental transition information
  - Sensitivity to trip dots
  - Surface visualization
  - Sensitivity to angle of attack and Reynolds number
- Most common solution for looks something like this with a CL of
  - 1.06 (RANS/HRLES)
  - 1.02 or 1.08 (WMLES)



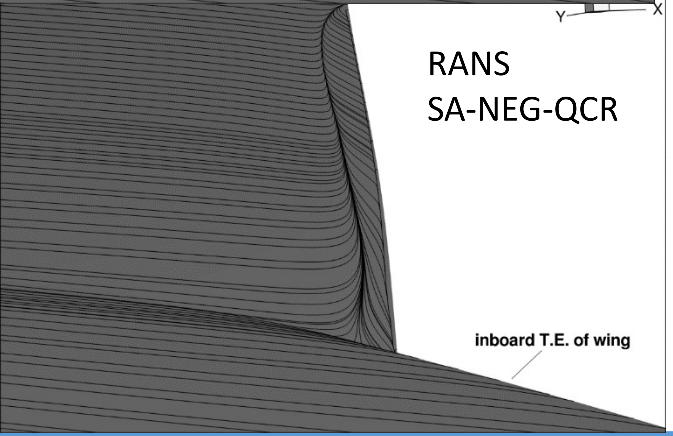
Test Case 1 – Key Question 4

4	Does the ensemble of answers amongst modelling approaches compared to the experimental free air corrected data tell us anything useful about uncertainty?

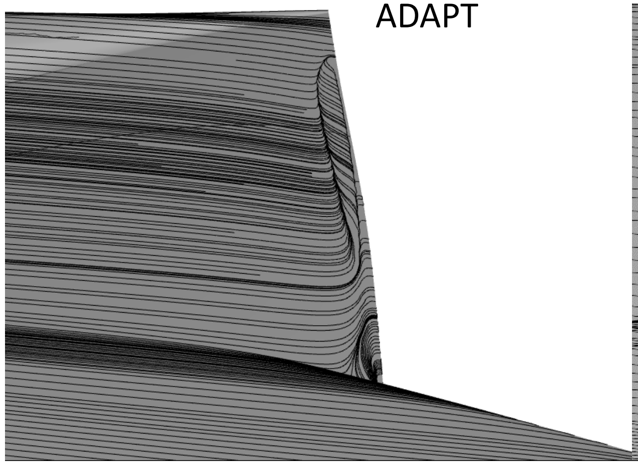
- Large variety in extents of trailing edge separation, sometimes from modelling choices, sometimes from gridding differences



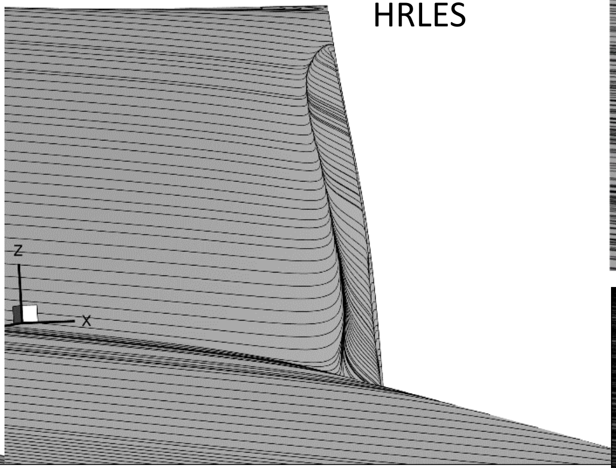
RANS
SA-NEG



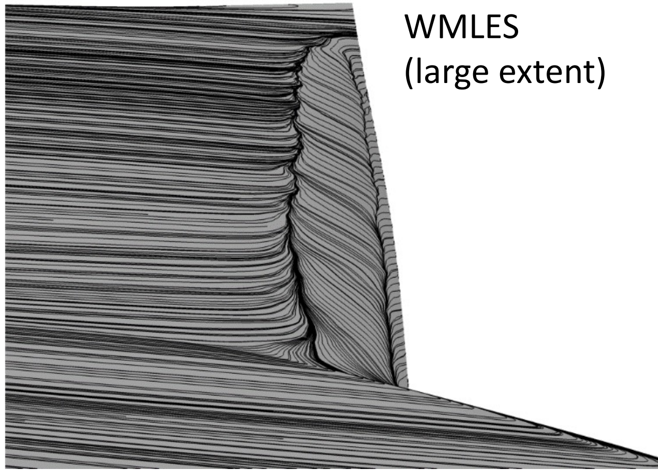
RANS
SA-NEG-QCR



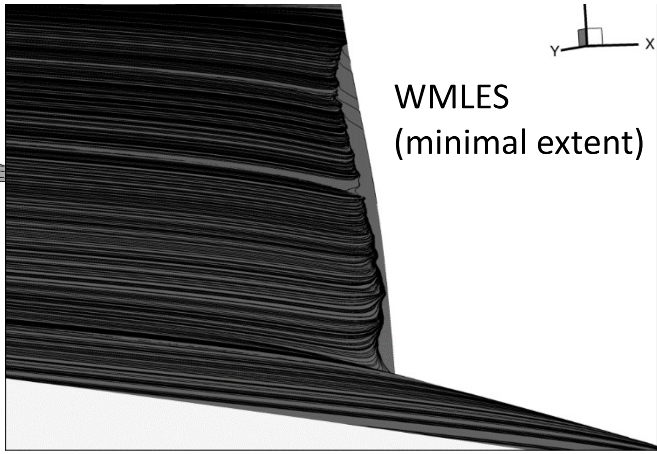
ADAPT



HRLES



WMLES
(large extent)



WMLES
(minimal extent)

Test Case 2
Configuration Buildup

Test Case 2 – Configuration Build-up

Flow solutions are requested to assess the ability of CFD to predict the effect of varying geometric fidelity through component build-up to help isolate specific types of flow physics associated with high-lift aerodynamics. Geometry is provided for four separate geometric configurations of increasing levels of complexity, with simulations to be performed free-air and compared to fully corrected data. Experimental data will be provided from wind tunnel campaigns utilizing both the ONERA [3] and Boeing models, tested at the ONERA F1 and QinetiQ 5m facilities, respectively. For this case, a set of grids should be employed with mesh size determined by current "best practice" guidelines.

Geometry

2.1: Wing-Body with HV (CRM-HL-WBHV)*
2.2: Wing-Body-Slat with HV (ONERA_LRM–WBSHV)
2.3: Wing-Body-Slat-Flaps with HV (ONERA_LRM–WBSFHV)
2.4: Wing-Body-Slat-Flaps-Nacelle with HV (ONERA_LRM–LDG)

Experimental Data

2.1: QinetiQ 5m (Expected May 2024)
2.2: ONERA F1 (Provided October 2023
2.3: ONERA F1 (Provided October 2023)
2.4: ONERA F1 (Expected Feb 2024)

Run Conditions

Mach Number	0.20
Chord Reynolds Number	5.4×10^6 (case 2.1) 5.9×10^6 (cases 2.2 - 2.4)
Angle of Attack	2.1: 6º, 10º, 12º, 13º, 14º 2.2: 6º, 10º, 17.7º, 20º, 21.5º, 23º, 23.8º 2.3: 6º, 10º, 14º, 16º, 17.7º, 20.7º, 23.5º 2.4: 7.6º, 10º, 14º, 16º, 17.7º, 19.7º, 23.6º
Reference Static Temperature	521 °R
Reference Static Pressure	14.696 psi

• Sample Key Questions

- Does the consistency in integrated forces/moments from CFD simulations improve when modeling geometrically simpler HL configurations?
- Are there unique CFD modeling requirements (e.g. mesh, solver, etc.) for an unprotected Leading Edge (LE)?
- How does the additional of the LE device (slat) effect CFD modeling, both in terms of accuracy and consistency?
- How does the additional of the TE device (flap) effect CFD modeling, both in terms of accuracy and consistency?
- How does the additional of the pylon/nacelle effect CFD modeling, both in terms of accuracy and consistency?

Details

- Geometry is provided in full-scale inches
- When using a dimensional code, it is recommended to adjust viscosity to a non-physical value to match requested Reynolds number
- All simulations are run Free-Air with no tunnel or support systems included

Optional Case 2a

- Several elements of the computational modeling can be investigated to explore sensitivity of solutions. These include, but are not limited to:
  - Use of specific wind tunnel model geometry associated with a particular test campaign
  - Use of static tunnel aeroelastic deformations
  - Performing in-tunnel simulations (either with the test section only, or including expansion/contraction sections)
  - Physical tripping or transition modelling
  - Systematic mesh refinement

* Reference configuration

Test Case 2 – Motivation

- The intent with this test case was to provide a series of increasingly complex configurations to expose different configuration components to systematically stress different aerodynamic features
- Presumably, if accuracy fell off due to a particular component, modelling practices could be modified to improve accuracy
- Not clear if this was entirely successful!
  - Perhaps too many cases were required, leading to limited collaboration on improving predictions

Test Case 2 Key Questions

#	Key Question
1	Does the consistency in integrated forces/moments from CFD simulations improve when modeling geometrically simpler HL configurations?
1a	Are there unique CFD modeling requirements (e.g. mesh, solver, etc.) for an unprotected Leading Edge (LE)?
1b	How does the addition of the LE device (slat) effect CFD modeling, both in terms of accuracy and consistency?
1c	How does the addition of the TE device (flap) effect CFD modeling, both in terms of accuracy and consistency?
1d	How does the addition of the pylon/nacelle effect CFD modeling, both in terms of accuracy and consistency?
2	If accuracy falls off due to the presence of a single component, can better modeling approaches be established to improve the predictions?
3	Are there any conclusions that can be made regarding accuracy of one particular method over another?

Test Case 2 – Key Question 1

1	Does the consistency in integrated forces/moments from CFD simulations improve when modeling geometrically simpler HL configurations?

In some cases, Yes, in others No.

- 2.1 (Wing-Body): Turns out that this was one of the MORE challenging cases. Results sensitive to LE transition (SRS), and separation (RANS); not yet fully explored experimentally or computationally
- 2.2 (Wing-Body-Slat): Addition of slat significantly improves correlation of results with test data across high-fidelity methods
- 2.3 (Wing-Body-Slat-Flap): Addition of flap component (and flap separation) increased scatter among all methods relative to 2.2
- 2.4 (Landing Configuration): Addition of nacelle component generally improves correlation with test data relative to 2.3
    - However, not obvious that correlation with test data for a full configuration has improved since HLPW-4. Perhaps this is due in part to more answer from more solvers in higher fidelity TFGs?

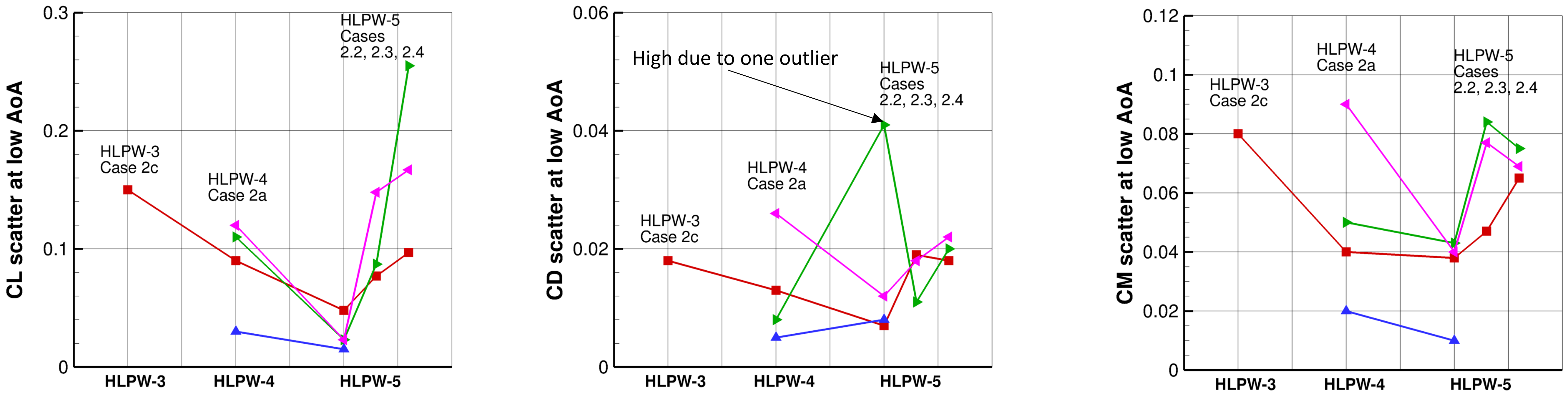
Test Case 2 – Key Question 1

1	Does the consistency in integrated forces/moments from CFD simulations improve when modeling geometrically simpler HL configurations?

- Scatter* for low AoA across workshops

With one exception (due to an outlier), scatter is smaller for Case 2.2 than for Cases 2.3 or 2.4 for all methods. This suggests that it is easier for CFD to get consistent results in the linear regime when there is no flap present.

Scatter trends in linear regime over last 3 workshops



RED=RANS BLUE=ADAPT GREEN=HRLES PINK=WMLES

*Scatter = 2*sqrt(3)*STDDEV

There were not enough ADAPT results at AoA=10 to determine a scatter trend for Cases 2.3 and 2.4 in HLPW-5

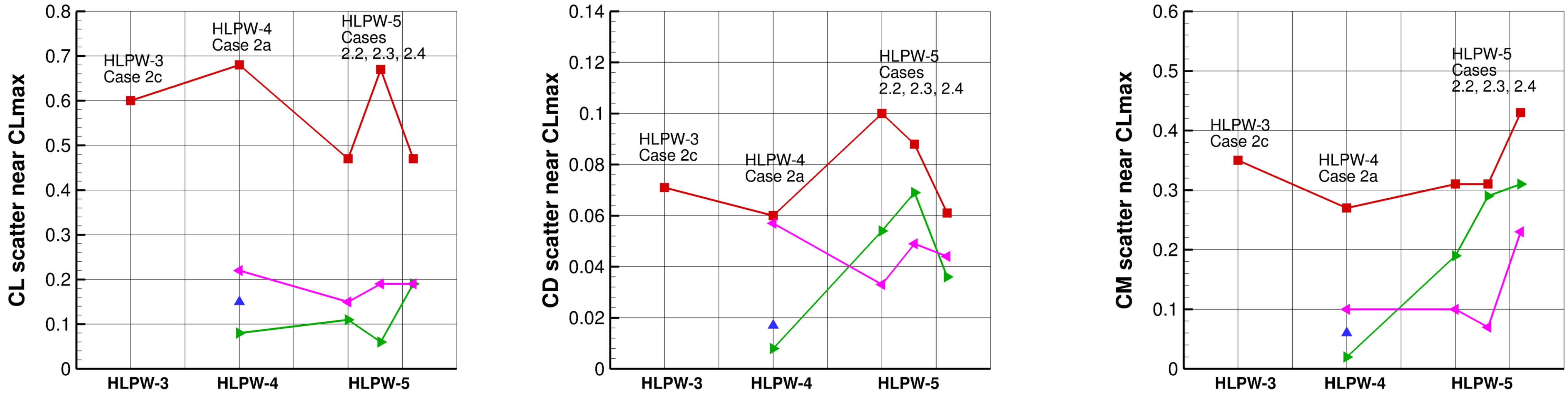
Test Case 2 – Key Question 1

1	Does the consistency in integrated forces/moments from CFD simulations improve when modeling geometrically simpler HL configurations?

- Scatter near CLmax across workshops

When we have workshops like this with different codes, models, and methods, we ALWAYS get a certain amount of scatter… it's not necessarily better for simpler configurations, and it's not going away over time

Scatter trends near CLmax over last 3 workshops



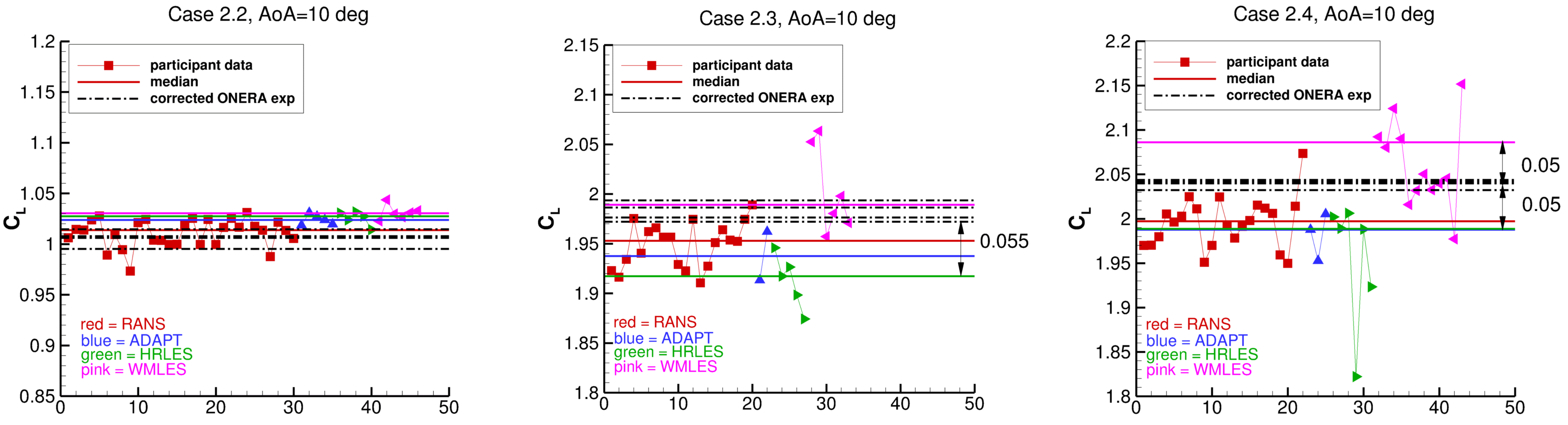
RED=RANS BLUE=ADAPT GREEN=HRLES PINK=WMLES

There were not enough ADAPT results at AoA=19 to determine a scatter trend for HLPW-5

Test Case 2 – Key Question 1

1	Does the consistency in integrated forces/moments from CFD simulations improve when modeling geometrically simpler HL configurations?

- At low AoA (in the linear regime), scatter is very small for Case 2.2, but increases for 2.3 and 2.4
  - For 2.3 and 2.4, RANS and HRLES tend to underpredict lift
  - For 2.3 and 2.4, a group of WMLES tends to overpredict lift



Case 2.2	Case 2.3	Case 2.4
RANS scatter = 0.048 (ADAPT=0.015)	RANS scatter = 0.077	RANS scatter = 0.097
HRLES scatter = 0.023	HRLES scatter = 0.087	HRLES scatter = 0.255
WMLES scatter = 0.023	WMLES scatter = 0.148	WMLES scatter = 0.167

Test Case 2 – Key Question 1

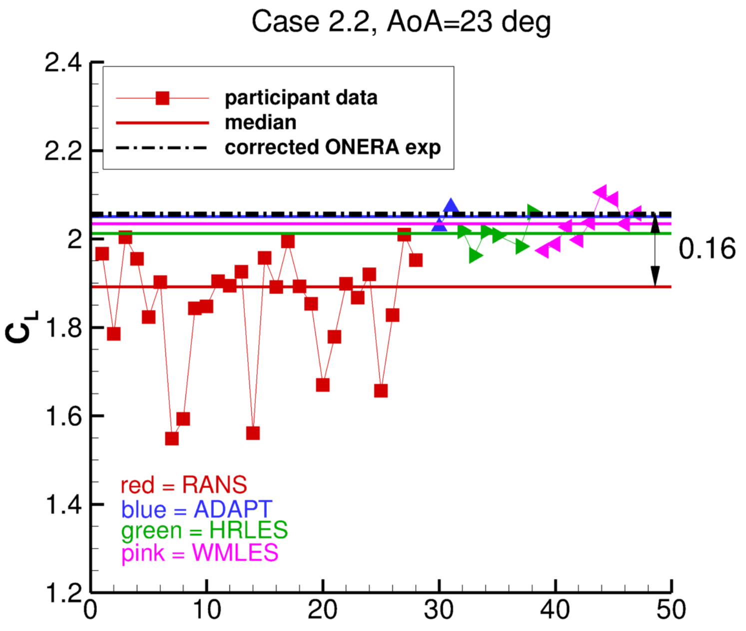
1	Does the consistency in integrated forces/moments from CFD simulations improve when modeling geometrically simpler HL configurations?

- Considering only results near CLmax:
- For RANS: Not really
  - No clear trend in scatter with test case.
  - The “best” of the RANS results are closer to the experimental data for Case 2.2; however, RANS has a big variation near CLmax for all cases; worst for Case 2.3.
  - Its median results near CLmax are best compared to experiment for Cases 2.2 and 2.4; worst for Case 2.3.
- For ADAPT: Not enough submissions to judge
  - However, ADAPT results appeared to be generally more consist than RANS on fixed grids (like at HLPW-4)
- For HRLES: Not really
  - No clear trend in scatter with test case.
  - Its median results near CLmax are best compared to experiment for Cases 2.2 and 2.4; worst for Case 2.3.
- For WMLES: Not really
  - No clear trend in scatter with test case.
  - Its median results are extremely accurate for Case 2.2.

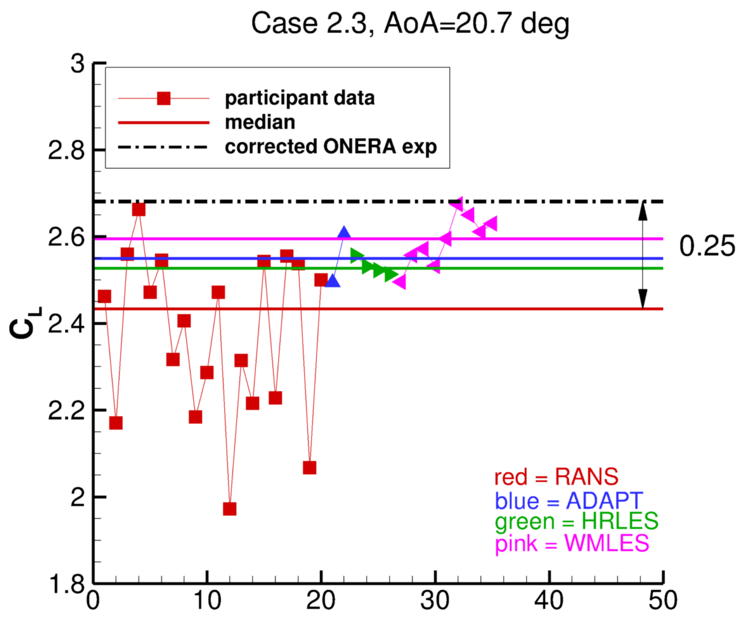
Test Case 2 – Key Question 1

1	Does the consistency in integrated forces/moments from CFD simulations improve when modeling geometrically simpler HL configurations?

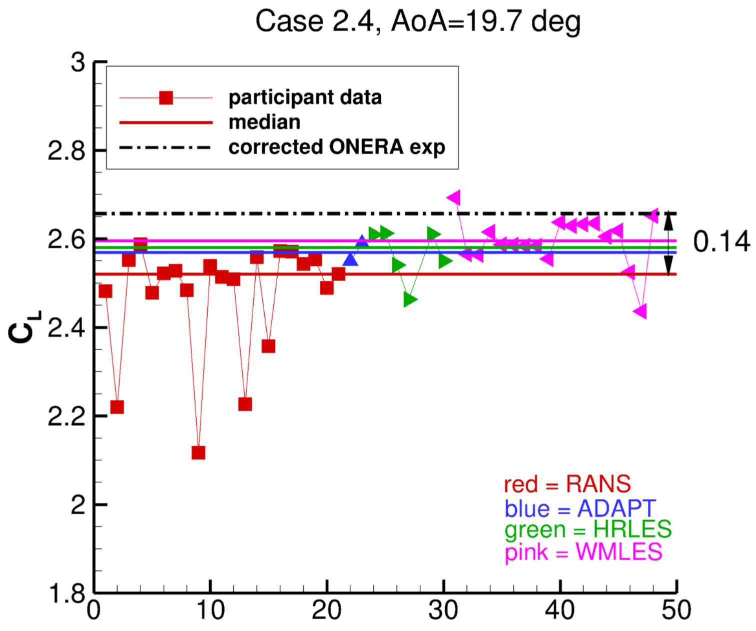
- Near CLmax, scatter among test cases is significant across all methods



RANS scatter = 0.47
HRLES scatter = 0.11
WMLES scatter = 0.15



RANS scatter = 0.67
HRLES scatter = 0.06
WMLES scatter = 0.19



RANS scatter = 0.47
HRLES scatter = 0.19
WMLES scatter = 0.19

Test Case 2 – Key Question 2

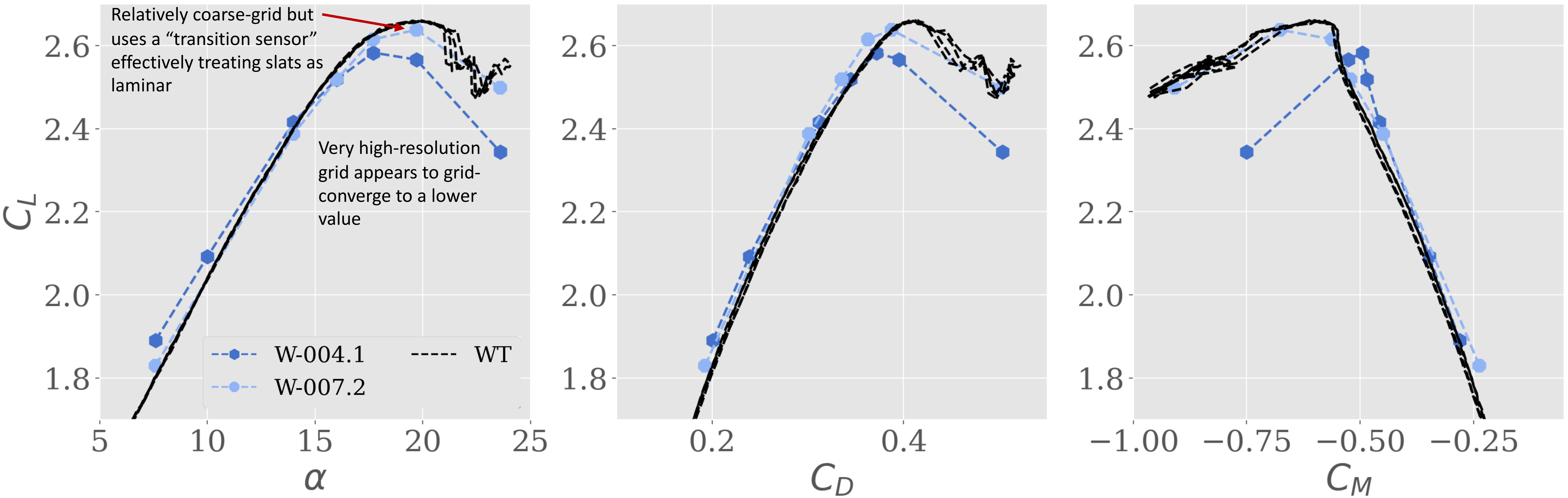
2	If accuracy falls off due to the presence of a single component, can better modeling approaches be established to improve the predictions?

- For several instances where modeling issues are noted, improved predictions were obtained based on evidence from more simple test cases:
  - RANS:
    - **NO:** Convincing evidence that RANS turbulence model cannot reliably predict separated flows – all have their own flavors of weakness
    - **NO:** Continuing focus on ‘pizza slice’ separation patterns behind slat brackets. Evidence suggests development of this type of separation is tied more strongly to poor residual convergence than previously thought.
  - HRLES:
    - **YES:** Simple test cases exposed a known weakness with HRLES shielding function. **Deck-Renard function** became ‘mainstream’ because of this (Test Case 1)
    - **NOT ADDRESSED:** Predictive capability also got considerably worse with the inclusion of the flap.
  - WMLES:
    - **YES:** Systematic shortfall from many participants in CLmax led to increased attention to transition, particularly the importance in modeling the correct boundary layer on the slat near CLmax. Led to exploring **transition sensor models** included in several codes.
    - **NOT ADDRESSED:** Noted differences in flap health between participants. Half of participants over-predicted flap health significantly.

Test Case 2 – Key Question 2

2	If accuracy falls off due to the presence of a single component, can better modeling approaches be established to improve the predictions?

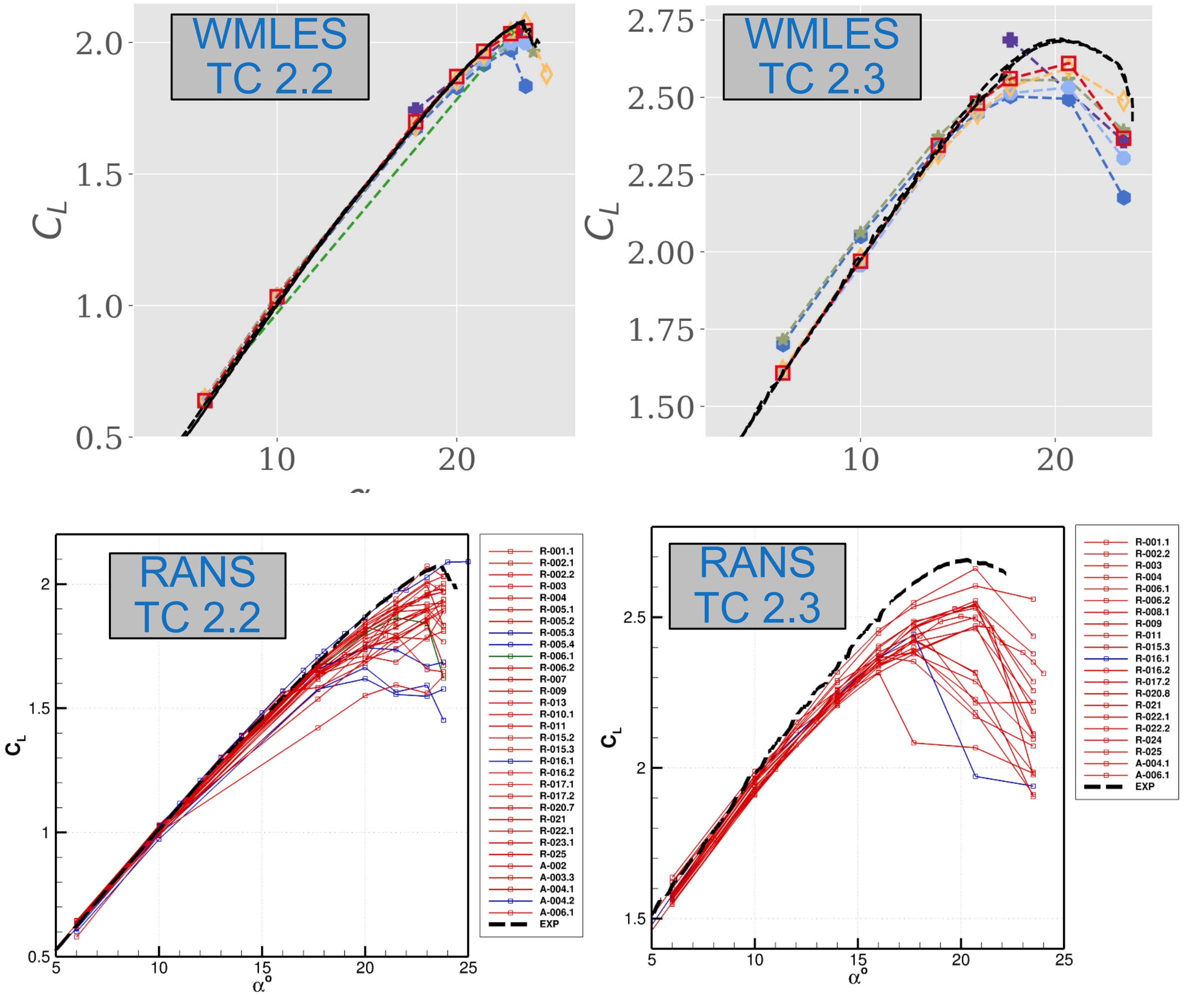
- Several examples where inclusion of transition sensor in WMLES dramatically impacts results at Clmax.
- Including laminar region results in a step change towards the experiment, but it's still unclear that this method can be truly predictive



Test Case 2 – Key Question 2

2	If accuracy falls off due to the presence of a single component, can better modeling approaches be established to improve the predictions?

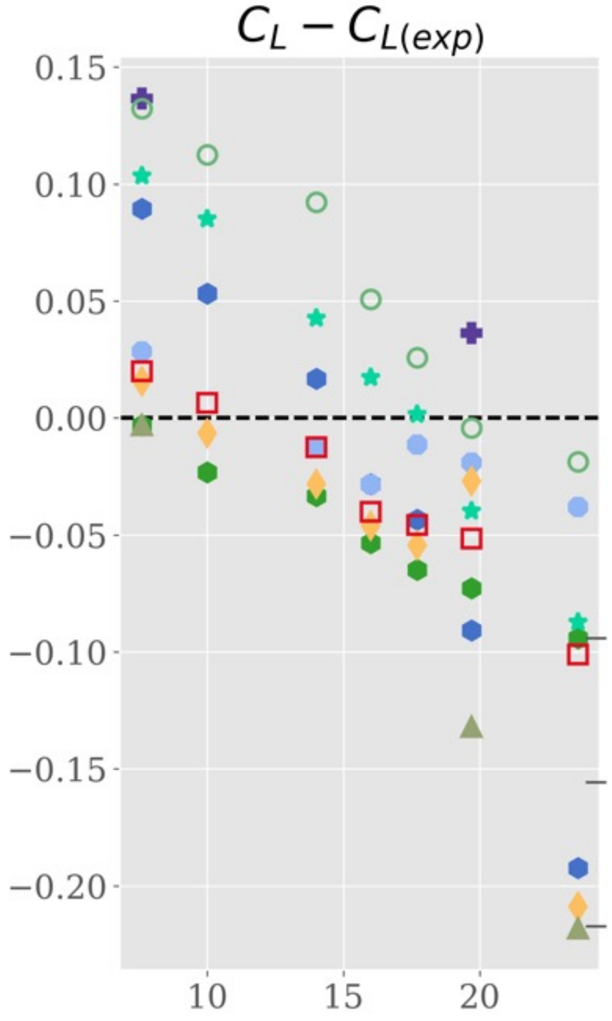
- Across all methods, inclusion of the flap dramatically negatively affected predictive accuracy.
- Wider spread in lift at alpha, peak loading on a flap is harder to predict
- Larger misses at CLmax – slightly more puzzling as the flap largely unloads by this point, though the local AoA is higher due to increased circulation



Test Case 2 – Key Question 2

2	If accuracy falls off due to the presence of a single component, can better modeling approaches be established to improve the predictions?

- For WMLES it looks like some participants are sensitive to flap over-prediction, and others are sensitive to transition
  - When looking at the error in CL, **all best-practice solutions exhibit similar slope**
  - Some combination of modelling / gridding choices can shift the error higher or lower at either end
  - Some are slightly steeper or shallower than others, but it appears **<u>all</u> exhibit similar modeling deficiencies**



WMLES Test Case 2.4 Lift Error

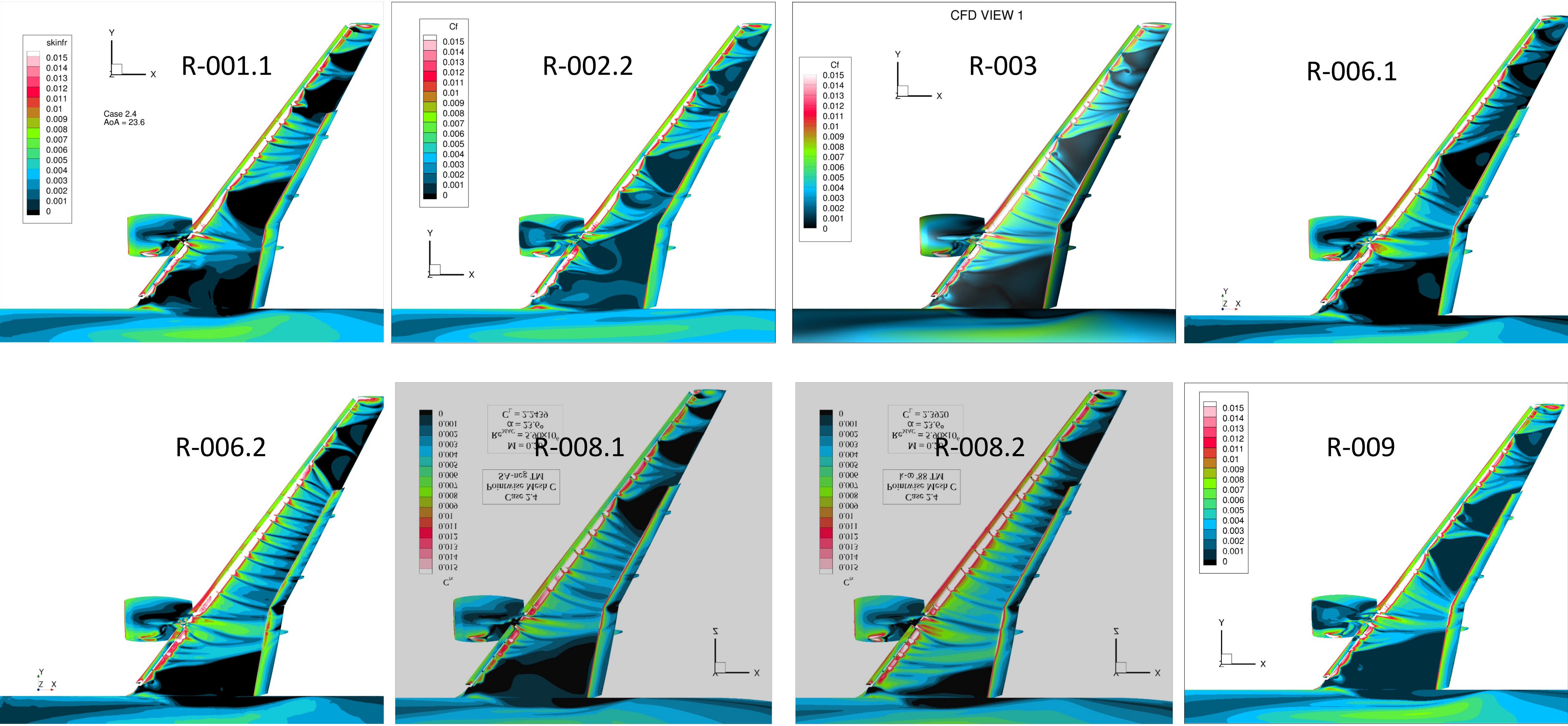
Test Case 2 – Key Question 3

3	Are there any conclusions that can be made regarding accuracy of one particular method over another?

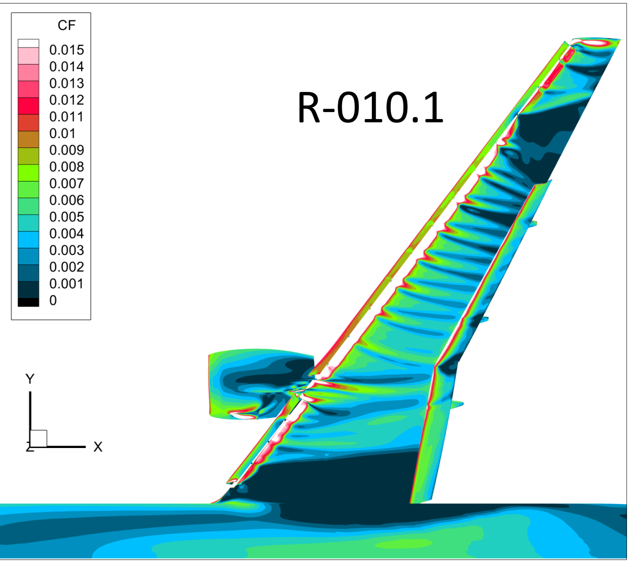
- For this, we chose to look at post-stall surface contours on case 2.4, across all participants
  - To have confidence in a high AoA solution pre-stall, we need confidence that maximum lift breaks down *for the right reason*

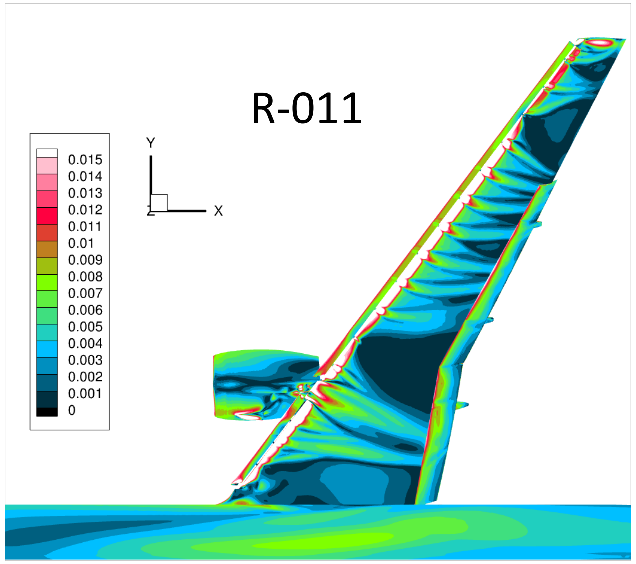
- Without exception, submitted RANS solutions produce spurious separation behind slat brackets to varying extents
- Without exception, submitted scale-resolving simulations (WMLES or HRLES) produce more physically realistic flow patterns over the wing past stall

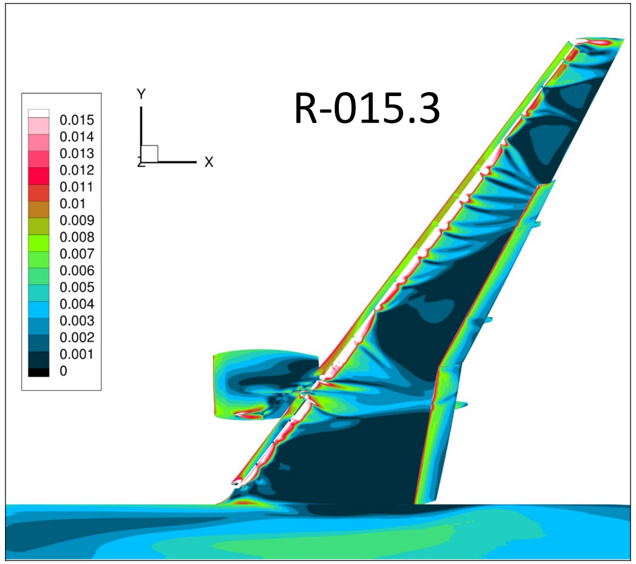
Test Case 2 – Key Question 3

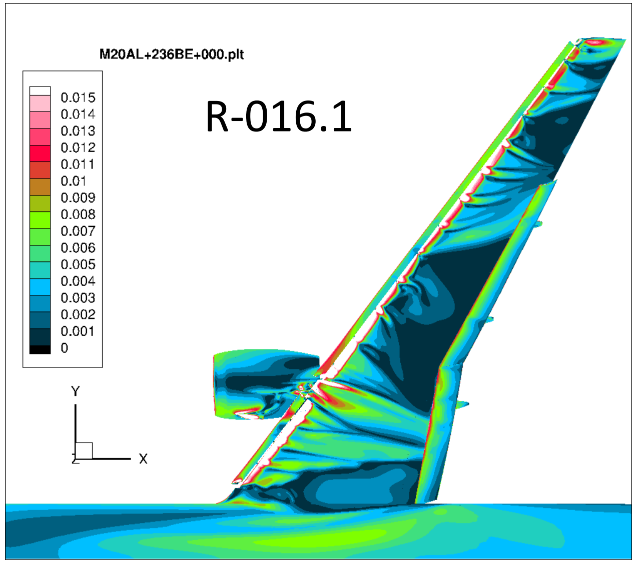


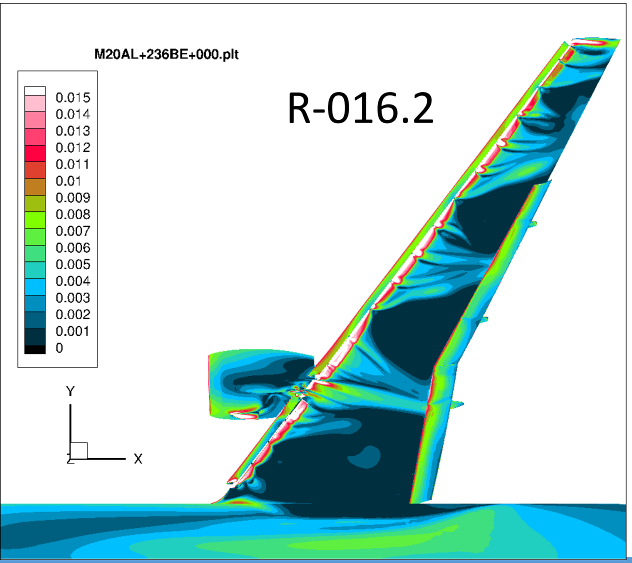
Test Case 2 – Key Question 3

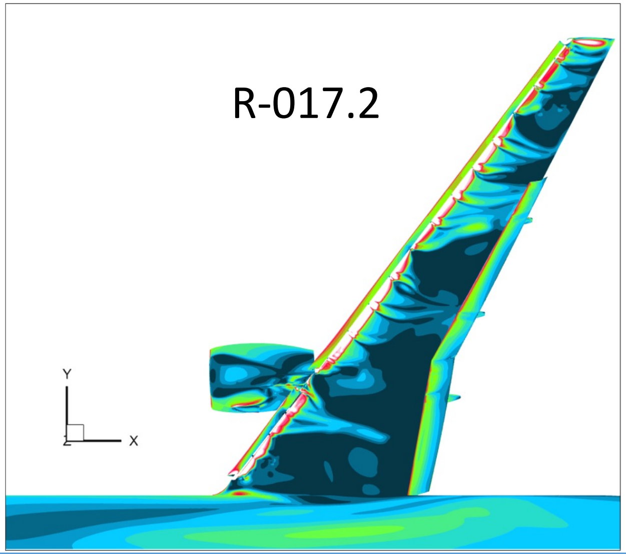


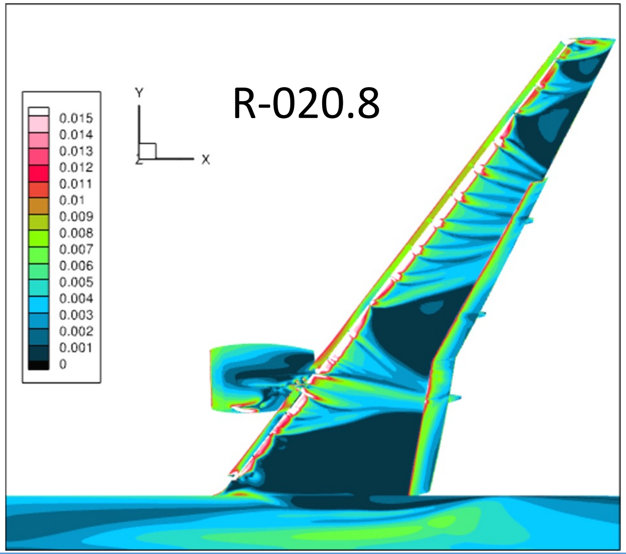


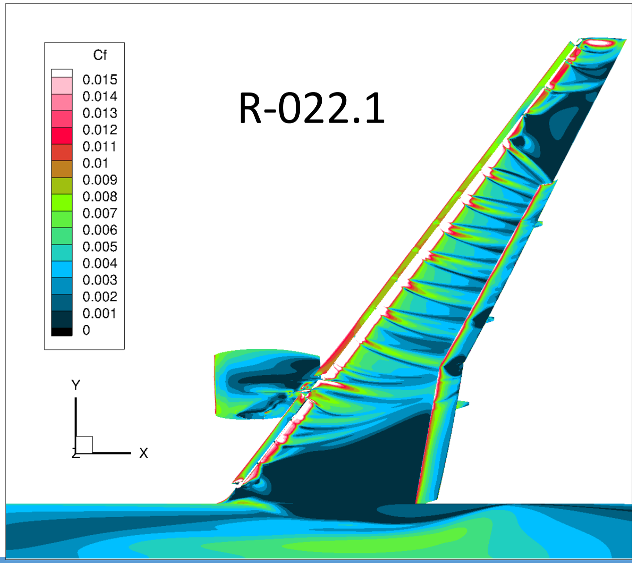




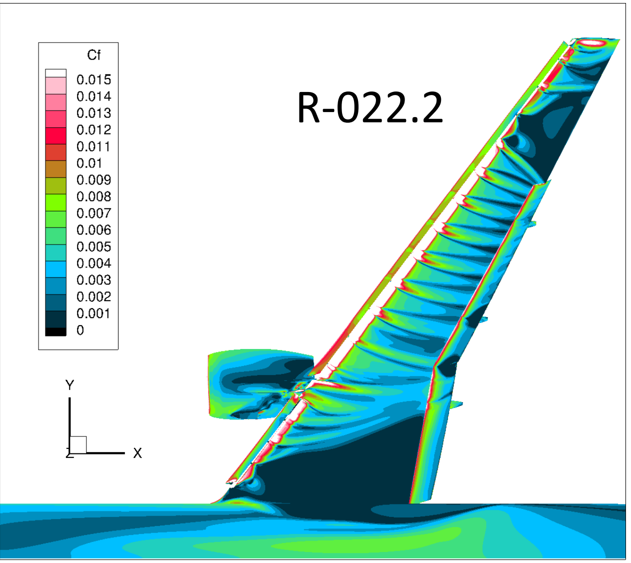


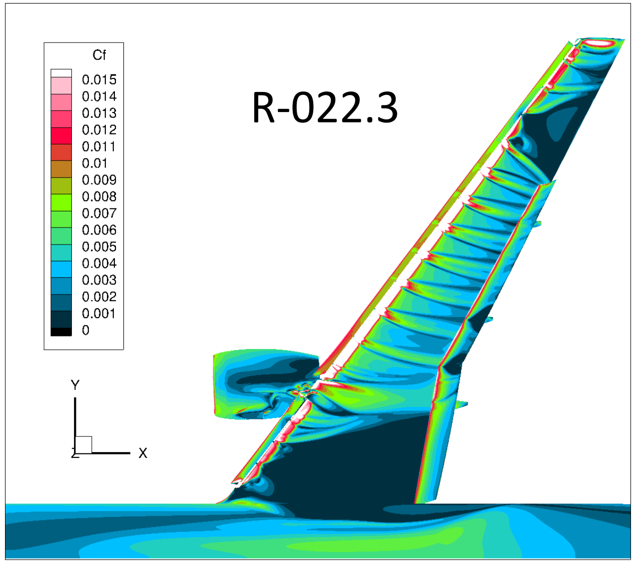


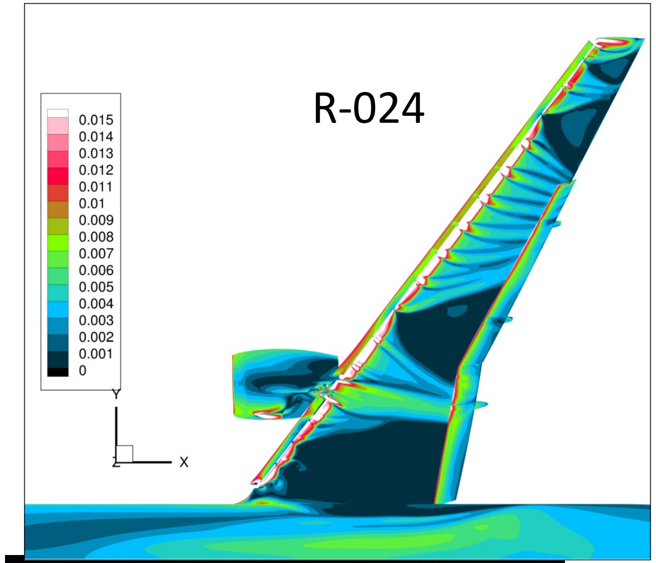


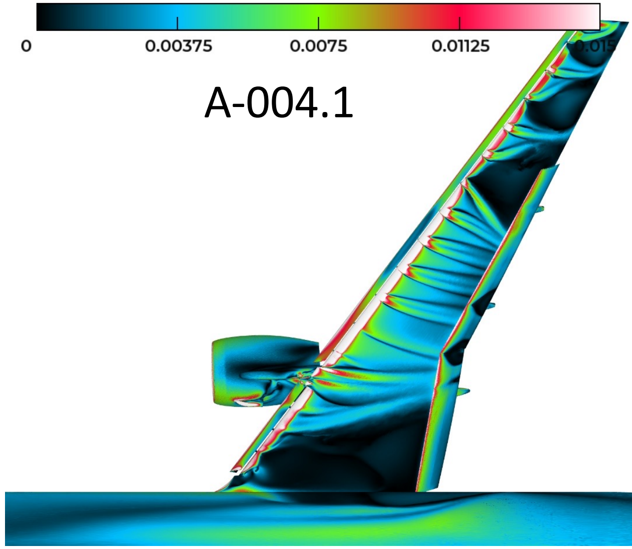


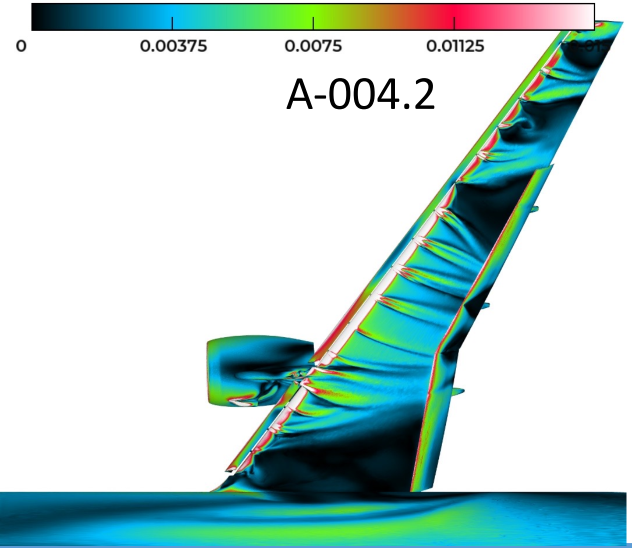
Test Case 2 – Key Question 3

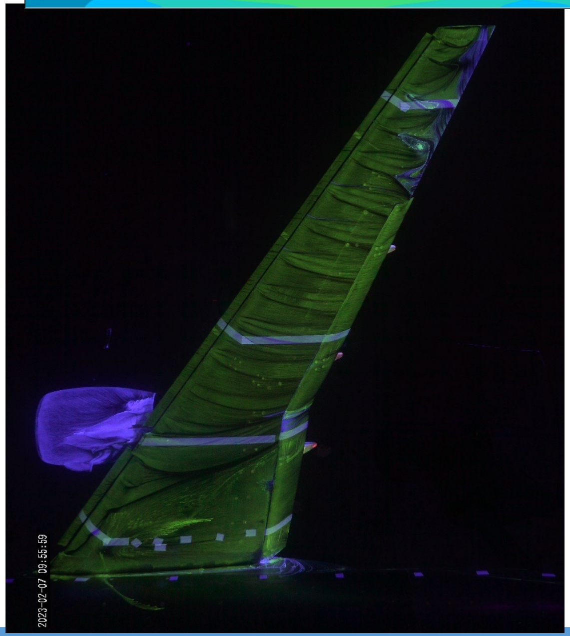




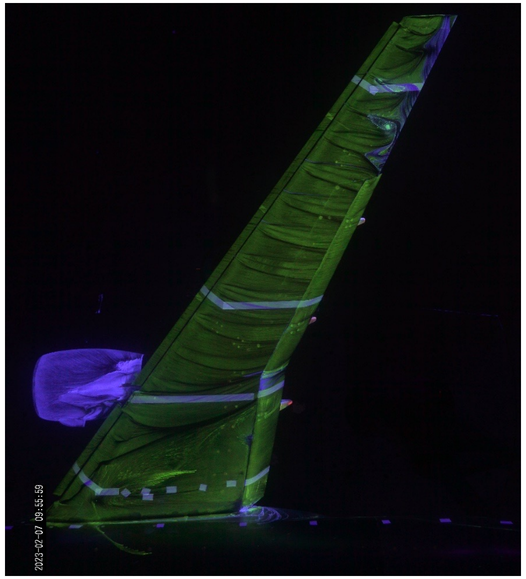


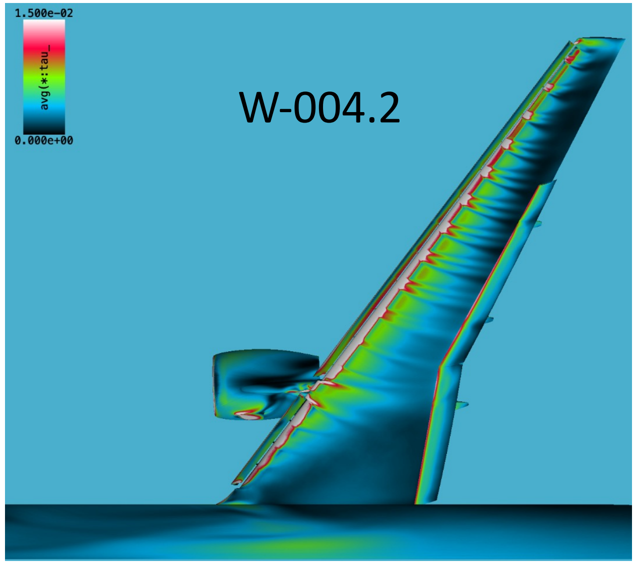


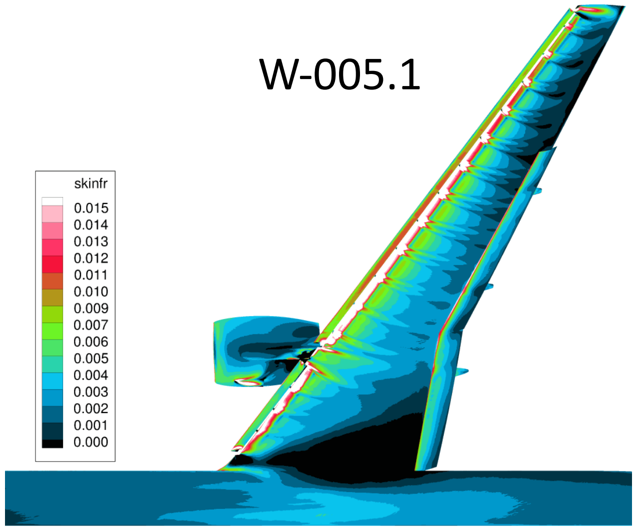


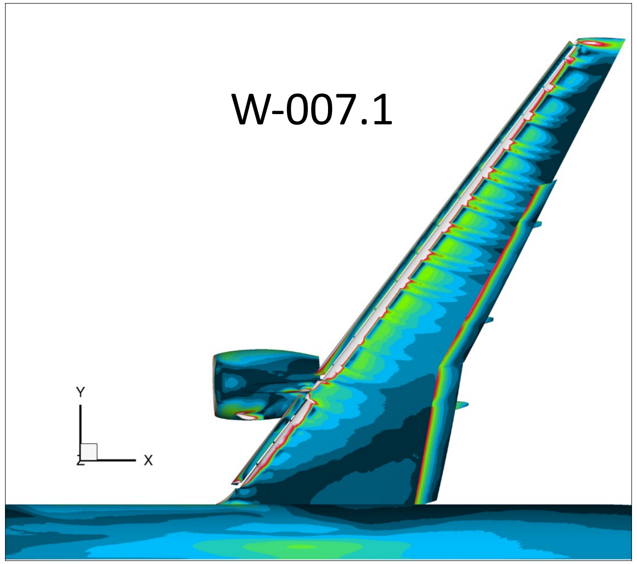


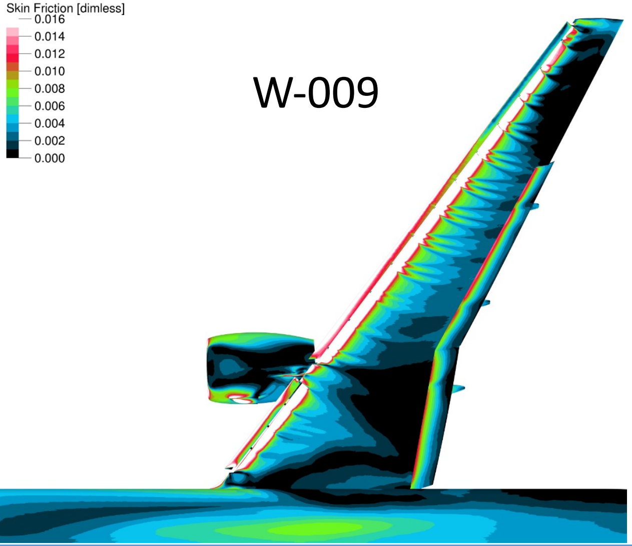
Test Case 2 – Key Question 3

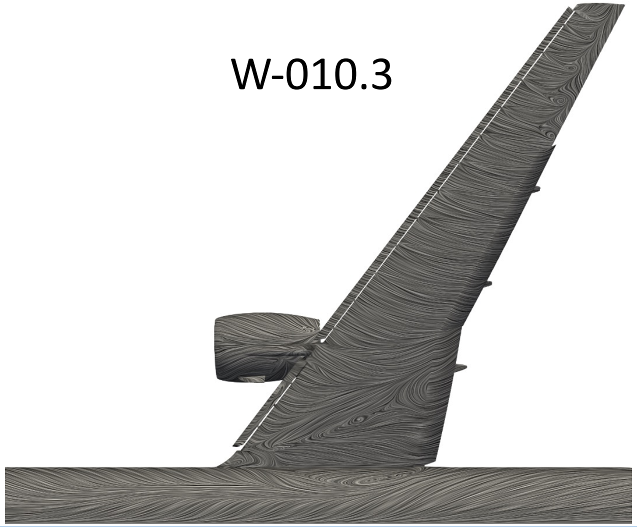


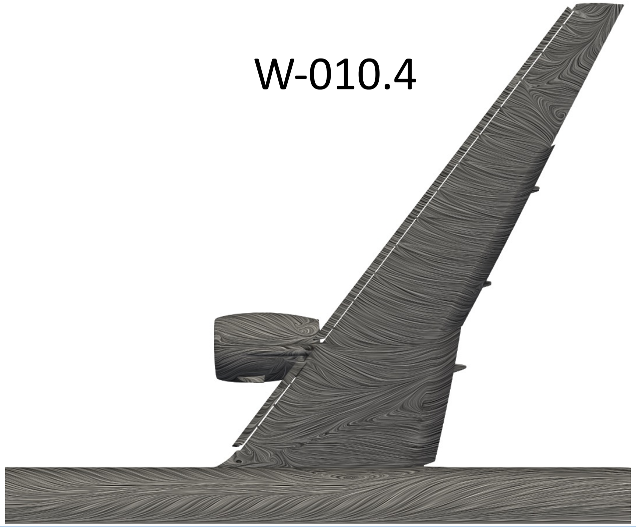


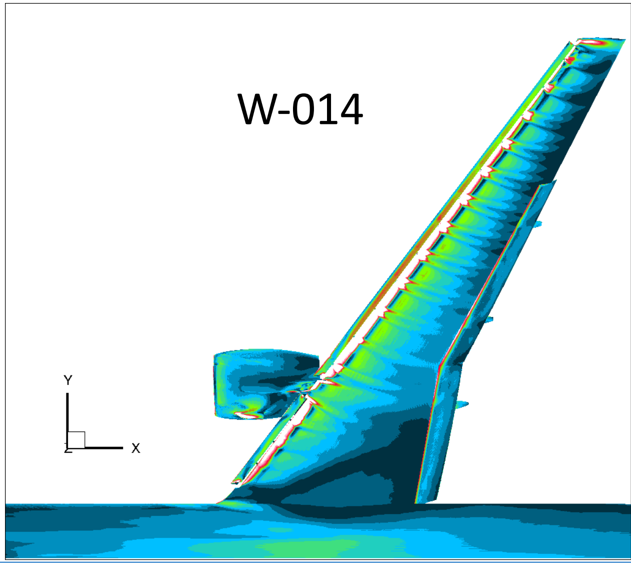




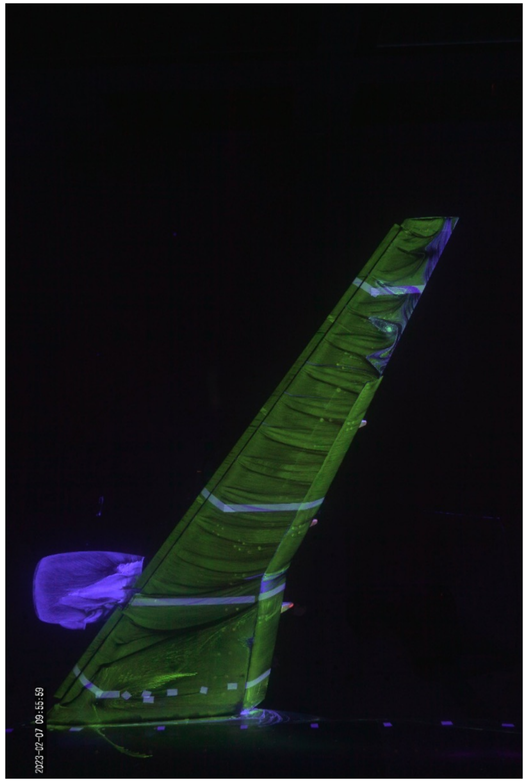


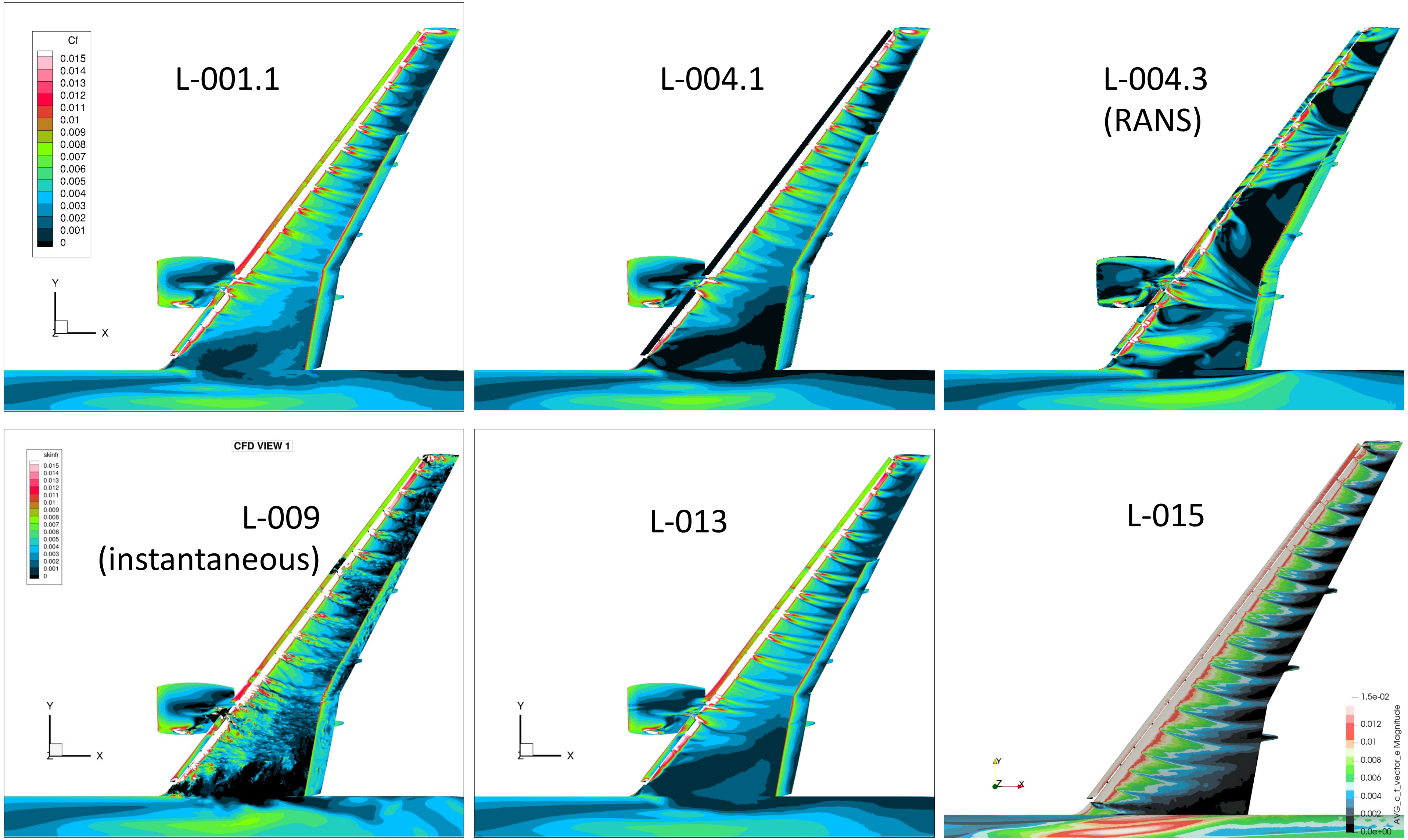






Test Case 2 – Key Question 3





Test Case 3
Reynolds Number Sensitivities

Test Case 3 – Reynolds Number Study

Flow solutions are requested to assess the capability of CFD to predict the effects of increasing Reynolds number on the aerodynamic performance of the CRM-HL in the reference landing configuration. Solutions are requested across specified angles of attack, at four different Reynolds numbers, and will be compared to fully corrected data obtained from several different facilities.

Geometry

- Wing-Body-Slat-Flaps-Nacelle (NASA_5.2%–LDG) *

Experimental Data

- KHI LSWT, ONERA F1, NASA NTF, QinetiQ 5-metre

Computational Domain

- Symmetry at y=0

Run Conditions

Mach Number	0.20
Chord Reynolds Number	1.05M (optional), 5.49M, 16M, 30M
Angles of Attack	6, 10, 14, 16, 18, 19, 20, 22 degrees for each Re
Reference Static Temperature	518.67 °R
Reference Static Pressure	14.696 psi

* As-designed NASA 5.2% scale model

Sample Key Questions

- Are there unique gridding requirements for a particular Reynolds number?
- Does CFD accurately capture Reynolds number trends in integrated forces and moments up to flight scale?
- Does CFD accurately capture trends in aerodynamic flow separation vs Reynolds number?
- How important is aeroelastic modeling for accurate predictions at higher Reynolds numbers?
- Is running simulations in free-air adequate to understand trends and increments, or is running in-tunnel simulations, compared against uncorrected data, required?

Details

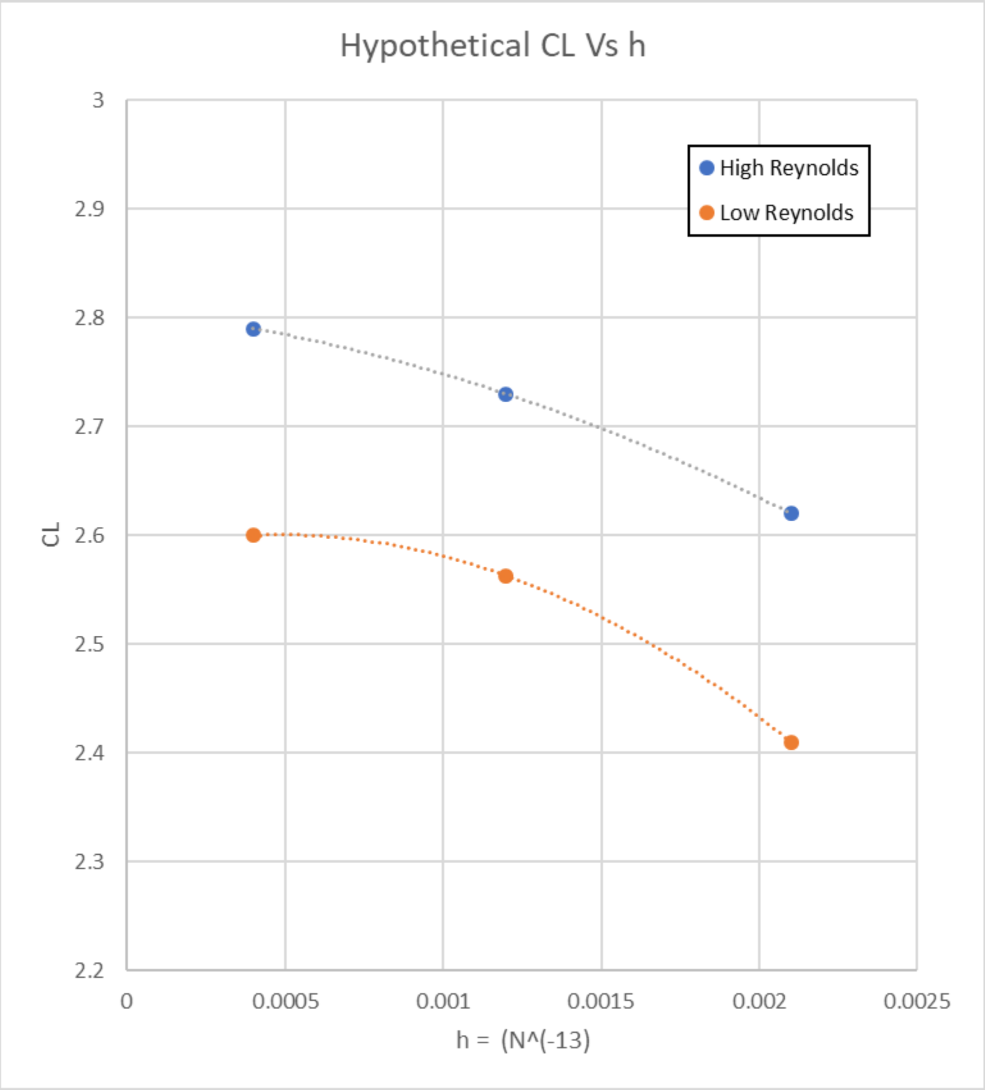
- Geometry is provided in full-scale inches
- When using a dimensional code, it is recommended to adjust viscosity to a non-physical value to match requested Reynolds number
- All simulations are run Free-Air, with no tunnel or support systems included

Optional

- Several elements of the computational modeling can be investigated to explore sensitivity of solutions. These include, but are not limited to:
  - Use of specific wind tunnel model geometry associated with a particular test campaign
  - Use of static tunnel aeroelastic deformations
  - Performing in-tunnel simulations (either with the test section only, or including expansion/contraction sections)
  - Physical tripping or transition modelling
  - Systematic mesh refinement

Test Case 3 – Motivation

- Test case 2 helped to establish best practices to accurately capture physics at a moderate Reynolds number – maybe?
- From here, what adjustments need to be made to capture Reynolds number trends?
- In particular, how do you establish the same 'level' of grid convergence when Reynolds changes from 1m to 30m?
- Desire for more accurate increment prediction than absolute value – perhaps 0.005 to 0.01 in CL?



Test Case 3 Key Questions

#	Key Question
1	How do gridding requirements change with Reynolds number?
2	How does grid convergence behavior change with Reynolds number?
3	How consistent are CFD predictions with each other across a range of Reynolds numbers?

Test Case 3 – Key Question 1

1	How do gridding requirements change with Reynolds number?
2	How does grid convergence behavior change with Reynolds number?

- Very hard question to answer without test data to compare against

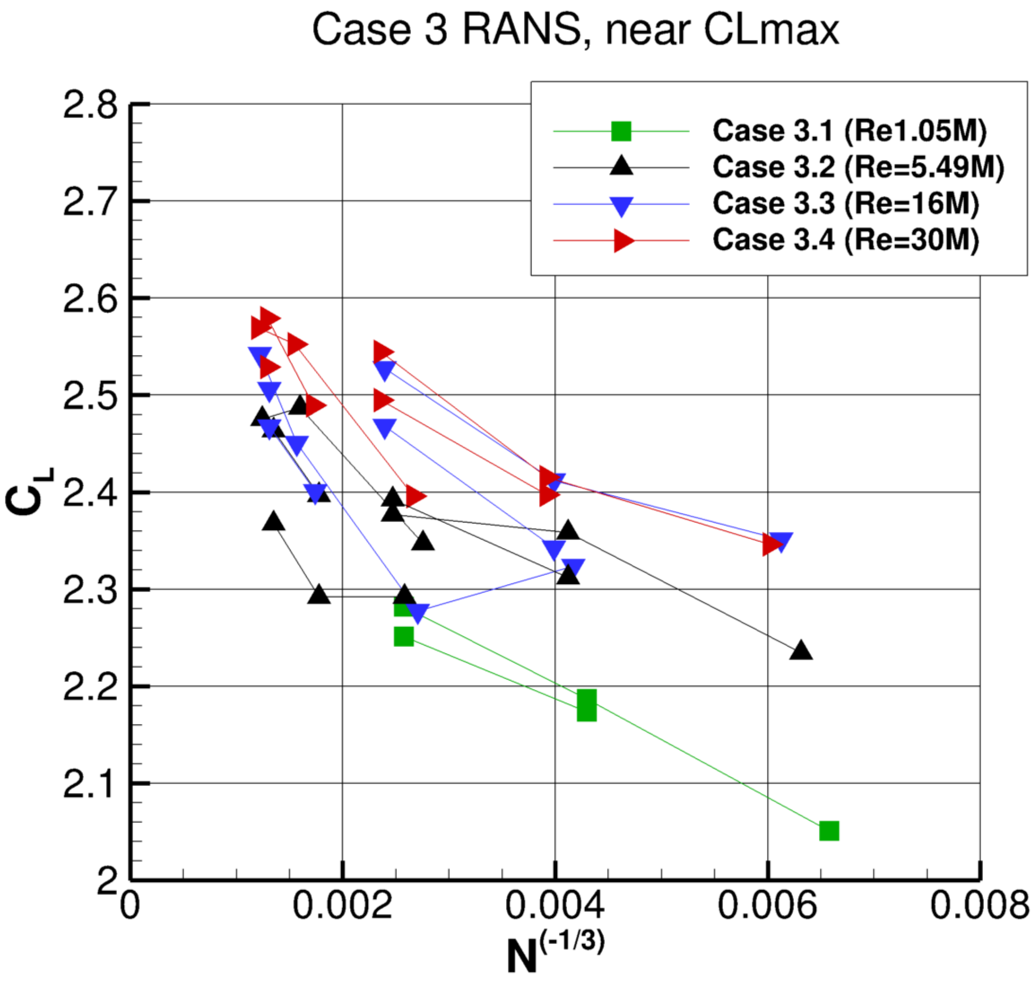
- RANS approach is 'well understood', where adjustment is made to first cell spacing to keep Y+ = 1 across Reynolds numbers
- Same approach is valid for HRLES, but with potentially additional requirements to resolve smaller scale turbulence far from the wall
- For WMLES, wall models make this exceptionally challenging as the model changes with grid refinement
  - do we expect to see 'grid convergence'? If so, what are the gridding requirements, if any?

- Many participants 'ran out of steam' at this point
  - Minimal 'exploration'
  - Minimal grid convergence
  - Fewer participants (eg. no Adaptive or HRLES results)

Test Case 3 – Key Question 1

1	How do gridding requirements change with Reynolds number?
2	How does grid convergence behavior change with Reynolds number?

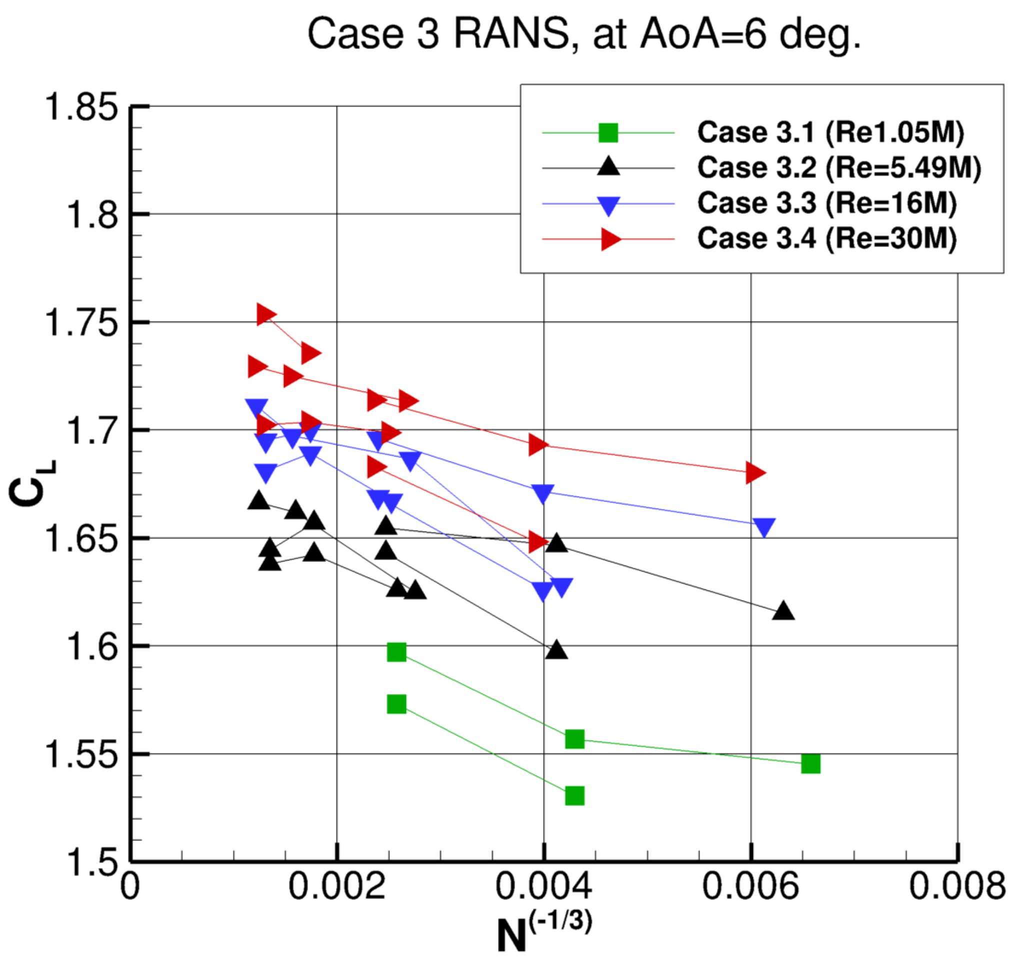
- Iterative convergence makes this extra challenging to be conclusive
- At CLmax, RANS unable to demonstrate grid convergence
  - We may need significantly more grid than can be afforded currently
  - May be that RANS fundamentally cannot capture CLmax trends due to modeling limitations
- Trends are consistent with 2.4 – perhaps it would be interesting to look at Re trends for TC 2.1 geometry



Test Case 3 – Key Question 1

1	How do gridding requirements change with Reynolds number?
2	How does grid convergence behavior change with Reynolds number?

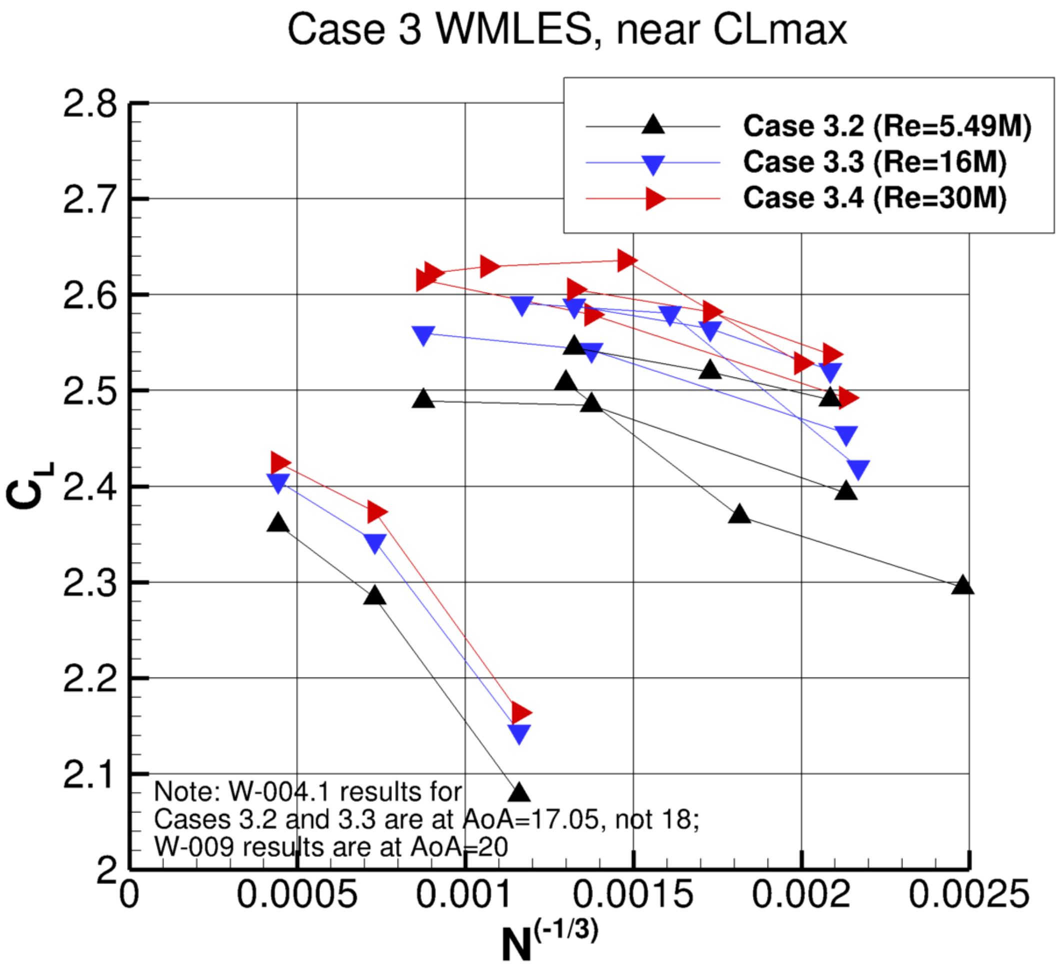
- At moderate angles of attack, RANS is unable to demonstrate grid convergence, so conclusions are difficult.
- 6° is still quite challenging in a full landing configuration, as this is where the trailing edge loading is the highest



Test Case 3 – Key Question 1

1	How do gridding requirements change with Reynolds number?
2	How does grid convergence behavior change with Reynolds number?

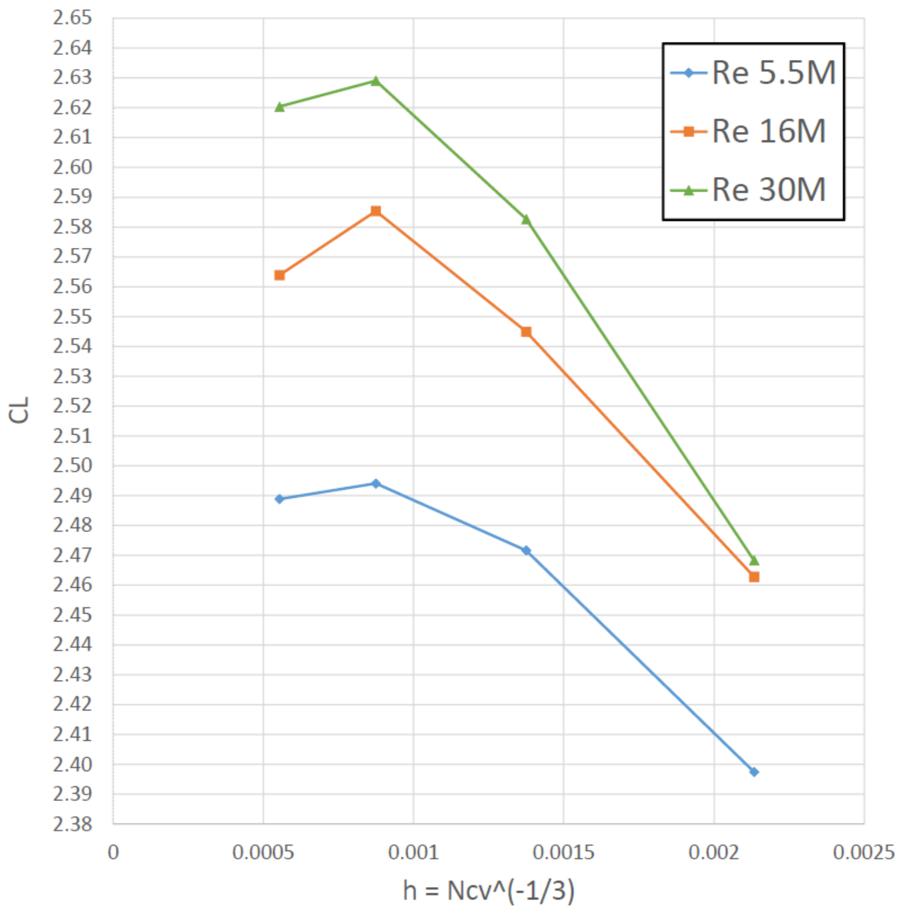
- From limited submitted WMLES results, it's not obvious that meshing requirements need to be any different at high Re compared to low Re
- At moderate Re, mesh resolution is often chosen to capture geometry, but should mesh resolution be chosen to capture expected smaller scale turbulence at high Re?
- Or are we not seeing the real trends due to poor grid convergence?



Test Case 3 – Key Question 1

1	How do gridding requirements change with Reynolds number?
2	How does grid convergence behavior change with Reynolds number?

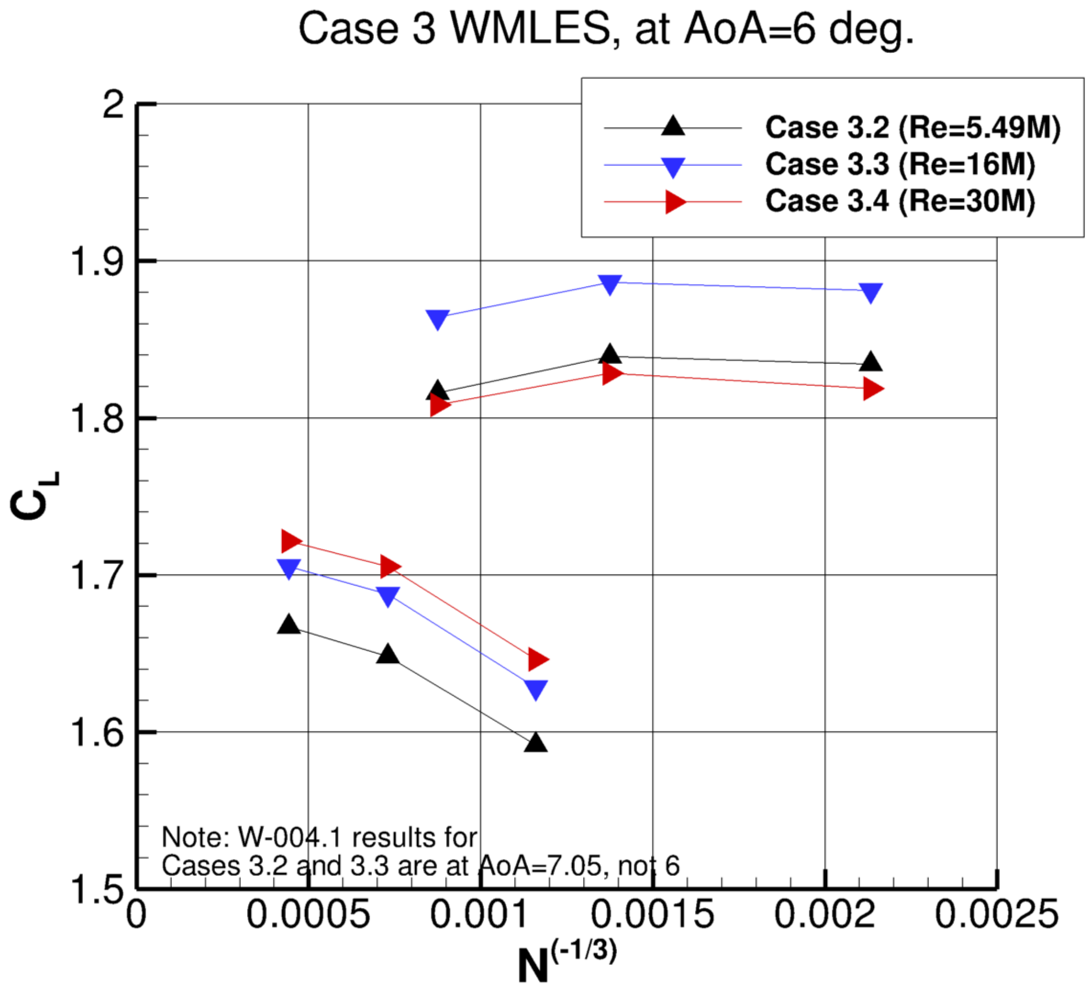
- At a different near-CLmax angle of attack, grid convergence trends appear similar for one WMLES participant regardless of Reynolds number



Test Case 3 – Key Question 1

1	How do gridding requirements change with Reynolds number?
2	How does grid convergence behavior change with Reynolds number?

- Less data available at lower angles of attack for TC 3
- WMLES is also unable to consistently demonstrate grid convergence here
  - Exposes known weakness in overprediction of flap health in one set of results



Test Case 3 – Key Question 3

3	How consistent are CFD predictions with each other across a range of Reynolds numbers?

- Results are not at all consistent across participants
  - Submitted TC3 data show significant variations – Even more than TC 2.4
  - Cannot make any useful conclusions on lift at moderate alpha or CLmax given data ensemble

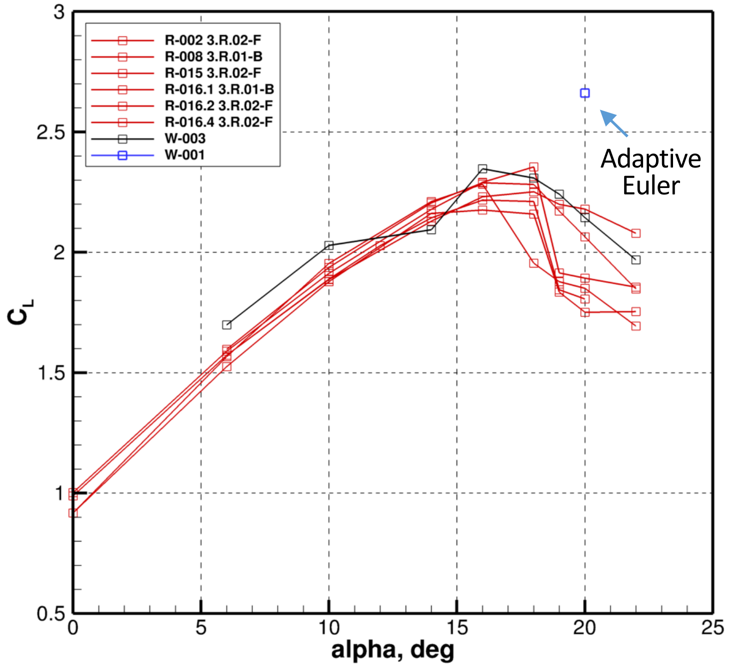
- However, comparing results from individual participants *does* reveal useful and consistent trends vs Reynolds number
  - Lack of trustworthy experimental results here make it again hard to draw conclusions, but consistency is a positive sign

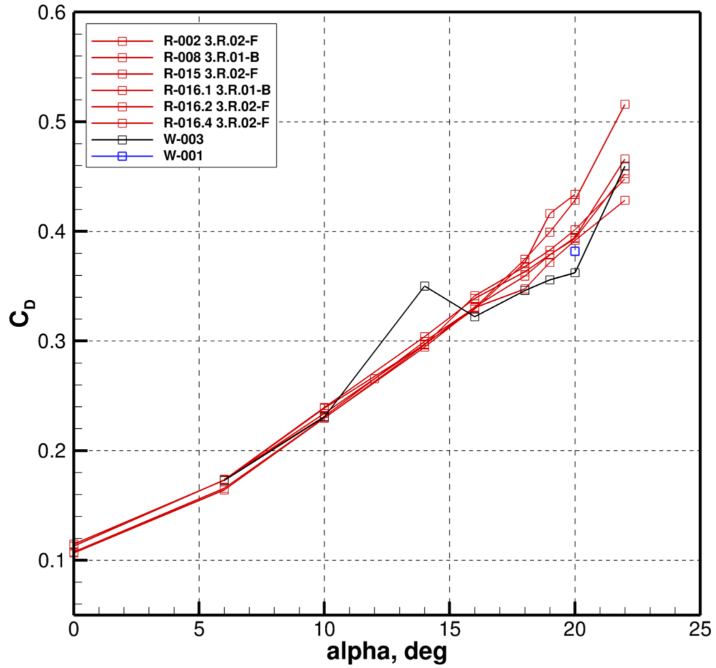
Test Case 3 – Key Question 3

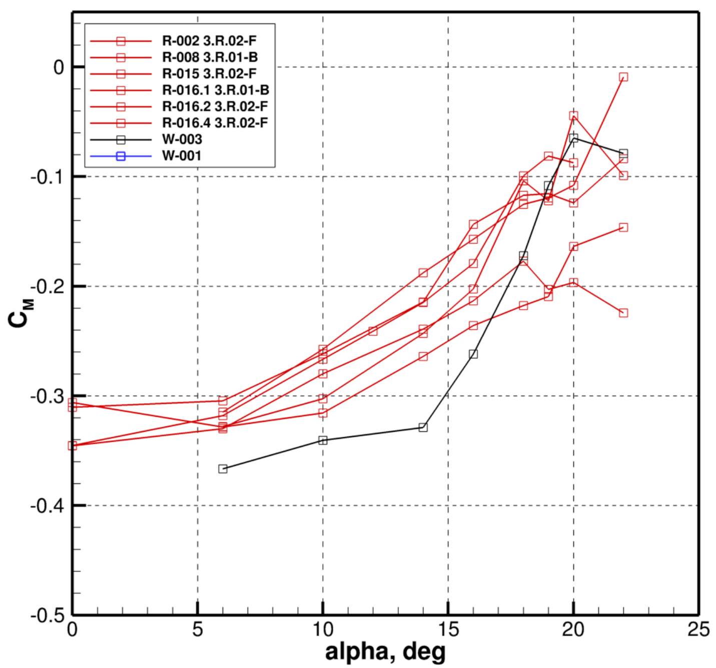
3	How consistent are CFD predictions with each other across a range of Reynolds numbers?

- Submitted TC3 data show significant variations in absolute values

Case 3.1





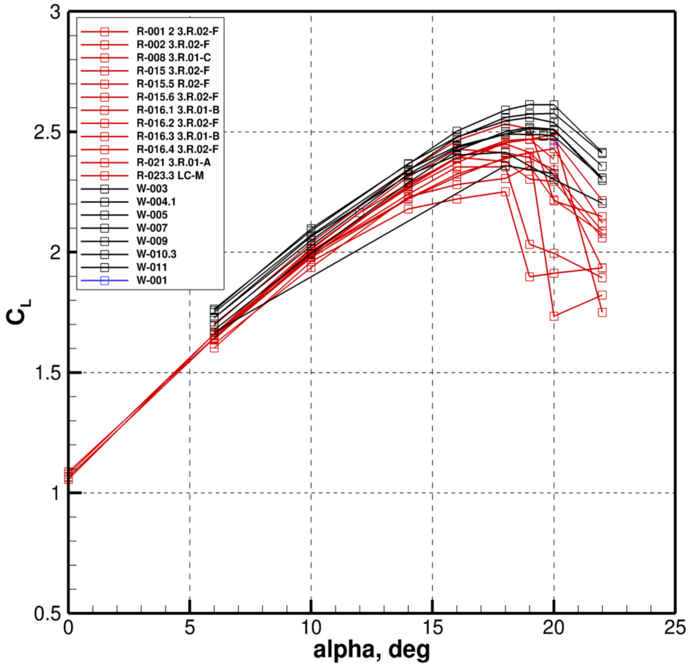


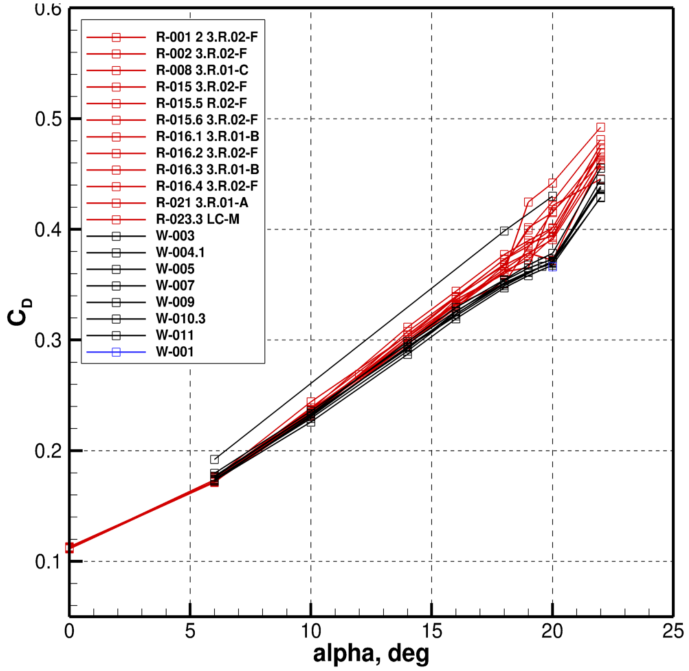
No CM data provided by Adaptive Euler

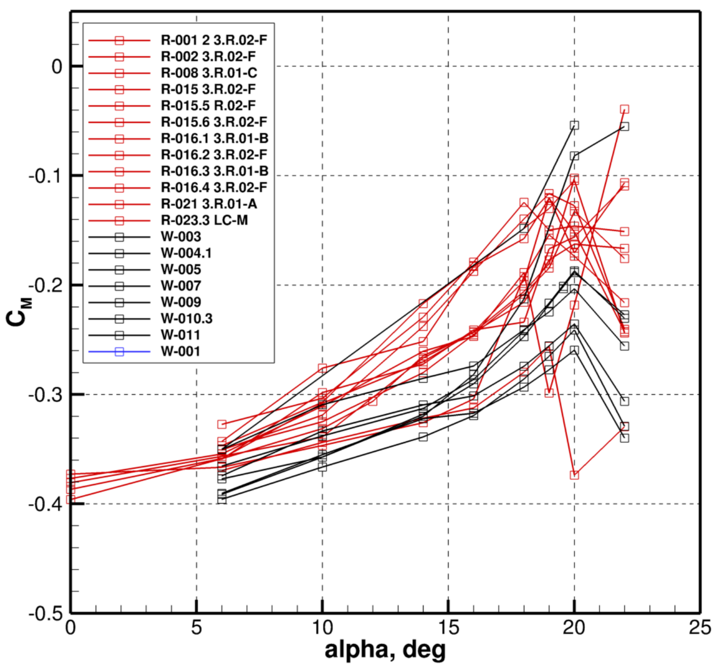
Test Case 3 – Key Question 3

3	How consistent are CFD predictions with each other across a range of Reynolds numbers?

Case 3.2







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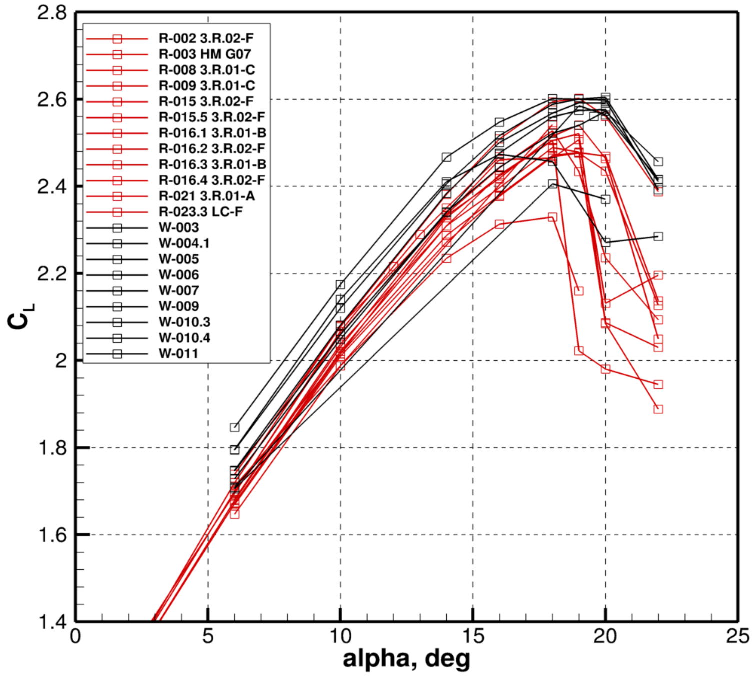
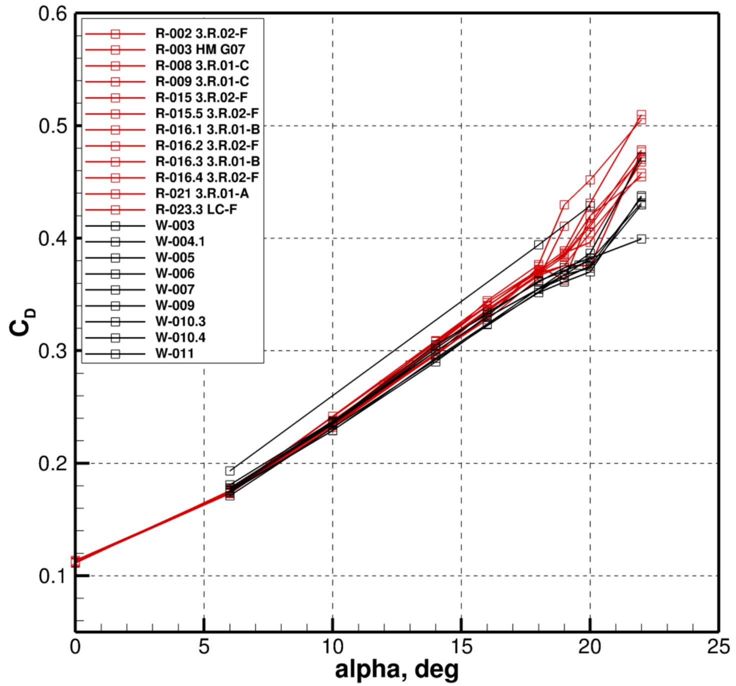
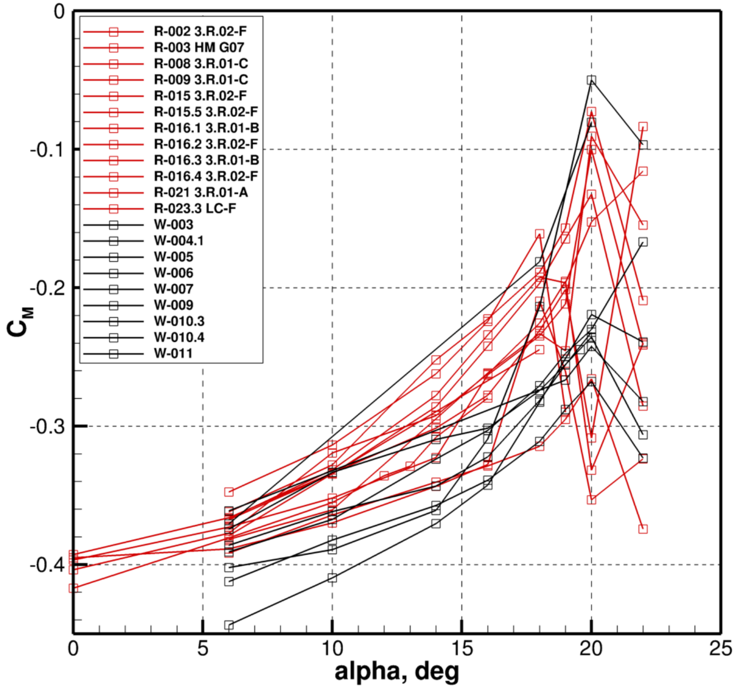
Test Case 3 – Key Question 3

3	How consistent are CFD predictions with each other across a range of Reynolds numbers?

Case 3.3





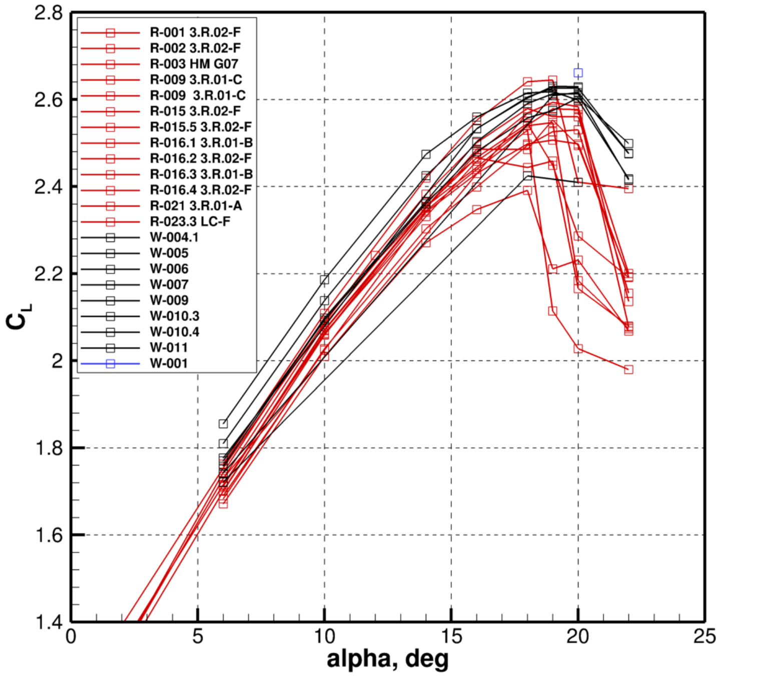


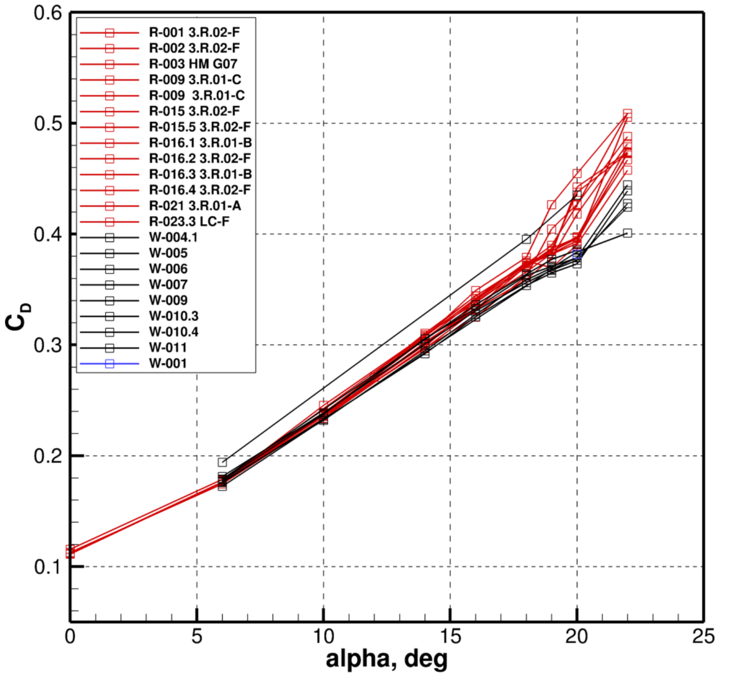
No CM data provided by Adaptive Euler

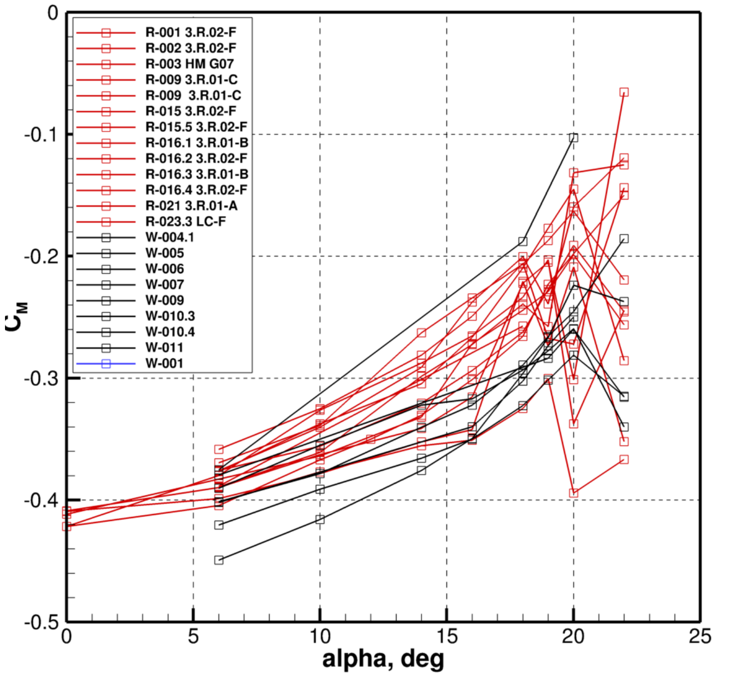
Test Case 3 – Key Question 3

3	How consistent are CFD predictions with each other across a range of Reynolds numbers?

Case 3.4





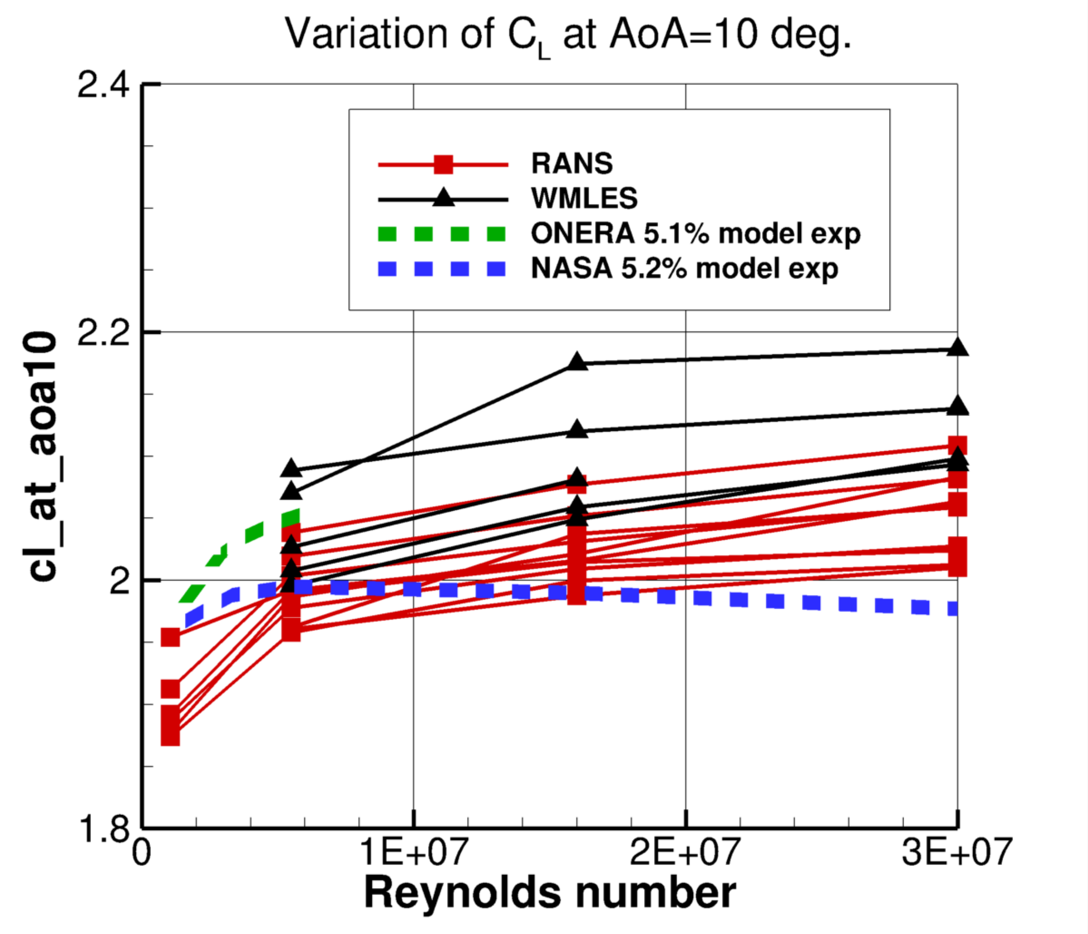


No CM data provided by Adaptive Euler

Test Case 3 – Key Question 3

3	How consistent are CFD predictions with each other across a range of Reynolds numbers?

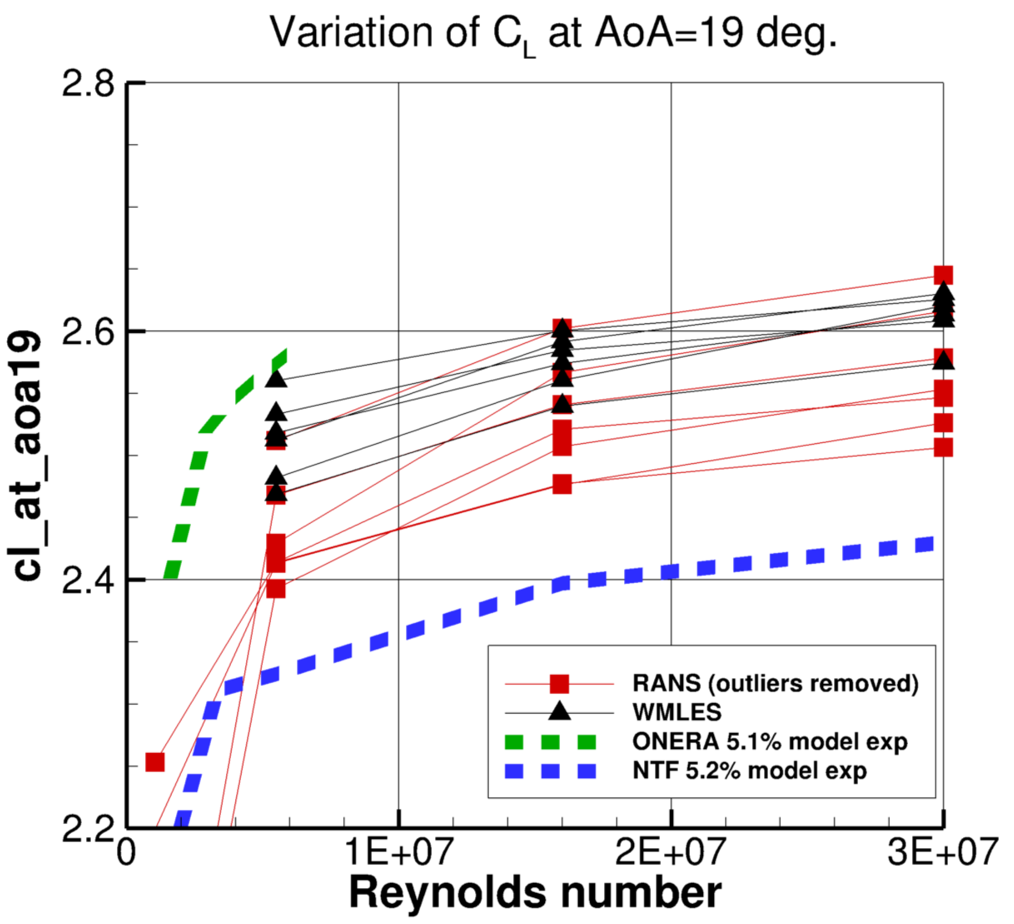
In the linear regime, both RANS and WMLES indicate an increasing (and asymptoting) CL trend with Re



Test Case 3 – Key Question 3

3	How consistent are CFD predictions with each other across a range of Reynolds numbers?

Most RANS and WMLES indicate a Re trend that appears to be fairly similar to preliminary experimental Re trends (with the exception of 1.05m Reynolds, where there isn't enough data to be conclusive)



Key Takeaways – Test Case 1

- Progress towards RANS consistency is notable
  - Able to show consistency when modeling approaches are constrained (eg. same turbulence model, good iterative convergence)
  - Can begin to make conclusions about modeling choices without being overwhelmed by gridding and numerics – though experimental data is necessary to make firm conclusions
  - A case with significant separation would be expected to make consistency more difficult
  - Adaptive methods continue to show the capability to demonstrate grid convergence without needing grid generation by an expert
- Consistency for case 1 is currently challenging for scale-resolving methods
  - Incremental improvements made in several instances (eg. Deck-Renard function)
  - Experimental data on transition would help WMLES

Key Takeaways – Test Case 2

- Demonstrated value in geometric build-up approach, where flow features can systematically be added and assessed
- Scope of workshop was too much – there's presumably a lot more that can be learned along each iteration, but no one had the bandwidth to systematically look at everything
- Across TFGs, adding a flap caused solutions to diverge from each other and the data, more than any other component addition
- Importance of transition noted in WMLES TFG – likely implies other TFGs are or should be sensitive to this too.
  - Could really use experimental data to further understand this and refine modelling approaches.
- SRS have a very high point of entry in terms of computational cost. Without adequate resolution, the results aren't meaningful.

Key Takeaways – Test Case 3

- We know grid convergence is important in accurately capturing a Reynolds number increment, some indications from WMLES that grid convergence is achievable on these configurations
- Huge scatter in both CLmax and CL at Alpha demonstrates that we really haven't converged on a consistent set of practices, even at a moderate 5-6m Reynolds that has been the focus for several workshops
- Despite the scatter and lack of grid convergence, Reynolds trends from simulations look to agree fairly well with experimental data – though more confidence in experimental data may cause this argument to fall apart

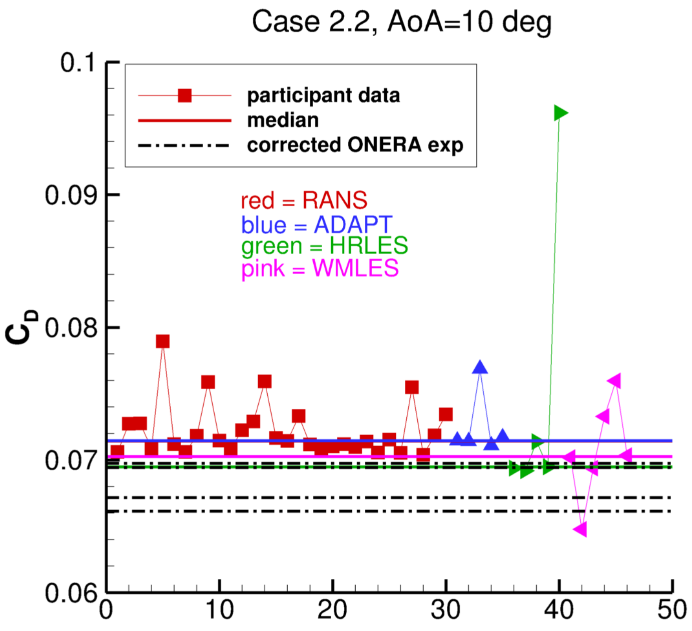
Acknowledgements

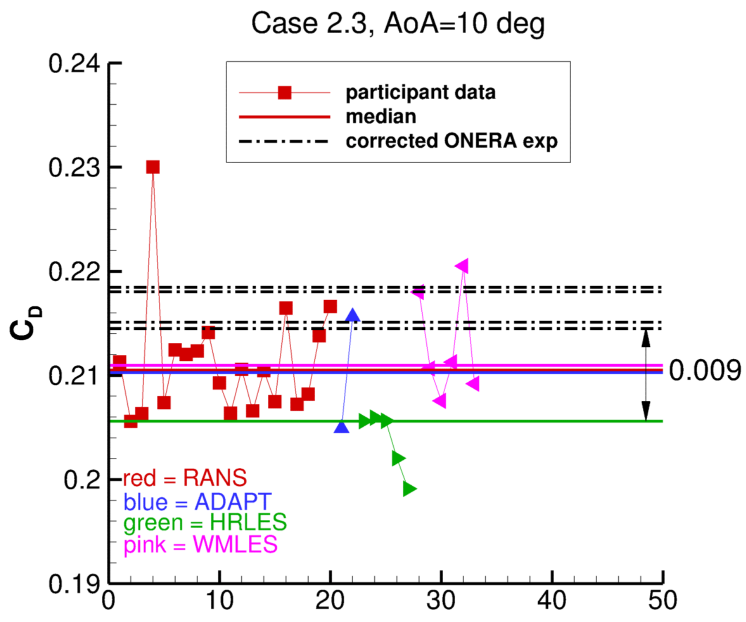
- Thank you to the **AIAA** and the **Applied Aerodynamics TC** for their sponsorship and support.
- Thank you to the **volunteers** and organizations, and especially the **TFG leaders** and **mesh generators**, who have contributed many hours of labor effort and/or resources over the last two years.
- Thanks to the **Oak Ridge National Laboratory** for providing computing time on Summit in 2023 to support many of the computations supporting HLPW-5.

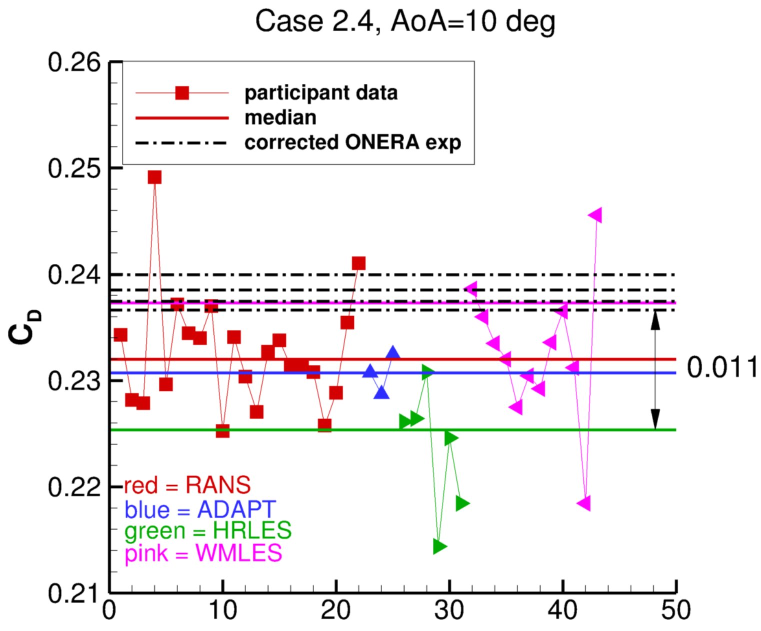
BACKUP

Test Case 2 – Key Question 1

1	Does the consistency in integrated forces/moments from CFD simulations improve when modeling geometrically simpler HL configurations?







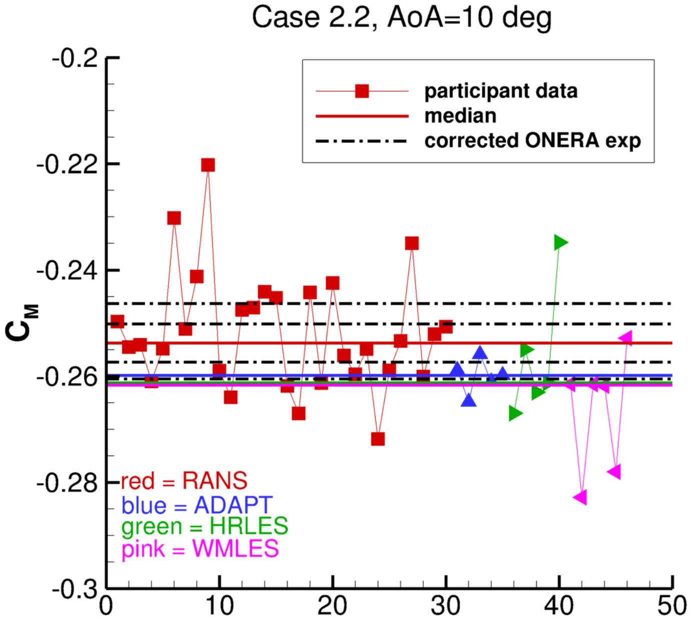
RANS scatter = 0.007 (ADAPT=0.008)
HRLES scatter = 0.041
WMLES scatter = 0.012

RANS scatter = 0.019
HRLES scatter = 0.011
WMLES scatter = 0.018

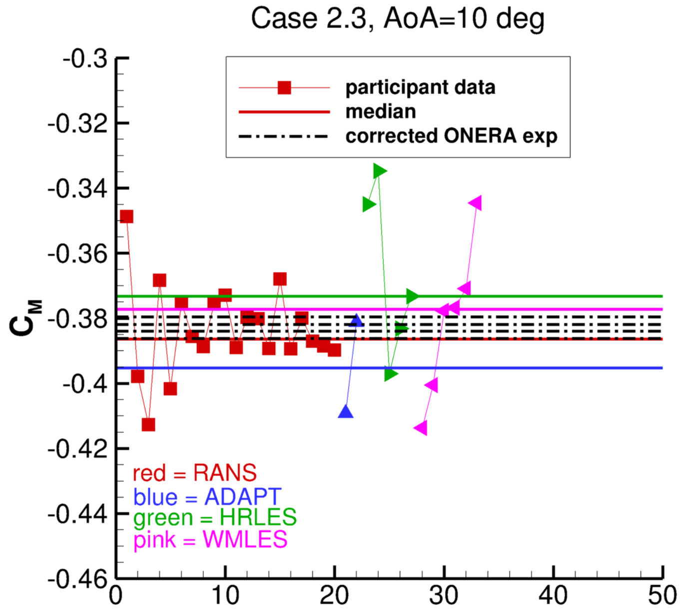
RANS scatter = 0.018
HRLES scatter = 0.020
WMLES scatter = 0.022

Test Case 2 – Key Question 1

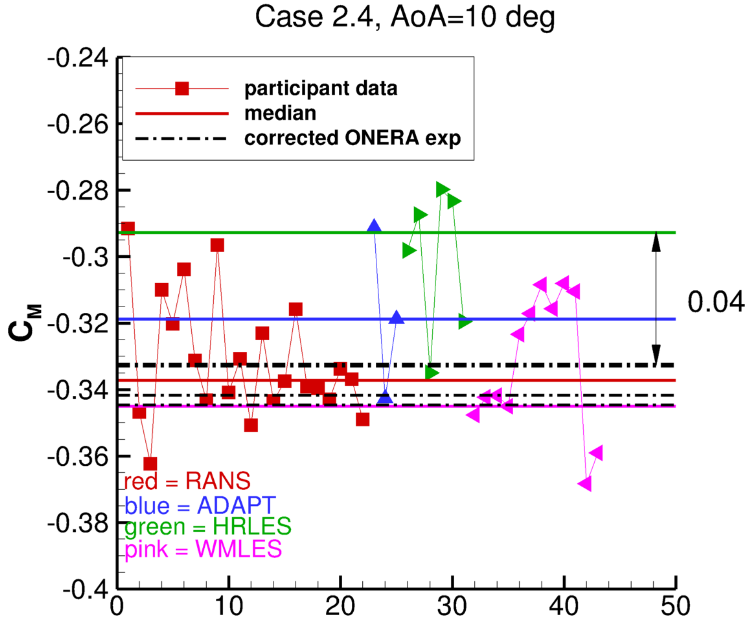
1	Does the consistency in integrated forces/moments from CFD simulations improve when modeling geometrically simpler HL configurations?



RANS scatter = 0.038 (ADAPT=0.010)
HRLES scatter = 0.043
WMLES scatter = 0.040



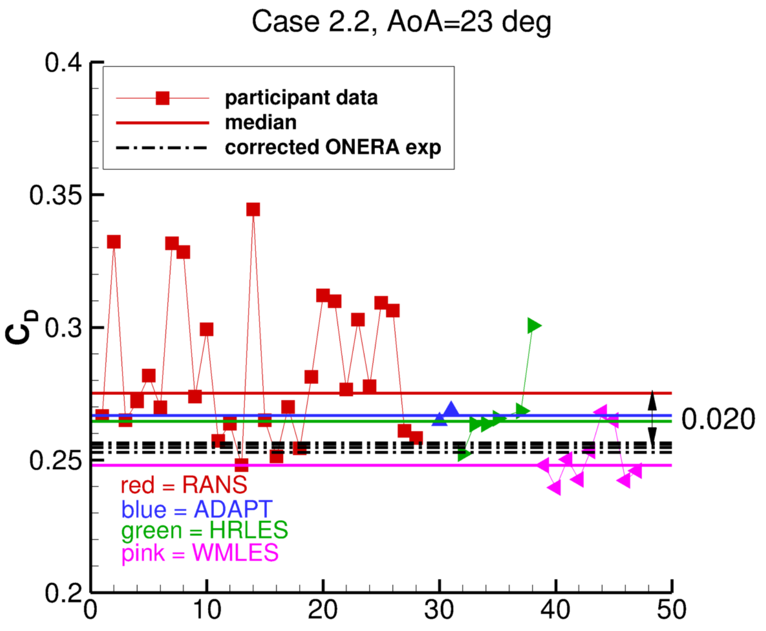
RANS scatter = 0.047
HRLES scatter = 0.084
WMLES scatter = 0.077

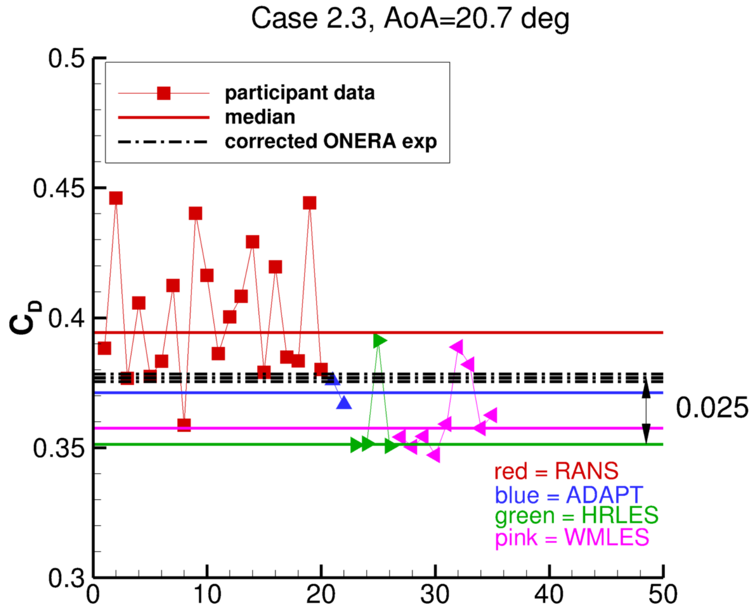


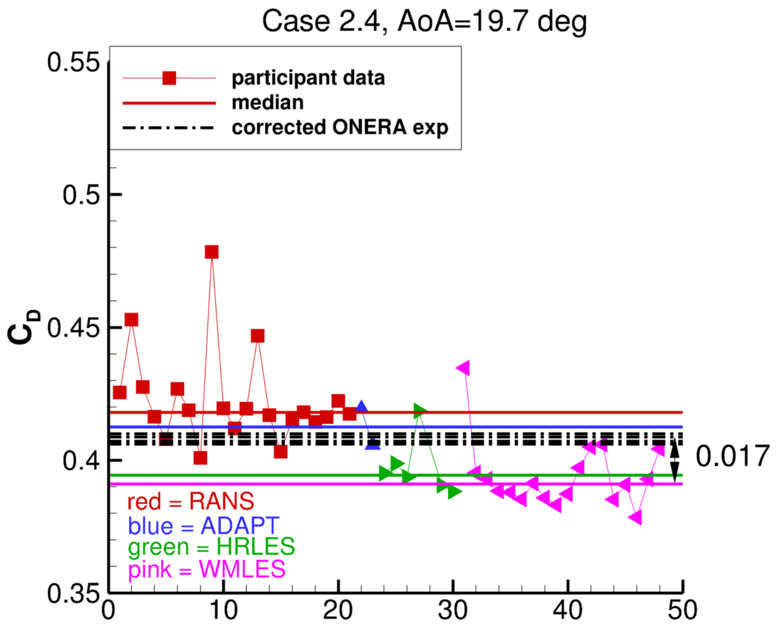
RANS scatter = 0.065
HRLES scatter = 0.075
WMLES scatter = 0.069

Test Case 2 – Key Question 1

1	Does the consistency in integrated forces/moments from CFD simulations improve when modeling geometrically simpler HL configurations?







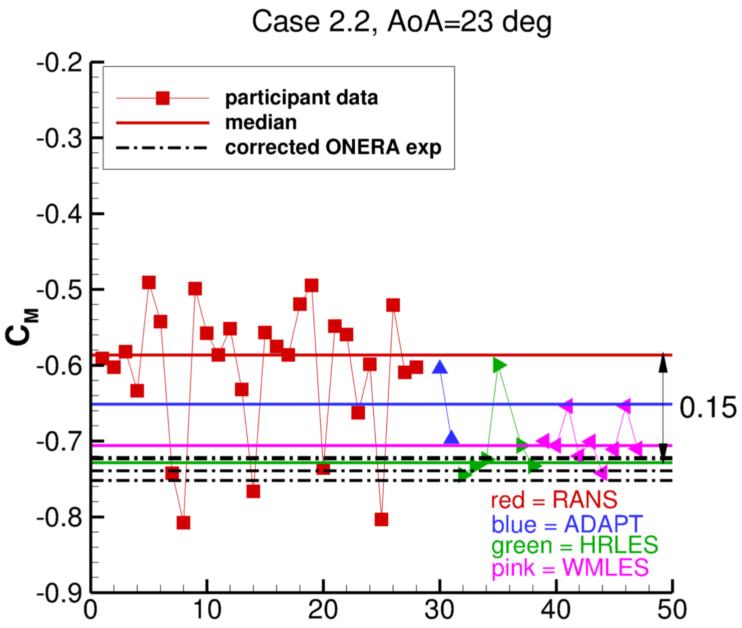
RANS scatter = 0.100
HRLES scatter = 0.054
WMLES scatter = 0.033

RANS scatter = 0.088
HRLES scatter = 0.069
WMLES scatter = 0.049

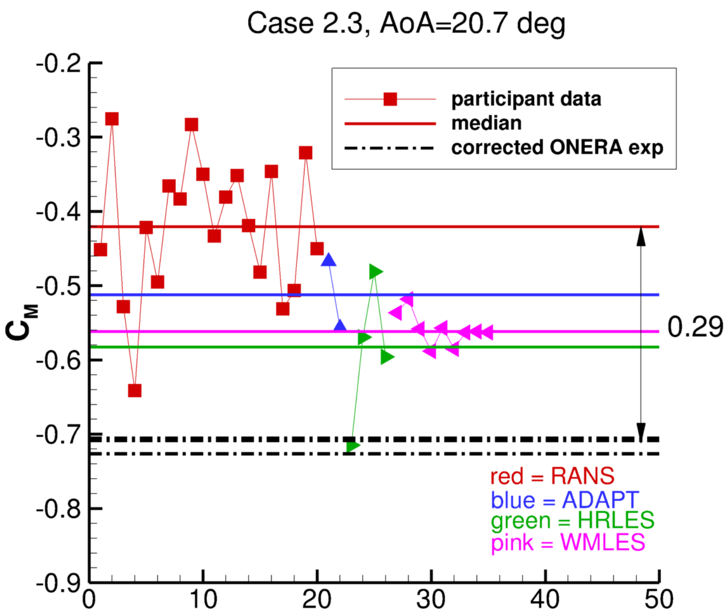
RANS scatter = 0.061
HRLES scatter = 0.036
WMLES scatter = 0.044

Test Case 2 – Key Question 1

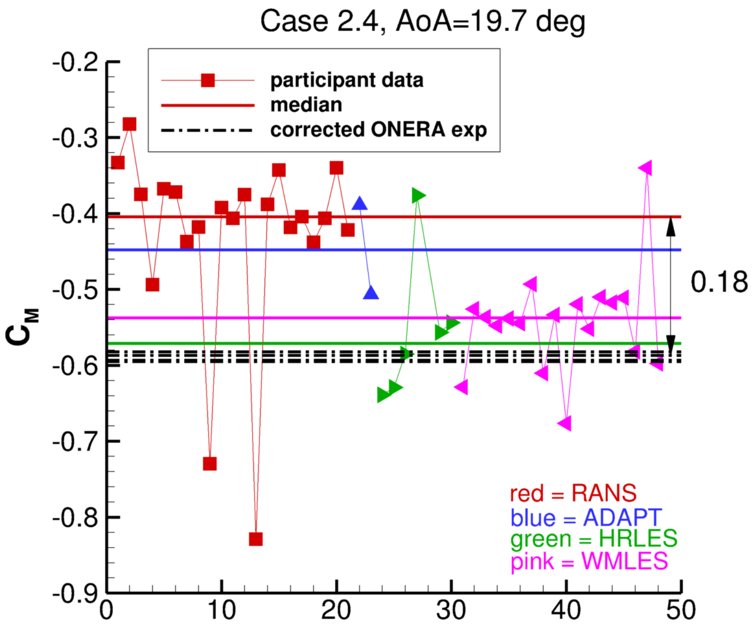
1	Does the consistency in integrated forces/moments from CFD simulations improve when modeling geometrically simpler HL configurations?



RANS scatter = 0.31
HRLES scatter = 0.19
WMLES scatter = 0.10



RANS scatter = 0.31
HRLES scatter = 0.29
WMLES scatter = 0.07



RANS scatter = 0.43
HRLES scatter = 0.31
WMLES scatter = 0.23