Overview and Workshop Summary

Chris Rumsey ***(NASA Langley Research Center)***
Jeff Slotnick ***(The Boeing Company)***
Carolyn Woeber ***(Cadence Design Systems)***

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The High-Lift Common Research Model (CRM-HL)

Introduction

- High-Lift Prediction Workshop (HLPW) combined with Geometry and Mesh Generation Workshop (GMGW) to form HLPW-4/GMGW-3
  - Held in San Diego, CA, January 2022 (associated with AIAA SciTech)
  - Long-term objectives relate to assessing/improving CFD and mesh generation capability
- Past workshops
  - Published summaries are available (see paper)
  - In the HLPWs, Reynolds-averaged Navier-Stokes (RANS) has been the most common method employed
  - With increasing computational capacity, grids have gotten finer and geometric fidelity has improved
    - But RANS has remained unreliable near $C_{L,max}$ at all workshops
- New approach for current workshop
  - Technology Focus Groups (TFG): people in 6 different areas work together in the 1+ year leading up to the workshop
  - Goal: accelerate progress compared to old workshop approach (individual work)

TFGs

- GEOM: Geometry modeling and preparation for meshing
- RANS: Fixed-grid RANS
- HO: High-order discretization (mostly RANS)
- ADAPT: Mesh adaptation for RANS
- HRLES: Hybrid RANS/Large-eddy simulation (LES)
- WMLESLB: Wall-modeled LES (WMLES) and Lattice-Boltzmann (LB)

GEOM had different test cases from all the others (not described in this paper)
The other 5 TFGs have companion summary papers at this conference

Note that the WMLESLB TFG participants were:

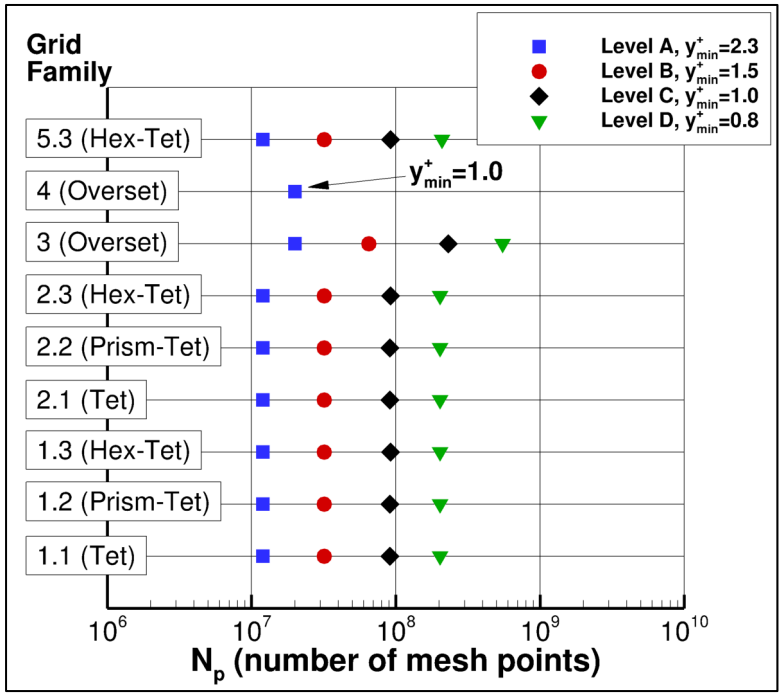
- Mostly WMLES
- One WMLES with HO discretization
- One LB
- One Euler with adaptive meshing

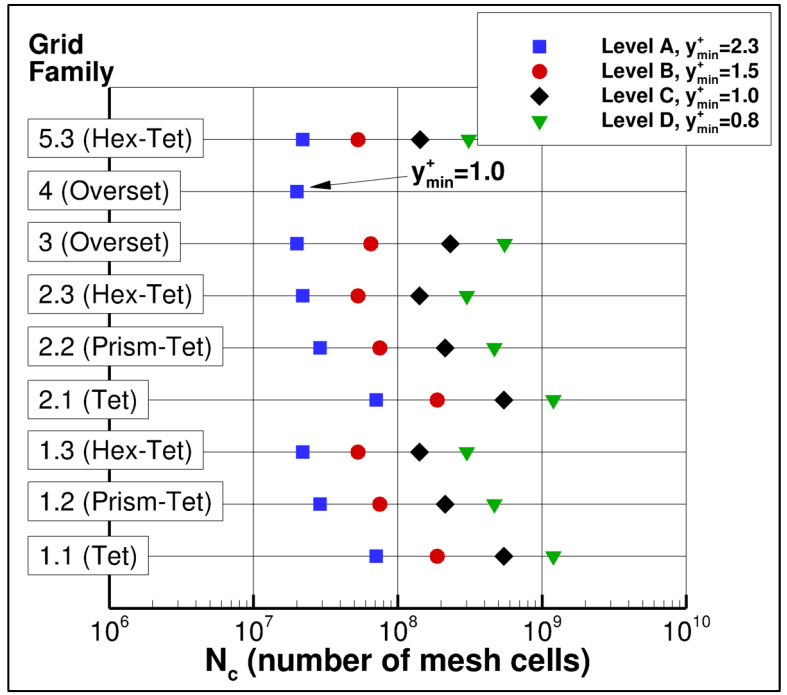
Test Cases and CFD Meshes

- Test cases
  - 1a – Flap deflection study at AoA=7.05 deg.
  - 1b – Mesh convergence study on nominal flap angle at AoA=7.05 deg.
  - 2a – $C_{L,max}$ study in free air
  - 2b – $C_{L,max}$ study with wind tunnel walls
  - 3 – Turbulence model verification study

- Nearly 170 different CRM-HL meshes were created and shared!
  - Some by committee (designed for RANS only), some by participants (designed for RANS, HO, HRLES, or WMLES)

Committee meshes:

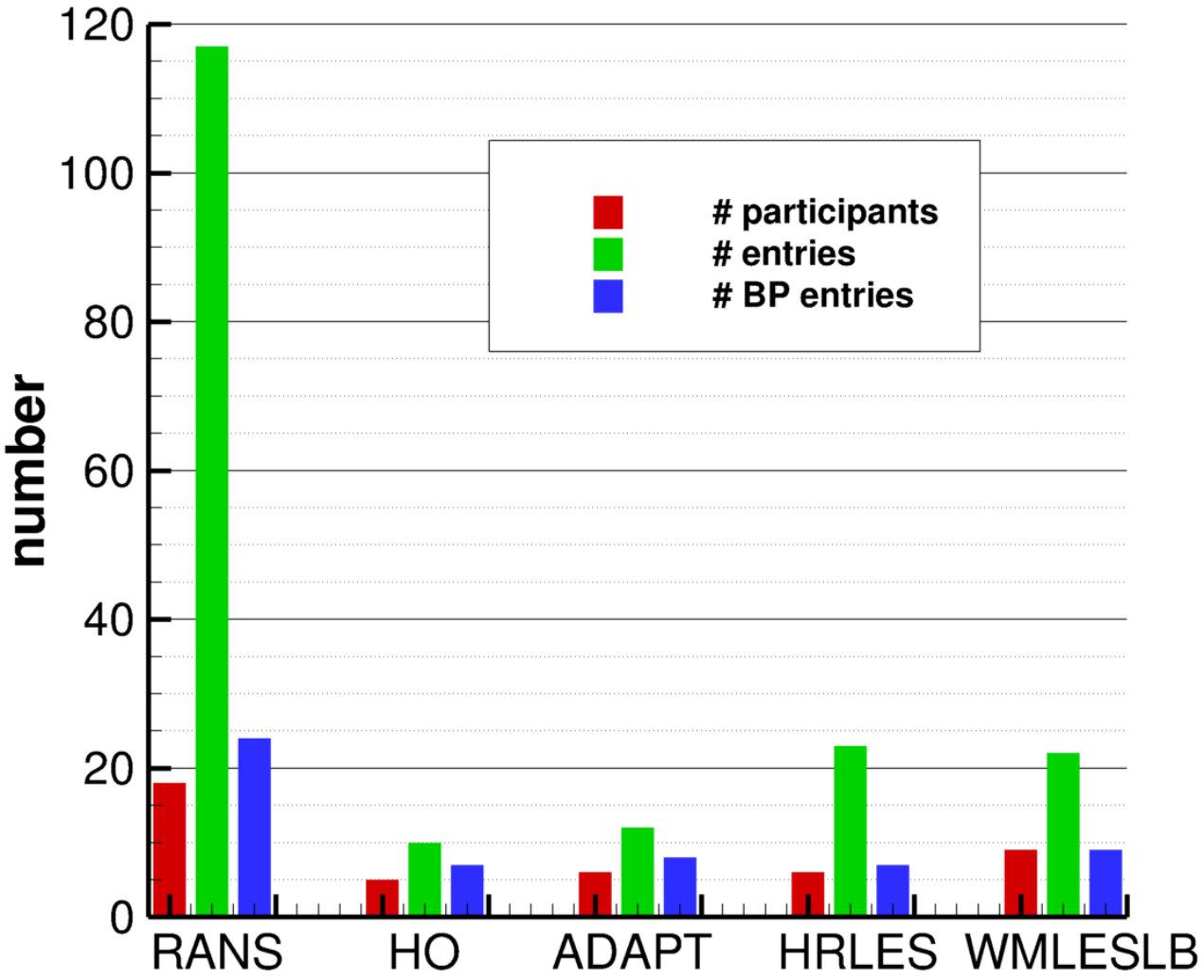




Summary of Entries

BP = best practice

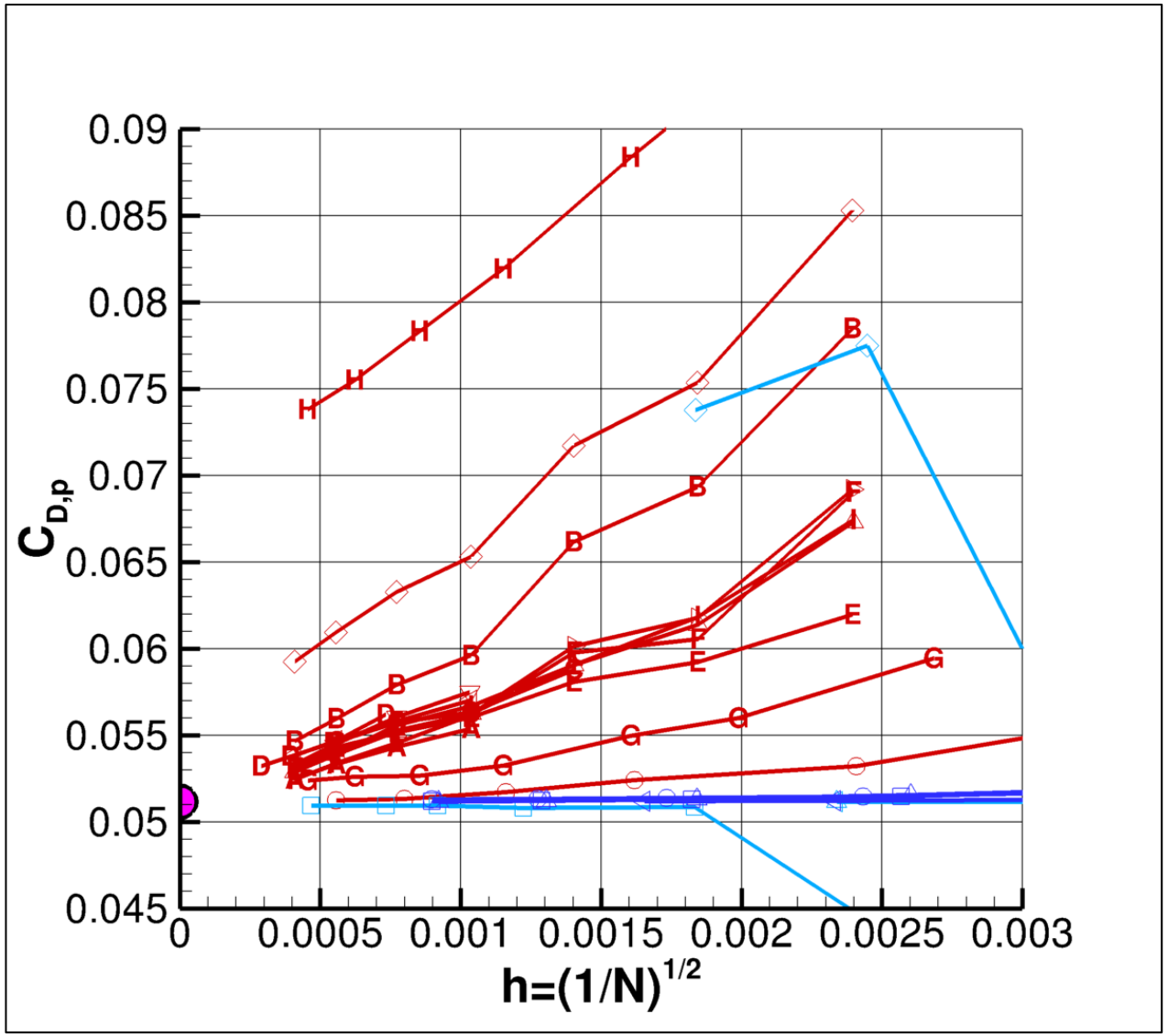
44 participants, 184 sets of submitted data



Mostly we only consider the 55 BP results; other results (which include parametric studies) are either covered in the TFG summary papers, in individual participant papers, or remain to be analyzed

Verification Results

- Verification exercise was a 2D 3-element airfoil (VERIF/2DMEA on NASA's TMR website*) using RANS with the Spalart-Allmaras (SA or SA-neg) turbulence model
- For HLPW-4, most (not all) participants who submitted Case 3 results ended up "passing" (with some minor deviations/issues)
- See paper for more details
- This is large improvement over HLPW-3, when only 30% passed

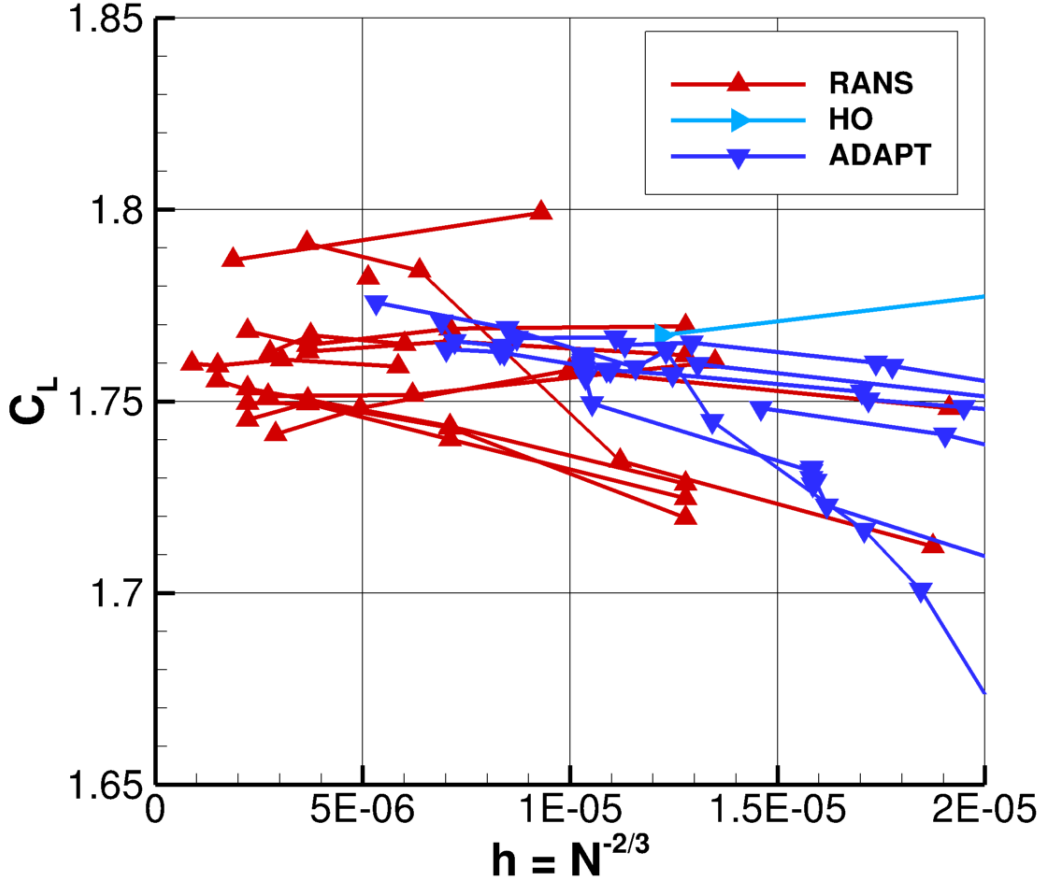


* https://turbmodels.larc.nasa.gov

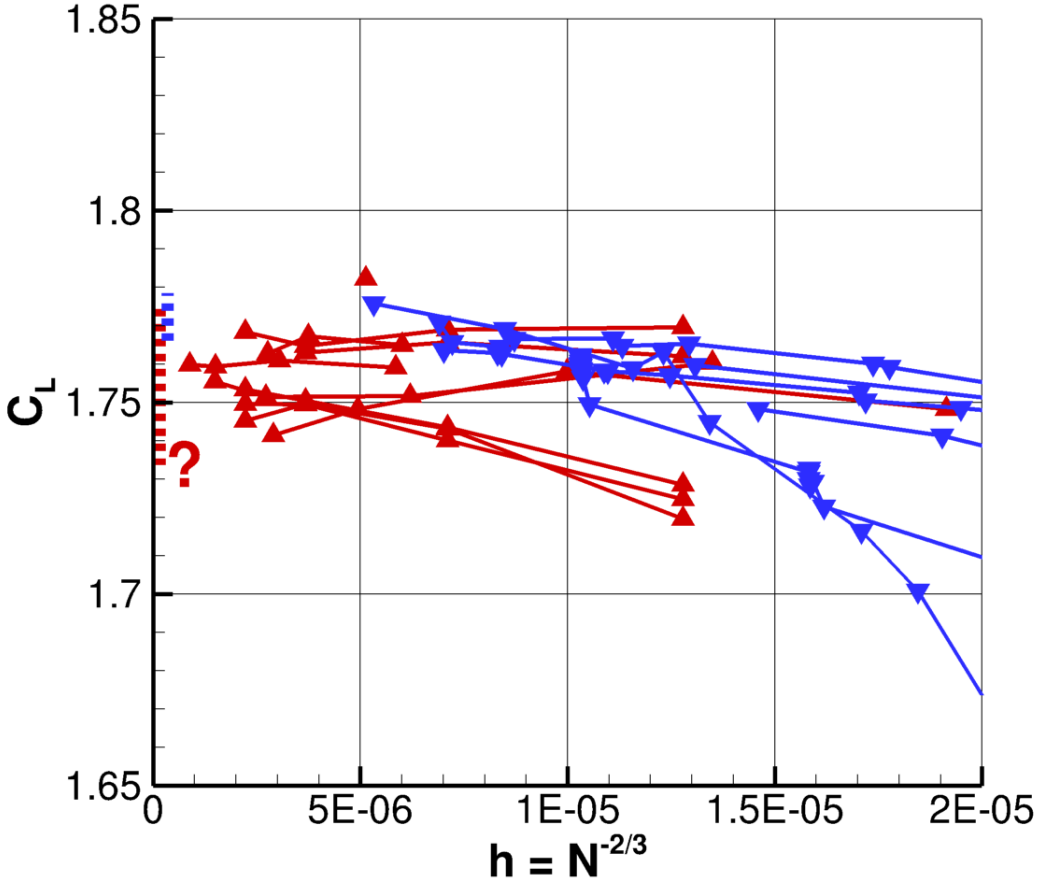
CRM-HL Mesh Convergence Study

AoA=7.05 deg.
Nominal flap config.

All Case 1b BP results using SA



Case 1b BP results using "verified" SA

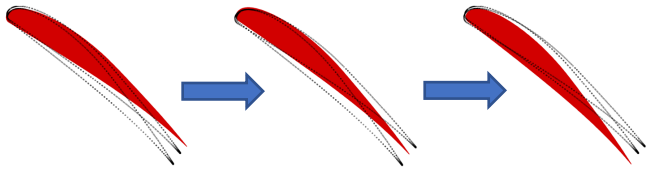


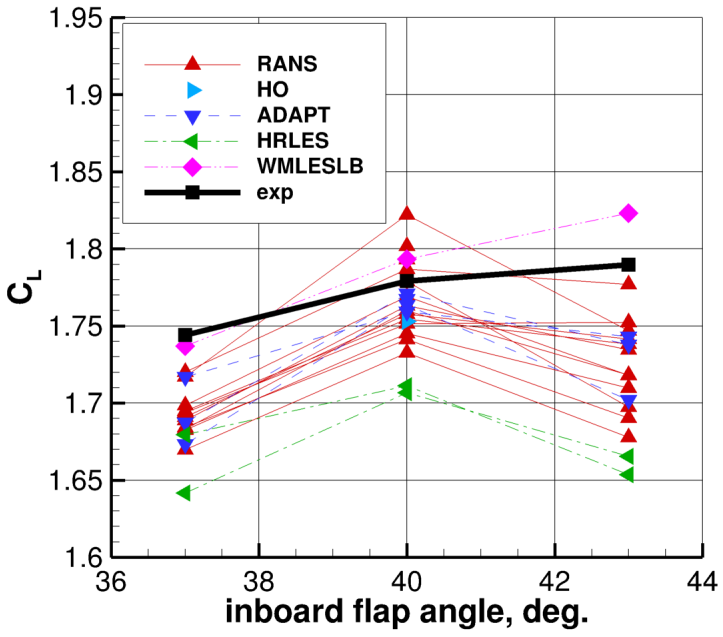
- Considerable spread among verified SA results (right) indicates discretization/iterative convergence errors are still dominant, even on finest workshop meshes
- ADAPT results appear to be better mesh-converged, using less unknowns

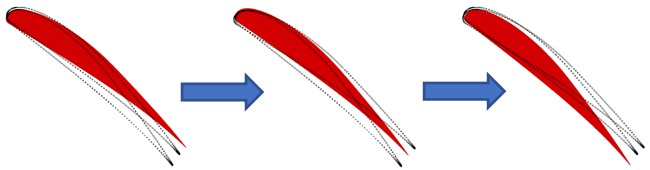
CRM-HL Flap Deflection Study

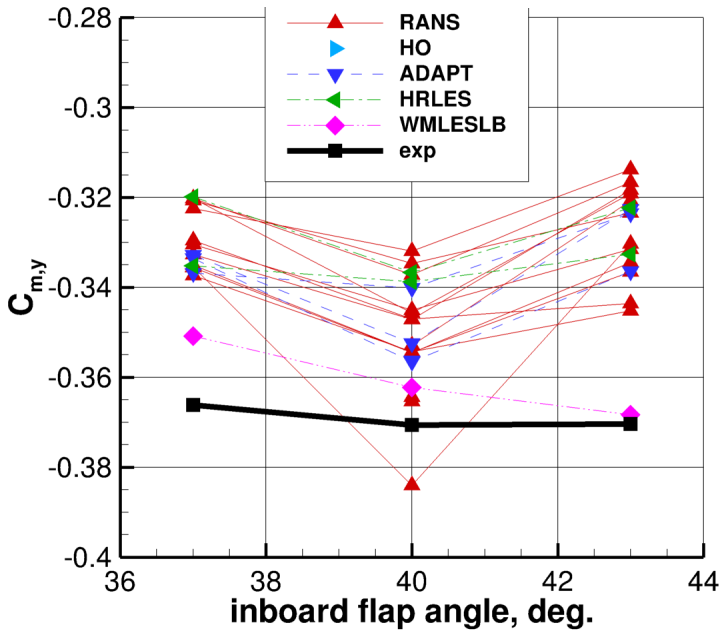
AoA=7.05 deg.

- Most CFD failed to predict flap angle effect on forces and moment, especially between 40 and 43 deg.
- One or two RANS results look reasonable for C_L, but probably fortuitous, because moment trends are still wrong
- Scale-resolving LB result indicates less outboard flap separation than the "best" RANS result
- Currently a LB result appears reasonable, but two HRLES results do not
- More experience with scale-resolving simulations still needed for this case





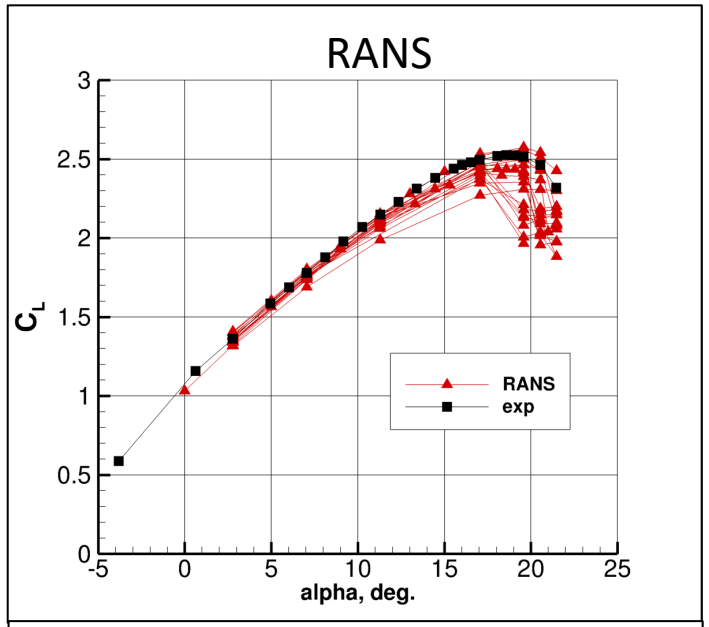


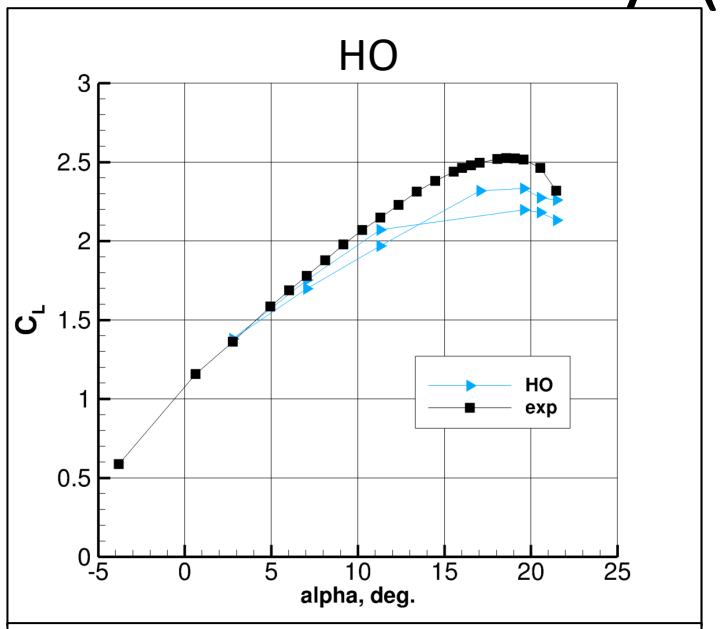


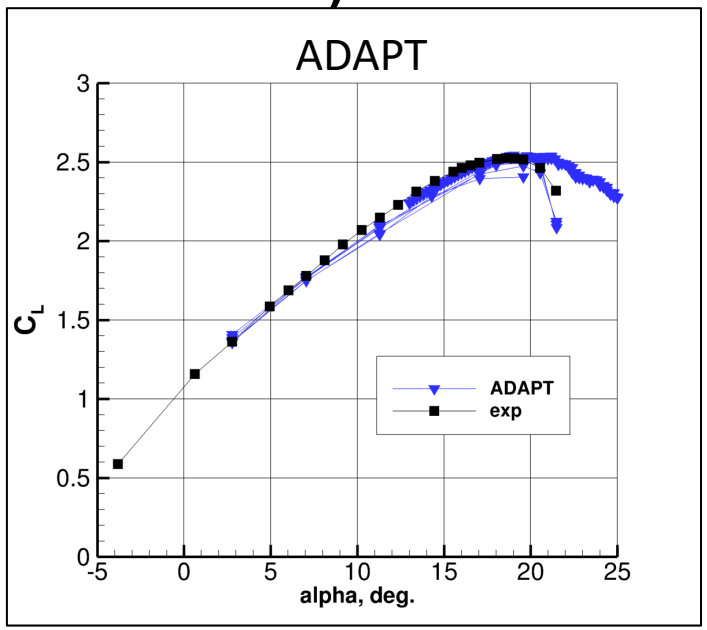
CRM-HL Maximum Lift Study (free air)

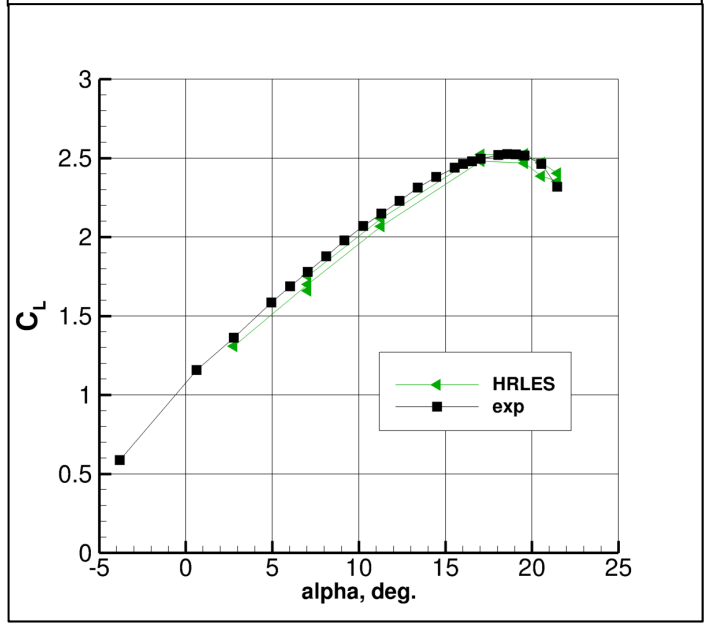
RANS based

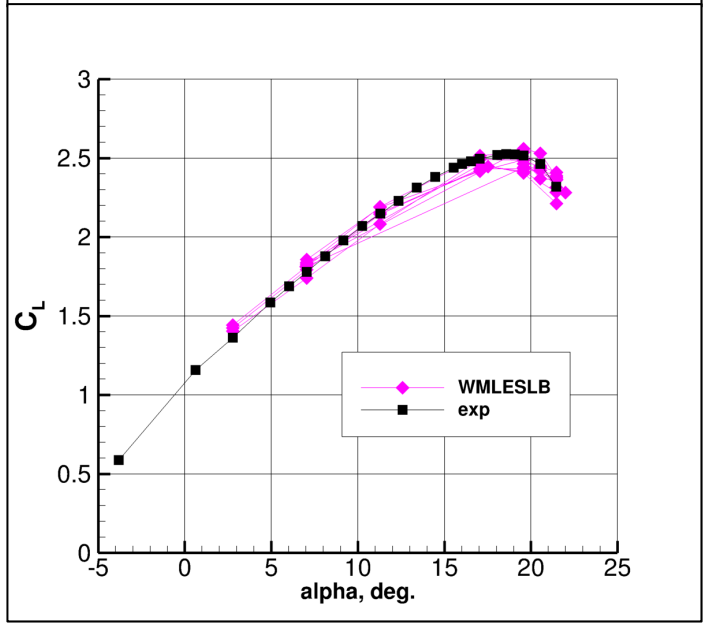
Scale Resol-ving







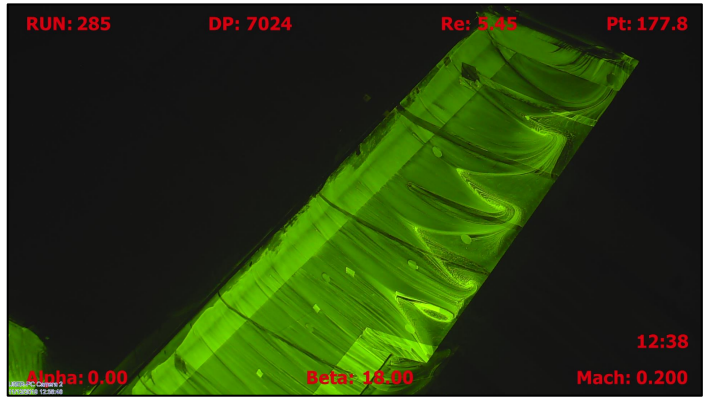




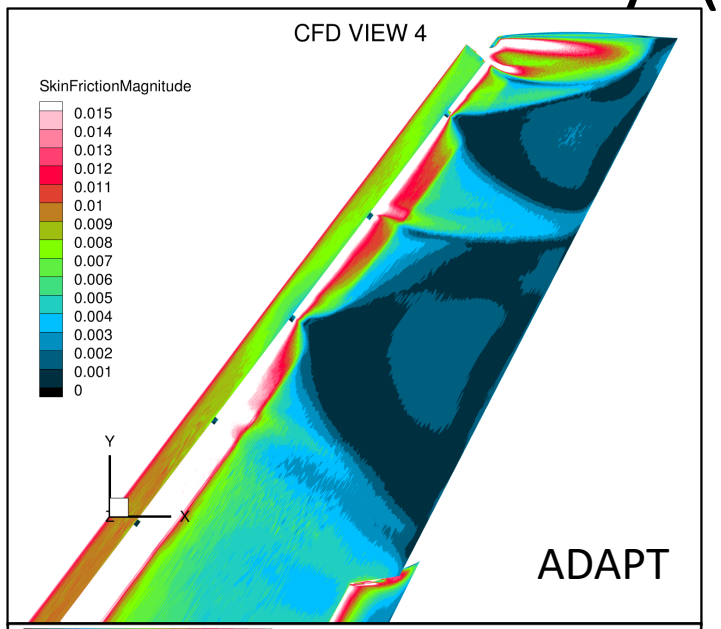
ADAPT, HRLES, and WMLESLB all seem to do reasonably well near $C_{L,max}$ (a few of the RANS also look OK)

Note: we did not delve deeply into results that included wind tunnel walls; there were only 5 BP entries (RANS, HRLES, and WMLESLB) – all performed well (see paper)

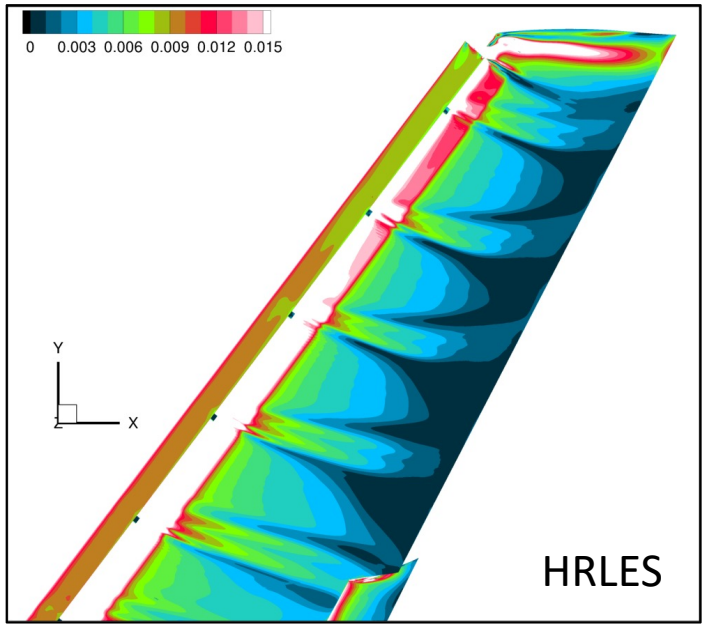
CRM-HL Maximum Lift Study (free air), cont'd



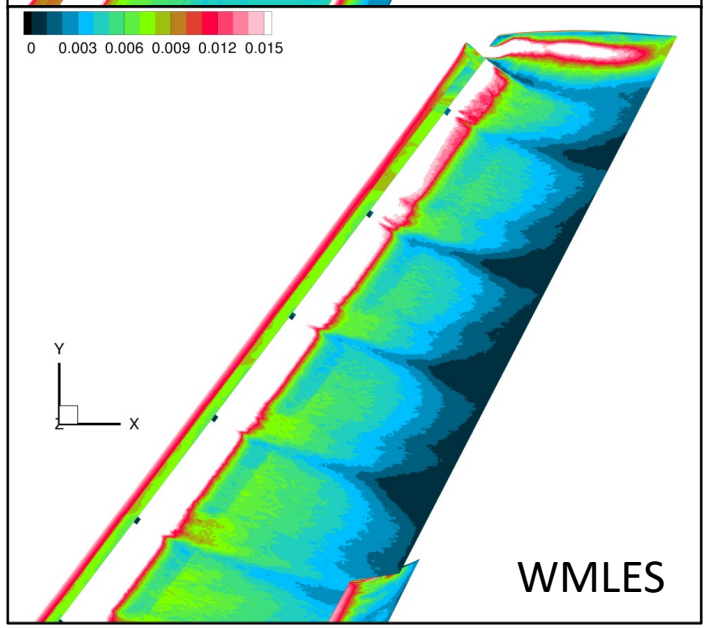
Oil Flow



ADAPT



HRLES

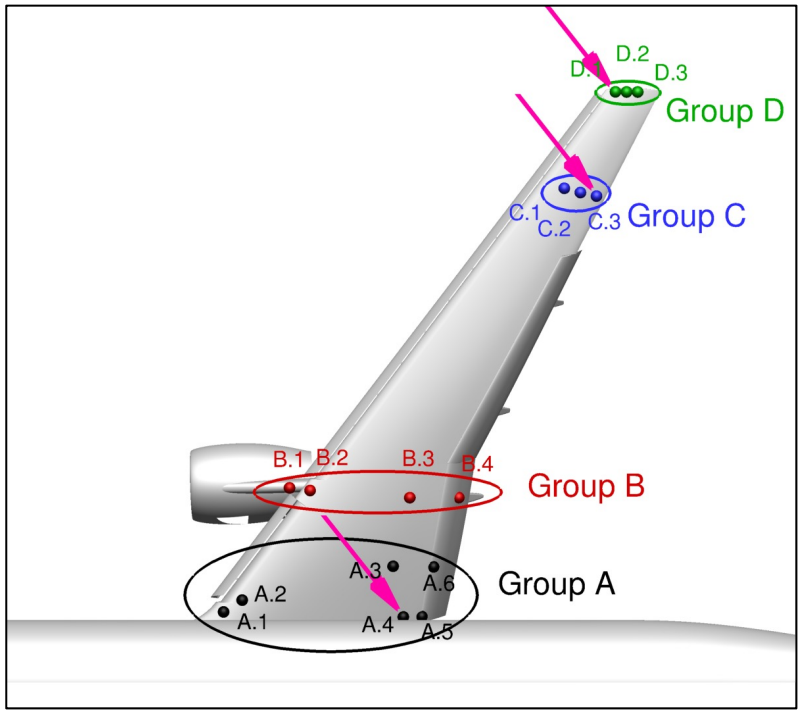


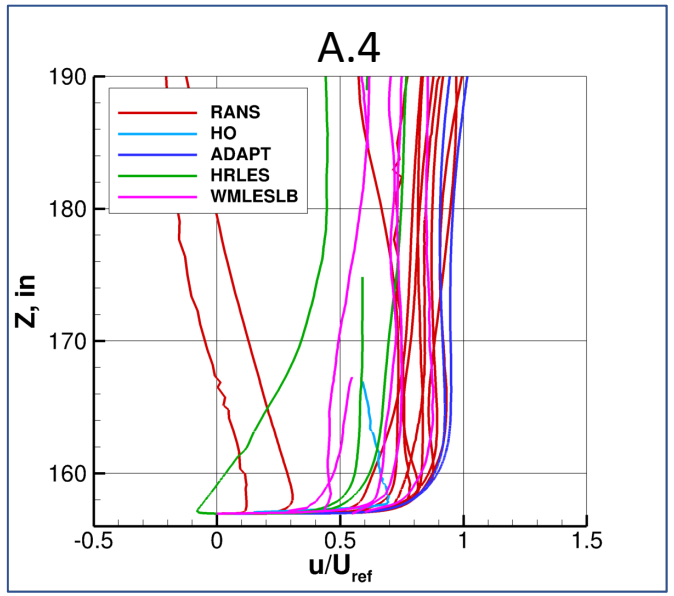
WMLES

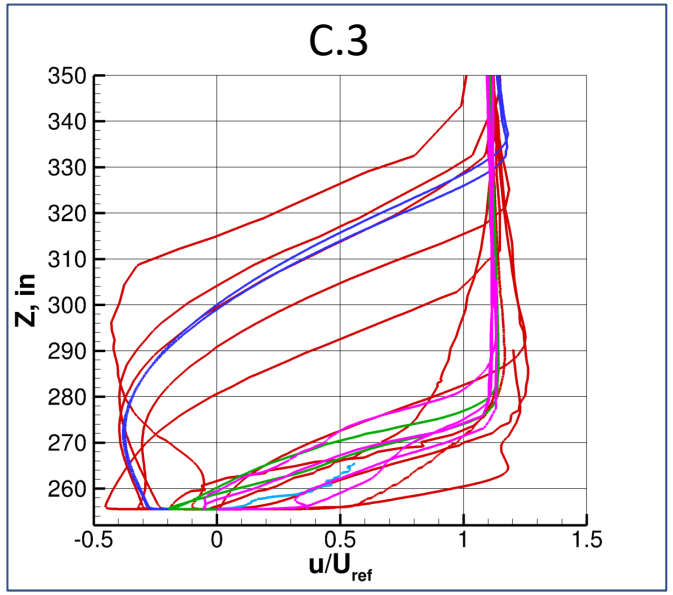
ADAPT (as an example of a typical RANS SA result) produces excessively large outboard separation

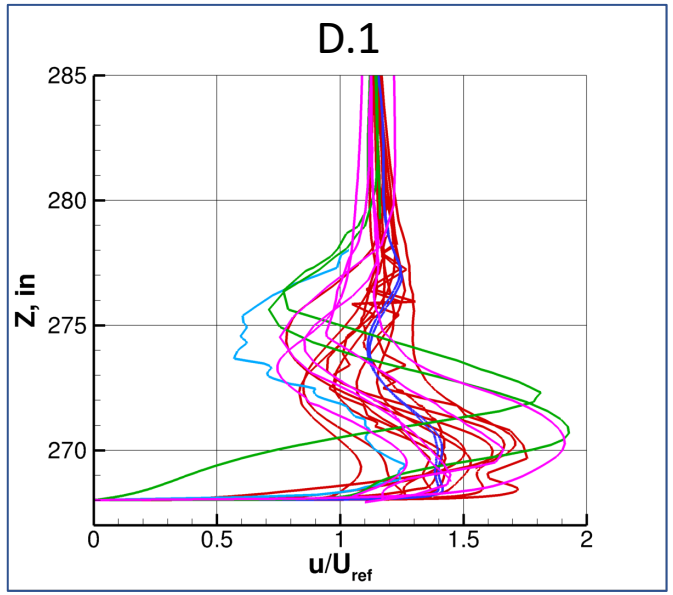
Scale-resolving methods yield better agreement with measured oil flow patterns

CRM-HL Velocity Profiles, AoA=19.57 deg.









Near $C_{L,max}$, all methods show notable inconsistencies from each other, even within a given TFG

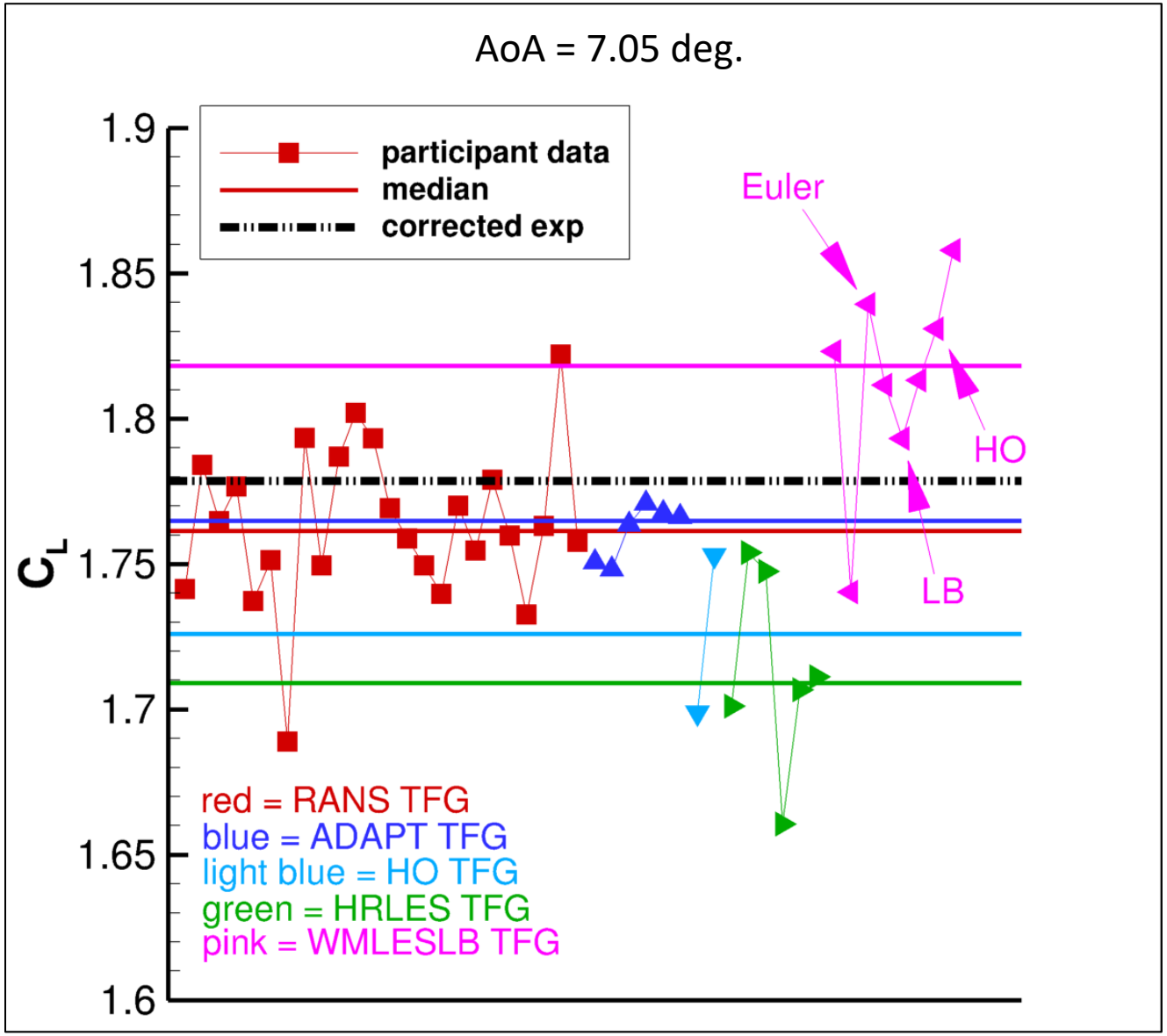
(experimental measurements would be extremely helpful)

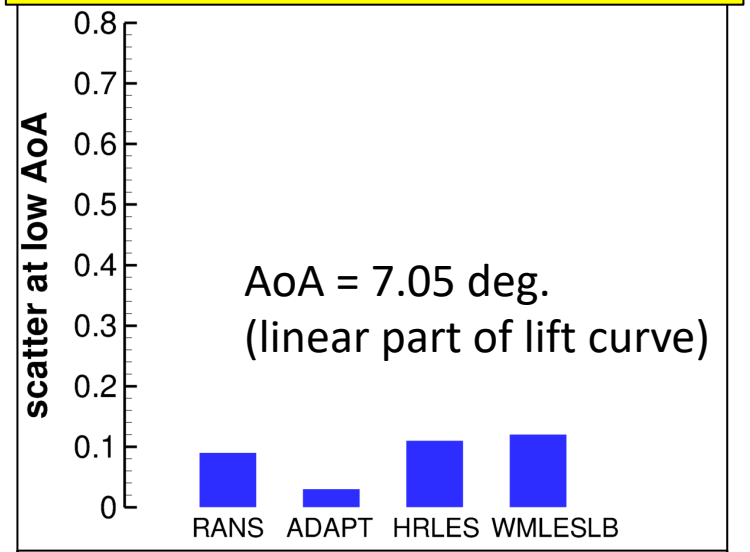
CRM-HL Statistical Analysis

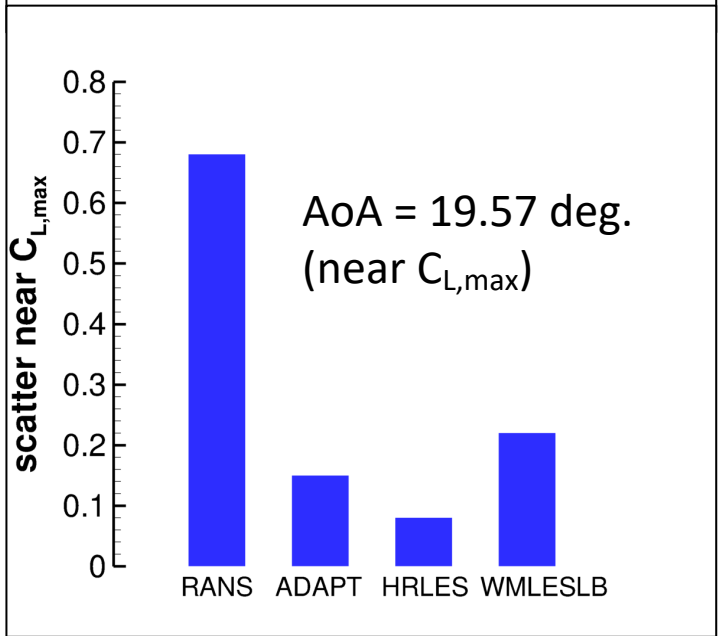
Scatter = $2K\hat{\sigma}$

$\hat{\sigma}$ = standard deviation

$K = \sqrt{3}$ (confidence interval coverage factor)



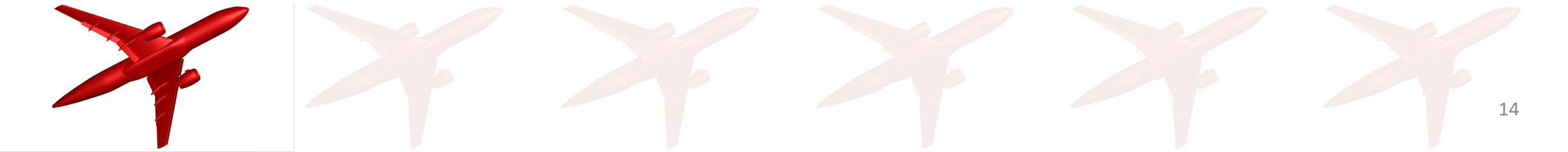




Workshop Key Questions and Status

- *KQ#1: What CFD solution methodology(ies) currently provides the best/most-consistent approach to predicting (a) increments due to flap deflection, and (b) maximum lift?*

  - (a) RANS-based methods unsuccessful; scale-resolving methods unclear (more studies needed)
  - (b) Scale-resolving methods better at getting right answer for right reasons; outboard separation physics captured more accurately
  - However, consistency is still lacking; additional best-practice guidelines needed



Workshop Key Questions and Status, cont'd

- *KQ#2: What are important lessons learned in high-lift CFD analysis explored in HLPW-4?*

  - Adequate mesh convergence for fixed-grid RANS not achieved
  - Mesh adaptation along with better iterative convergence helped in some cases to overcome the "multiple solution" issue seen with RANS
  - Typical time-averaged HRLES 10-15x more costly than RANS
  - Typical time-averaged WMLES 5-10x more costly than RANS
  - Other details in paper

Workshop Key Questions and Status, cont'd

- *KQ#3: What geometry and meshing best practices are appropriate for high-lift CFD analysis for RANS, Wall Modeled LES, and Hybrid RANS/LES simulations?*

  - Topological geometry modifications aided mesh generation workflows (guidelines needed for consistency)
  - Best practices for fixed grid meshing between RANS, HO*, HRLES*, and WMLES* vary significantly, and also differ at different parts of the lift curve
  - Other details in paper

* Still being explored/developed

Workshop Key Questions and Status, cont'd

- *KQ#4: What roadblocks in geometry preparation and mesh generation for CFD prevent analysts from creating geometry/meshes suitable for high-lift aerodynamics simulations in a turn-key, rapid manner?*

  - Lack of understanding how geometry preparation choices in complex regions impact meshing and flow solutions
  - Lack of best practices for geometry build-up and modification in complex regions*
  - Lack of sufficient computational resources for routinely running CFD on very large meshes (billions of unknowns)
  - Other details in paper

* Needed to reduce manual intervention in meshing processes

Workshop Key Questions and Status, cont'd

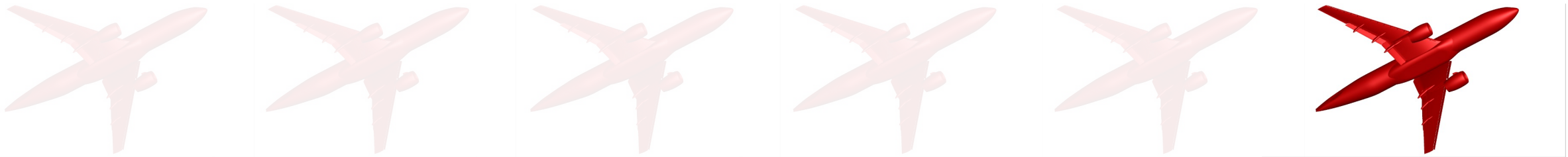
- *KQ#5: What was the impact/effectiveness of the existing test data collected for the CRM-HL configuration in understanding high-lift flow physics? If not effective, what is needed?*

  - Combination of forces/moment and surface Cps with surface flow visualization (e.g., oil flow) was helpful
  - More measurements are needed:
    - Better characterization of wind tunnel inflow and wall boundary layer (BL) development
    - Off-body BL and wake profiles

Workshop Key Questions and Status, cont'd

- *KQ#6: What are the significant remaining technical areas that require additional focus in future workshops?*

  - Meshing
    - Guidelines on fidelity of mesh needed near $C_{L,max}$ for different methodologies
    - Continue to develop HO capabilities
    - Mesh adaptation for scale-resolving methods
  - Verification, reproducibility, consistency
    - Verification method(s) for scale-resolving simulations still needed
    - Additional turbulence model studies
  - Other details in paper



Conclusions

- HLPW-4/GMGW-3 introduced TFGs
  - Greater collaboration and interaction prior to the workshop
- Meshing still has a dominant influence on CFD solutions
  - Mesh adaptation appears to be a viable solution to this issue (more codes need it)
- Code and solution verification are crucial
  - Most codes are (finally) agreeing for the SA turbulence model
- RANS fails near $C_{L,max}$ and for prediction of flap angle effects
  - Both involve separated flow
  - When RANS happens to agree with measured forces, it is usually for the wrong reasons (compensating errors involving separation)
- Scale-resolving methods appear promising for predicting $C_{L,max}$
  - However, more consistency still needed
  - At low AoA, these methods were somewhat less accurate than RANS in the workshop
  - More work needed to mature these approaches