HLPW6 Mini-Workshop 1 Scale-Resolving Simulation TFG Test Case 1 (CRM-HLS) Summary

Konrad Goc[1], Eduardo Molina[2], Daniel Heathcote[3]

Adam Clark[1]

1 - The Boeing Company, 2 – Embraer, 3 – Aurora Flight Sciences

AIAA AVIATION 2026, San Diego, 6/11/26

Outline

- Background
- CRM-HLS Results
  - Aggregated Results
  - Individual Participant Highlights
- Summary

Outline

- Background
- CRM-HLS Results
  - Aggregated Results
  - Individual Participant Highlights
- Summary

SRS TFG Leadership Team

- Konrad Goc
  - Boeing
  - Co-Leader with an emphasis on LES methods
- Eduardo Molina
  - Embraer
  - Co-Leader with an emphasis on HRLES methods
- Daniel Heathcote
  - Aurora Flight Sciences
  - Deputy leader
- Adam Clark
  - Boeing
  - Advisor

TFG Schedule (Notional)

- Test Case 1 – CRM-HLS: January to June 2026
  - Compute baseline solutions, limited comprehensive sensitivity studies
  - Looking for willing participants to run **WRLES/DNS**.
  - Mini-Workshop 1: AIAA Aviation 2026 (8-12 June, San Diego, CA)

- Test Case 2 (Tentative) – ONERA LRM 2.3 or 2.4
  - Focus on laminar-to-turbulent transition on slat and flap lift overprediction
  - Mini-Workshop 2: AIAA SciTech 2027 (11-15 January, Orlando, FL)

- Test Case 3 (Tentative) – CRM-HL Take-off Configuration

- HLPW6: AIAA Aviation 2027 (7-11 June, San Diego, CA)

Bi-Weekly Meetings

- Meeting schedule: bi-weekly on Tuesdays 7 am PT/10 am ET
  - **188** people on the mailing list, **25-50** attendees at TFG meetings
  - **22** participant ID’s assigned for SRS TFG
  - **9** data submissions received for Mini-Workshop 1 (as of 6/11/26)

- Meeting Agenda:
  - SRS TFG Leadership Updates (short)
  - Participant Updates (majority of time)
    - Verbal & prepared updates
  - Open Discussion

SRS TFG Key Questions

➢ General Key Questions:

1. Are there meaningful distinctions in the **predictive accuracy** among the various types of scale-resolving methods (e.g. WMLES, DES, LBM)? What are the relative strengths/weaknesses of the methods in predicting aircraft maximum lift and the flow features that drive it (e.g. wing root separation, slat bracket wakes, flap separation)?
2. What is the state of **affordability** of scale resolving methods for high-lift prediction? Are these methods feasible for routine industrial use on modern compute hardware?
3. Are there certain types of **turbulence model** choices/frameworks that are needed to systematically improve the accuracy of high-lift flow predictions?
4. What choices regarding **grid** distribution/topology/density are needed to achieve accurate predictions of high-lift flows? What are the implications for different SRS methods of near-wall grid size (e.g. WMLES/HRLES running at y+ in the log layer)?

SRS TFG Key Questions

- Test Case 1-Specific Key Questions:

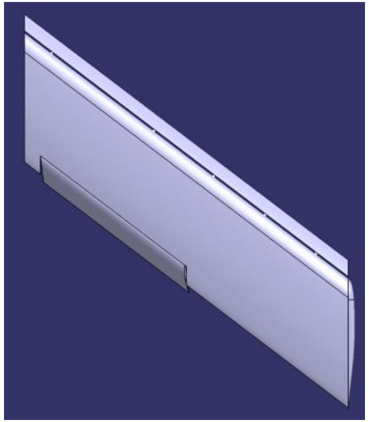
1. Can scale-resolving methods be used to provide a **high-fidelity reference solution** set for the High-Lift CRM Simplified Wing (CRM-HLS) model, including solutions on highly resolved meshes (potentially WRLES/DNS)?
2. How should scale-resolving methods be handling **laminar-to-turbulent transition,** especially on the slat? How can the state of the leading-edge boundary layer predicted by scale-resolving methods be validated to build confidence in the predictions (e.g. using experimental or DNS/WRLES data)?

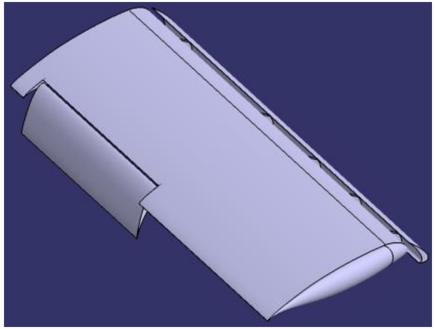
Outline

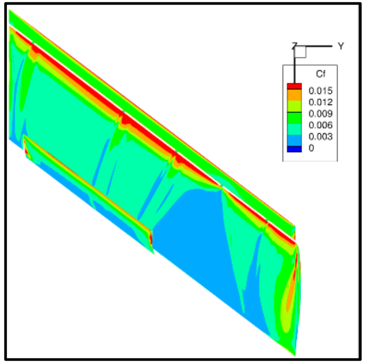
- Background
- CRM-HLS Results
  - Aggregated Results
  - Individual Participant Highlights
- Summary

Test Case 1: CRM-HLS

- Simplified High-Lift configuration, developed with Boeing/University of Washington Collaboration
- Features finite span wing, full span slat, partial span flap
- No experimental data yet, but maybe mid-workshop
- Free air with Y=0 Symmetry, $Re_c = 3.55e6$
- Built to target **slat bracket wake separation on 2nd from outboard bracket**
- Many geometric variations possible
  - ➢ slat bracket width / depth
  - ➢ removable flap
  - ➢ removable slat
  - ➢ deflection changes, etc.





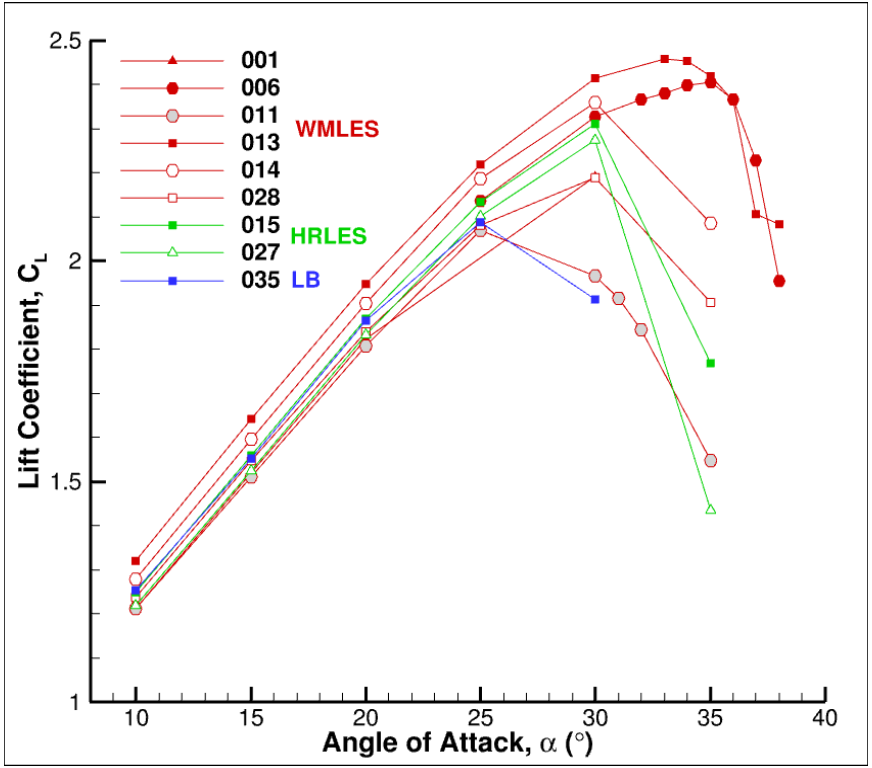


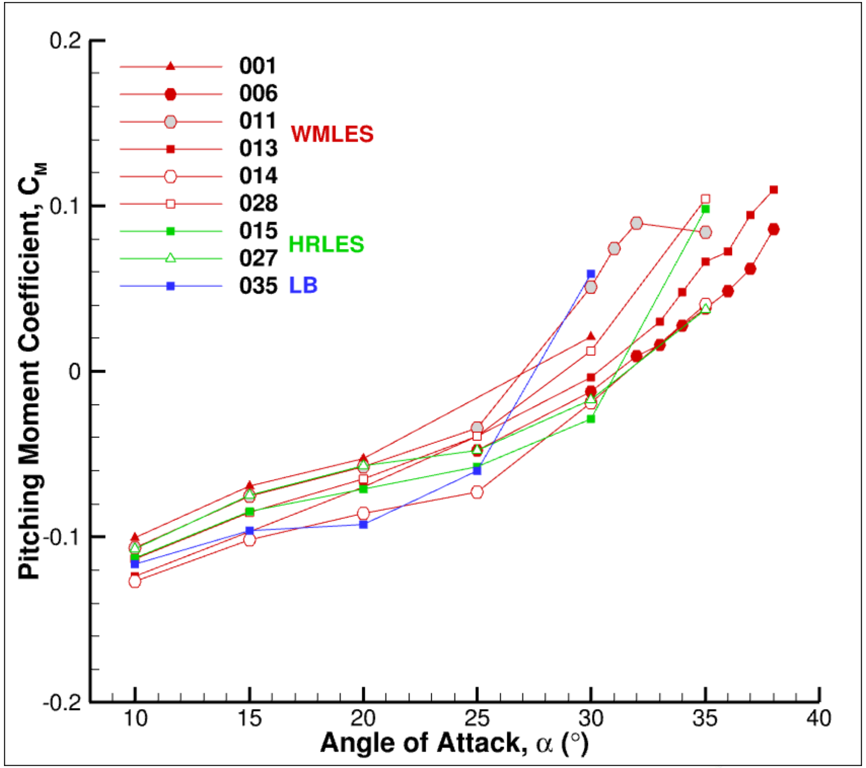
SRS TFG Active Participants

WMLES HRLES LBM

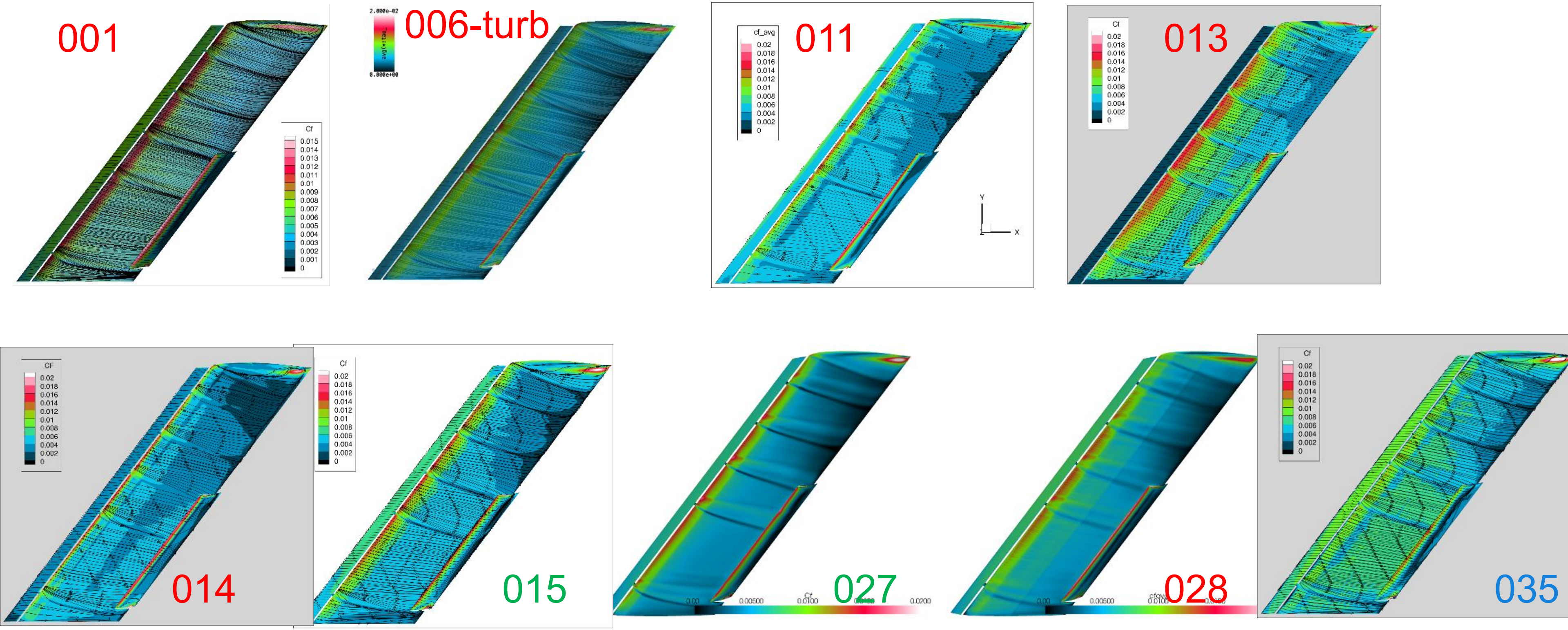
- **001_KU_hpMusic**: Avery Hantla, ZJ Wang
- **006_BoeingCadence_charLES**: Adam Clark, Konrad Goc, Brett Bornhoft, Reza Djeddi
- **011_Caltech_charLES**: Imran Hayat, Yuenong Ling, Adrian Lozano-Duran
- **013_NASA_LAVA, Cartesian**: Mike Barad
- **014_NASA_LAVA, Unstructured**: Emre Sozer
- **015_NASA_LAVA, Curvilinear**: Jeff Housman
- **027_Embraer_Flow360**: Eduardo Molina
- **028_Embraer_ScaLES**: Eduardo Molina
- **035_ONERA_ProLB**: Thomas Renaud

Forces/Moments – All Participants

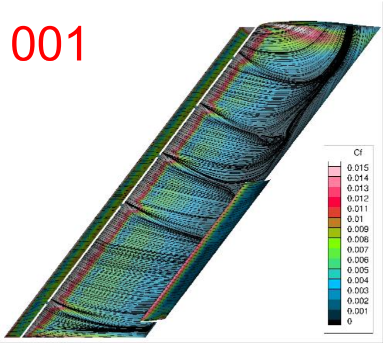


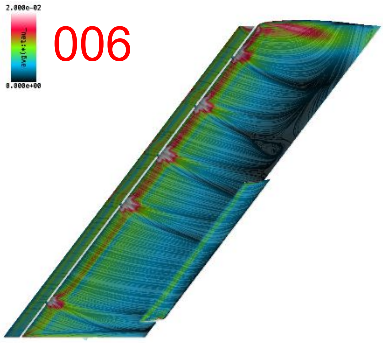


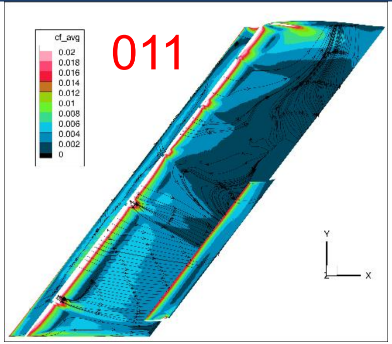
Top Views, $\alpha = 10°$, All Participants

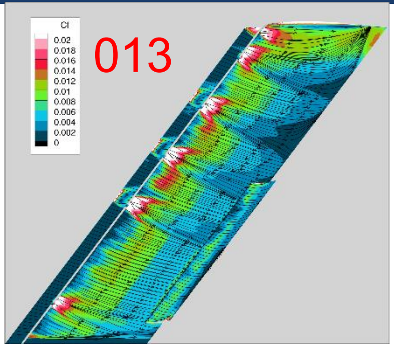


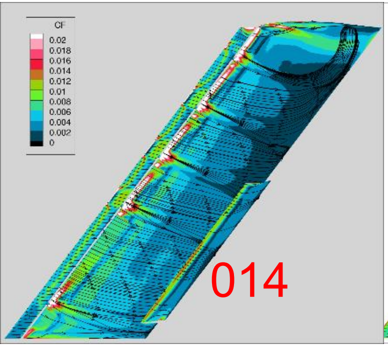
Top Views, $\alpha = 30°$, All Participants

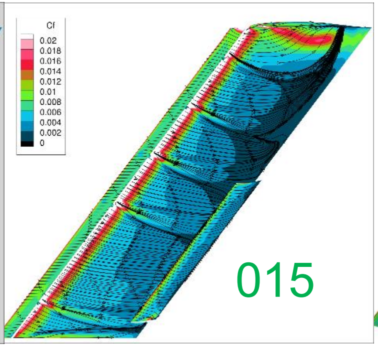


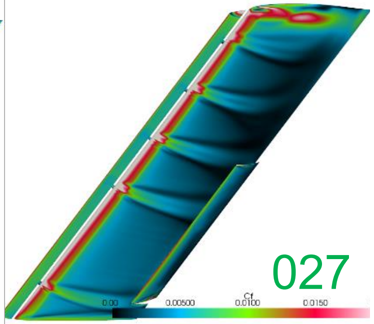


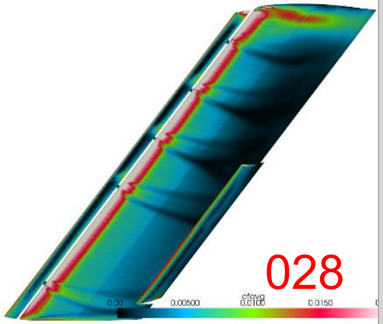


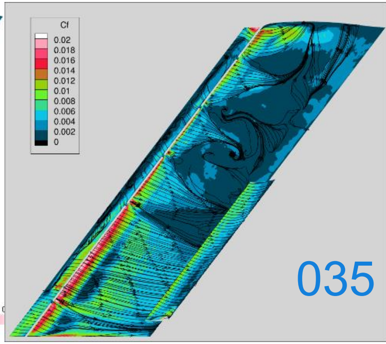








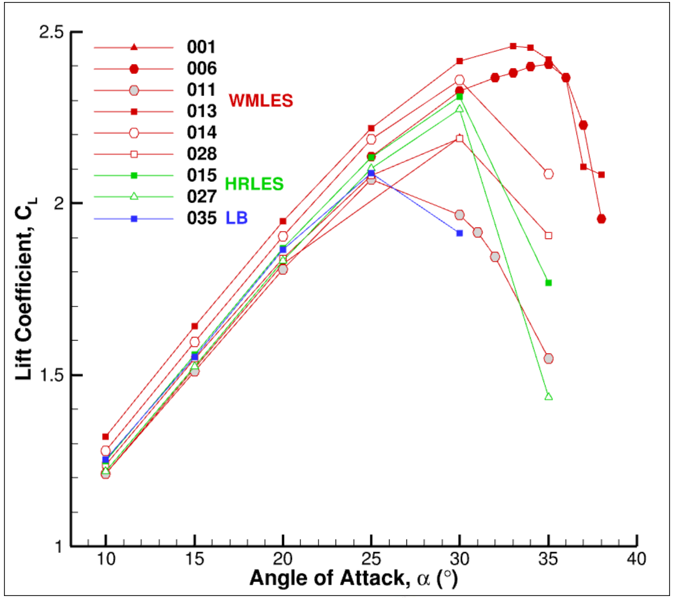




SRS TFG Key Question 1

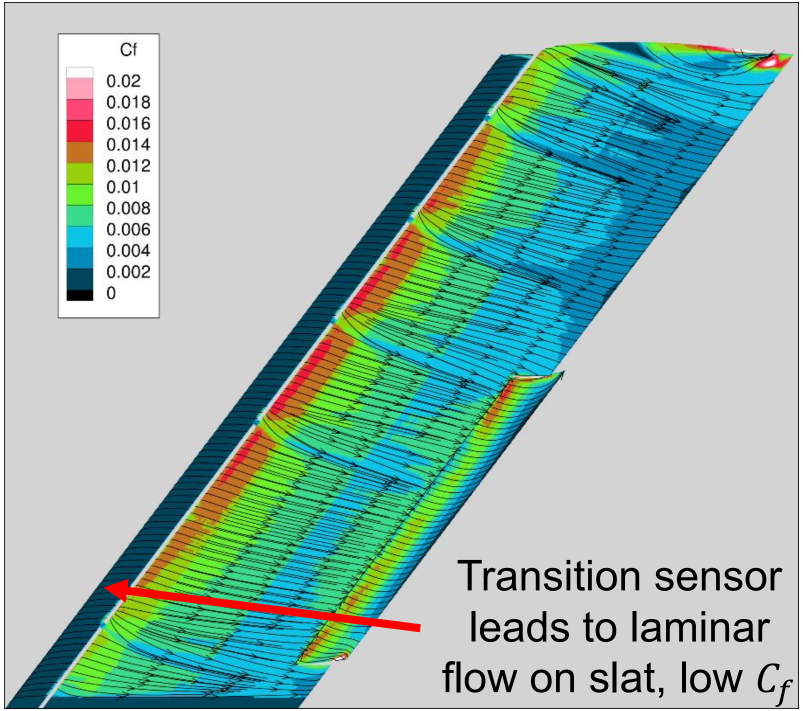
1. Can scale-resolving methods be used to provide a **high-fidelity reference solution** set for the High-Lift CRM Simplified Wing (CRM-HLS) model, including solutions on highly resolved meshes (potentially WRLES/DNS)?

- ➢No participant was able to run a WRLES/DNS ahead of the mini-workshop, owing to massive computational cost
- ➢High amount of scatter (0.1-0.15) in linear range of CL curve
  - ➢**Less scatter in HRLES** at low α, but only 2 submissions
- ➢At 35°, 5 solutions are stalled, 2 solutions are still attached, 2 did not run
- ➢SRS TFG needs an **experimental reference solution**, in addition to further computational solutions

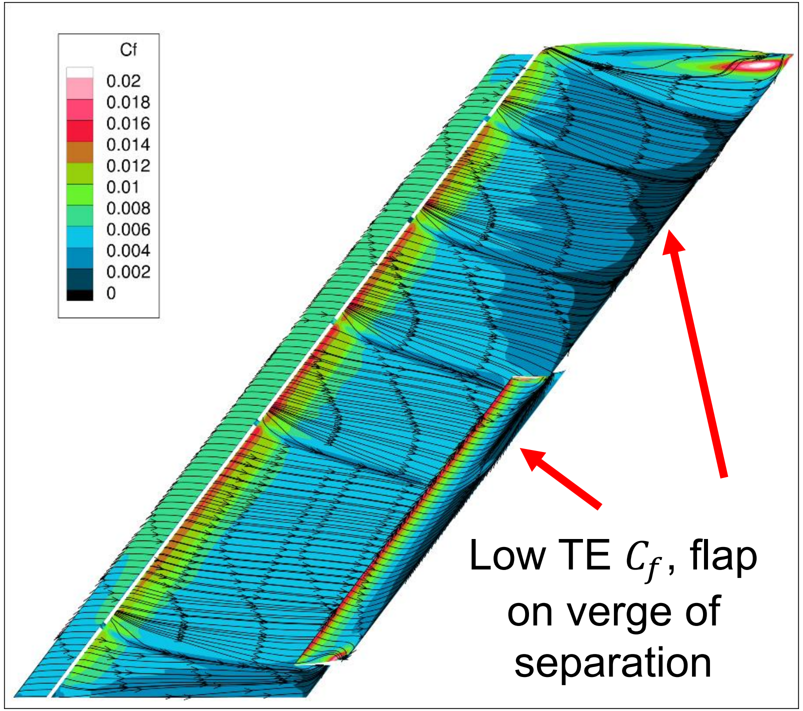


Low α Scatter: Skin Friction, $\alpha = 10°$

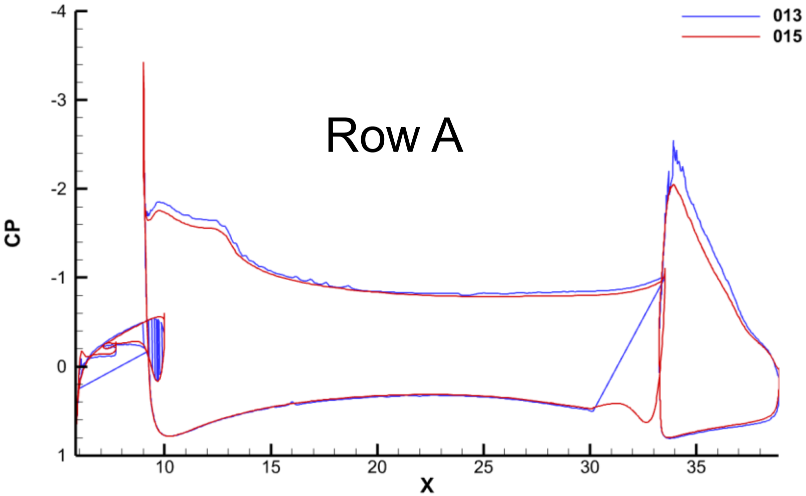
High C_L = 1.32 Solution, 013



Low C_L = 1.25 Solution, 015

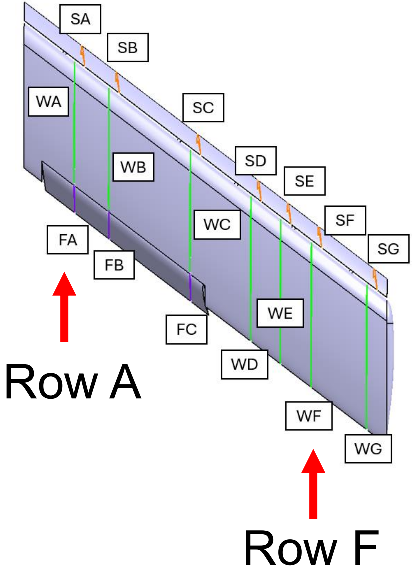


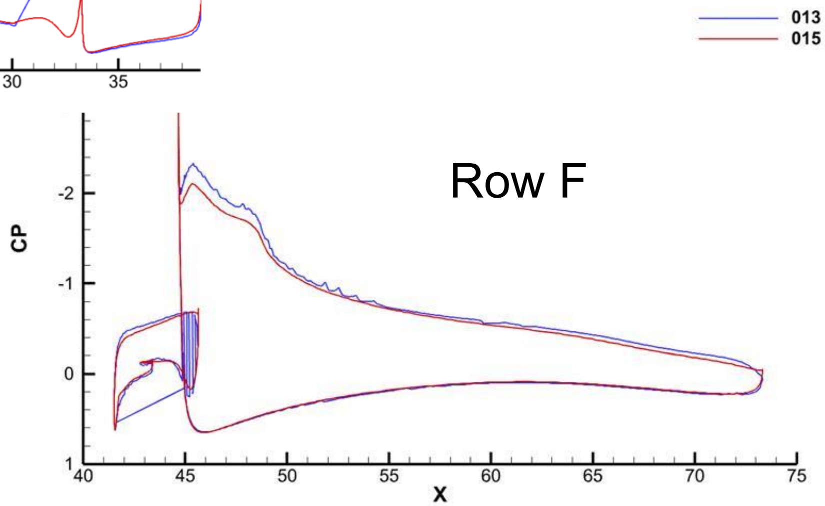
Low α Scatter: Cp plots



High C_L = 1.32 Solution, 013

Low C_L = 1.25 Solution, 015

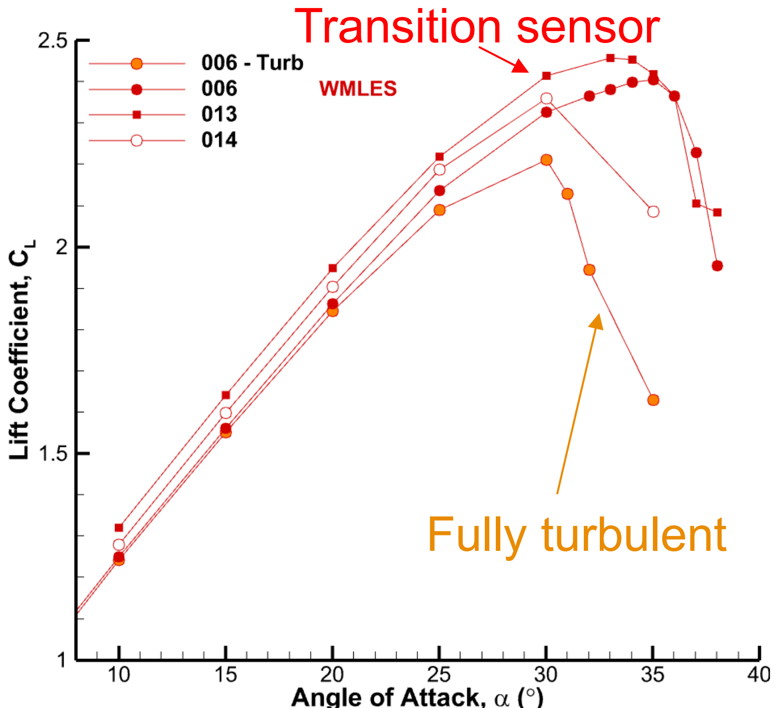




SRS TFG Key Question 2

2. How should scale-resolving methods be handling **laminar-to-turbulent transition**, especially on the slat? How can the state of the leading-edge boundary layer predicted by scale-resolving methods be validated to build confidence in the predictions (e.g. using experimental or DNS/WRLES data)?

- ➢**Significant sensitivity to laminar-to-turbulent transition** treatment on the slat was exposed by TC1
    - ➢Three participants employed a sensor inspired by approach of Bodart & Larsson, *CTR Annu. Res. Briefs* (2012).
- ➢Laminar sensor tends to augment lift near stall and delays stall onset
    - ➢Also augments lift in linear range
- ➢Key area of interest moving forward for SRS TFG:
    - ➢Sensitivity to sensor threshold
    - ➢WRLES transition data



Outline

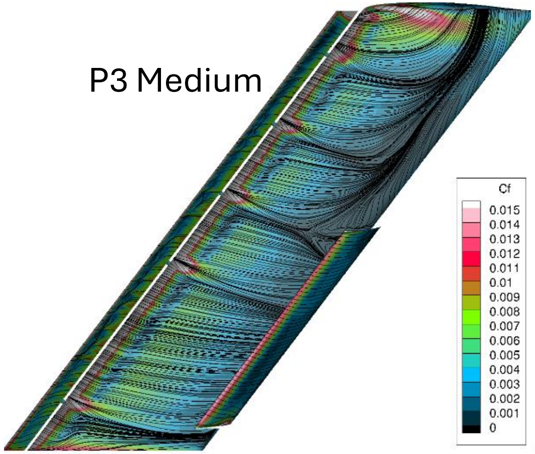
- Background
- CRM-HLS Results
  - Aggregated Results
  - Individual Participant Highlights
- Summary

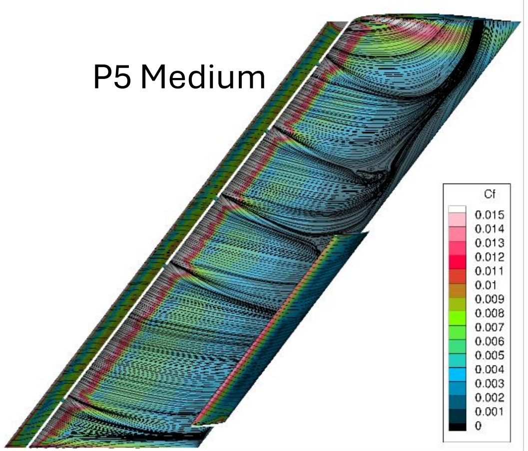
001: U of Kansas: High-Order FR/CPR LES Solver, hpMusic

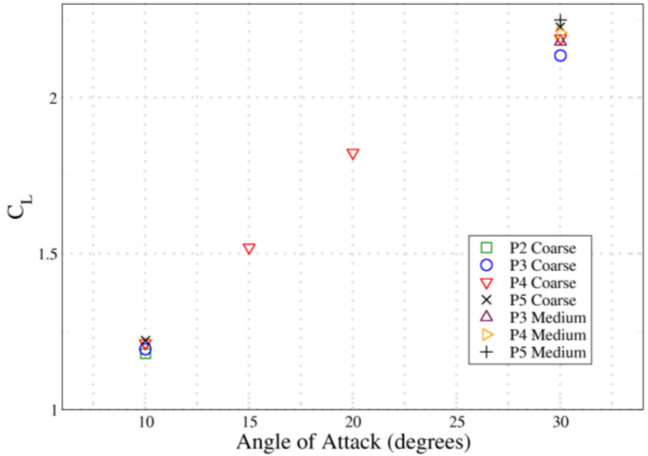
KU

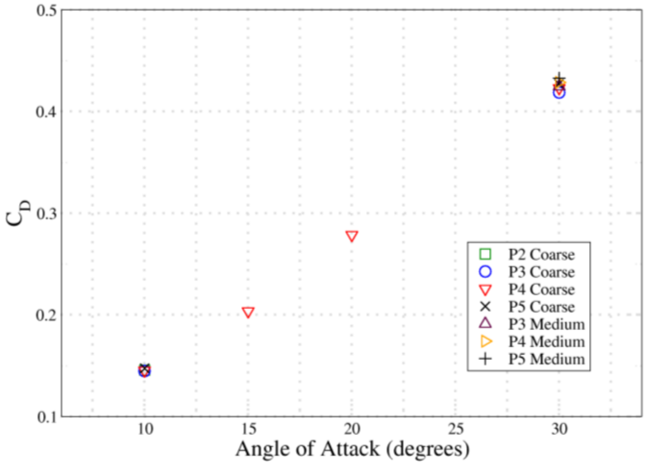
Key features

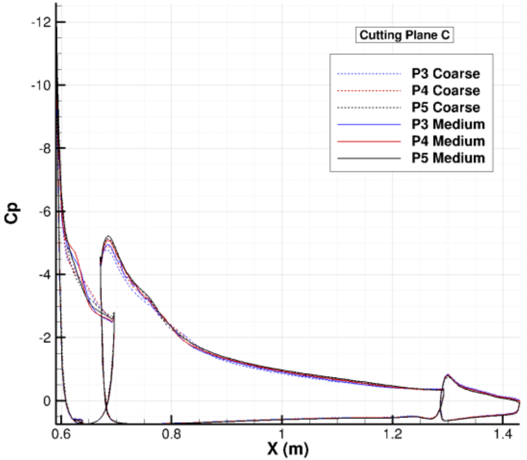
- Mixed meshes in CGNS or Gmsh format
- Explicit and implicit time integration schemes
- High-order accuracy (up to 6th order)
- Overset and sliding meshes for moving grids
- Wall-resolved or wall modeled
- Explicit (Vreman SGS) or implicit LES









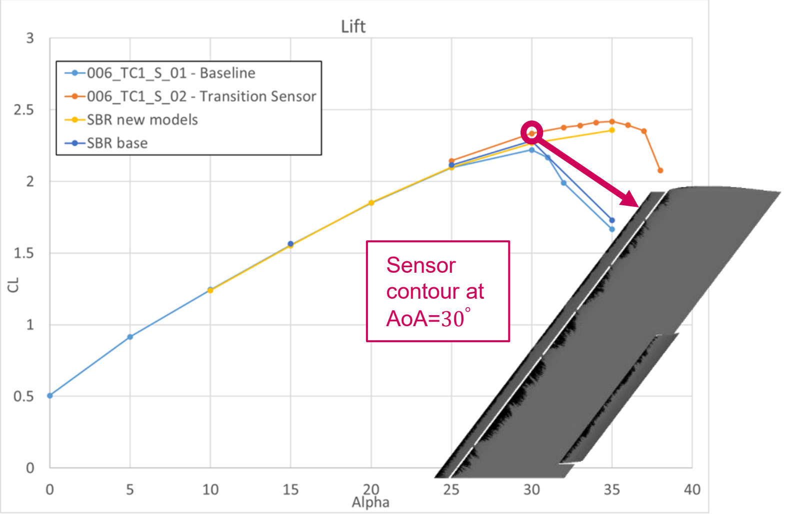


006: Boeing/Cadence

1. Agrawal et al. *Phys. Rev. Fluids* (2024)
2. Agrawal et al. *AIAA Journal* (2024)
3. Agrawal et al. *Phys. Rev. Fluids* (2022)

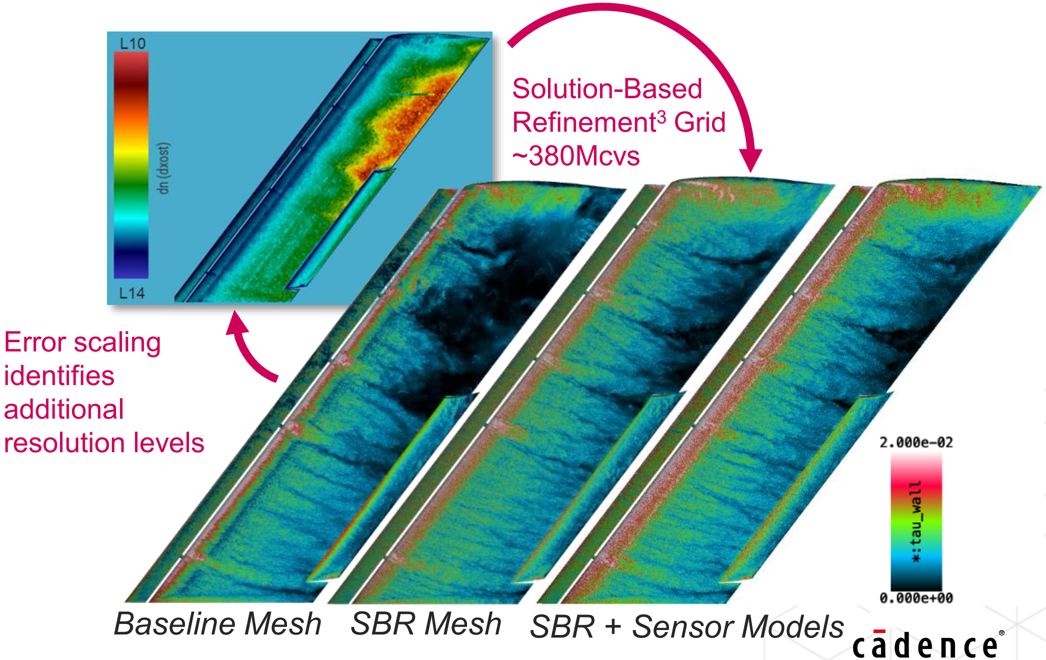
Solver: Fidelity Charles

- GPU-Accelerated 2nd-order Finite Volume Voronoi-mesh LES solver
- **Approaches**:
  - *Models*
    - Baseline : DSM + EQWM
    - Updated : Transition and/or Separation Sensor WM[1] + DTCSM[2]
  - *Meshes*
    - Baseline : Isotropic LVL 10 + 11 (LVL0=MAC)
    - New meshes : Solution-Based Refinement[3] + Aspect Ratio ~2:1



Early Findings:

- Critical AoA is not sensitive to increasing grid resolution
- Transition sensor extends critical AoA by ~5° while only being activated at small regions of the leading edges of the wing elements



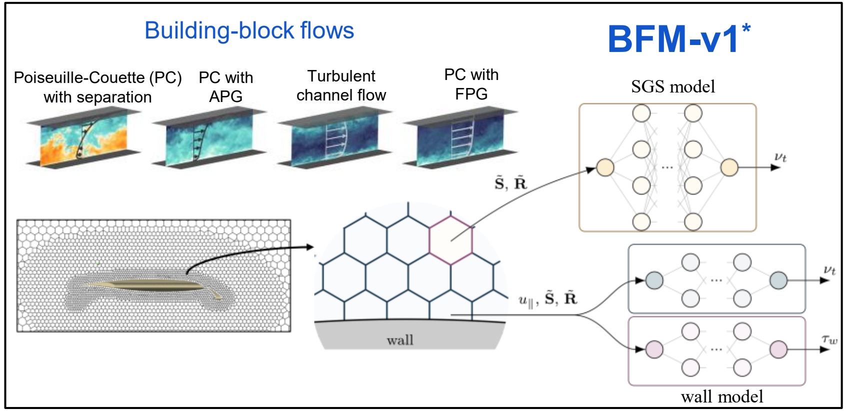
011: Caltech

Method

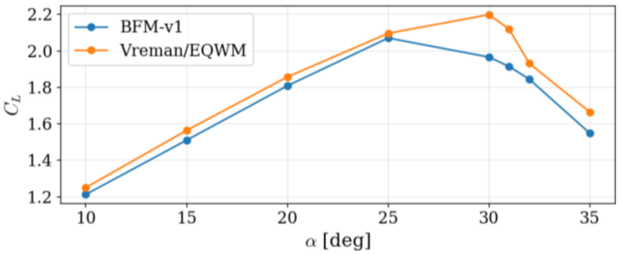
Solver: Fidelity CharLES; Grid: unstructured, voronoi (309M CVs)

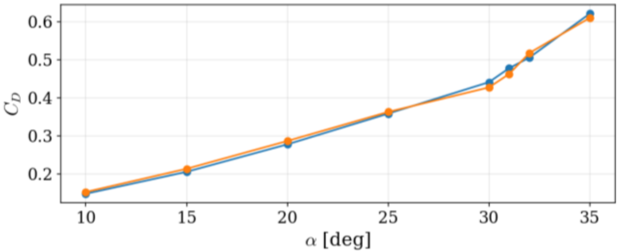
SGS and WM: **1. BFM-v1; 2. Vreman & EQWM** (w/o transition sensor)

Building-block flow model: ML-based SGS + wall model trained on DNS of canonical cases capturing essential flow physics in real flows

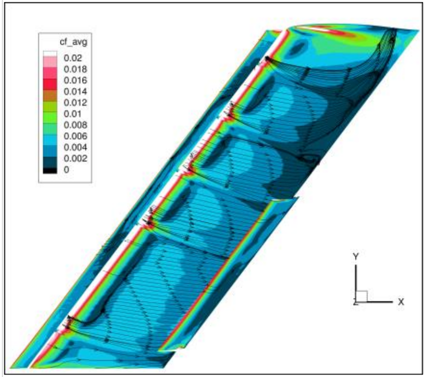


Results





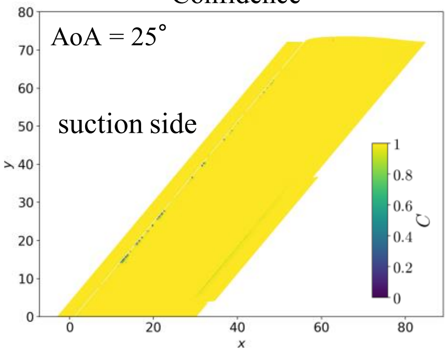
BFM-v1 (AoA=25°)



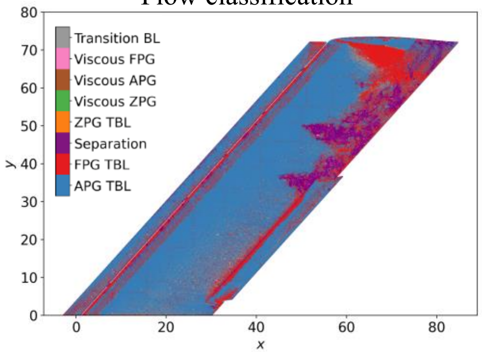
BFM-v2† under development

- Trained on a richer collection of flows: external TBL, large PG, separation, wall curvature effects…
- Provides: uncertainty quantification, confidence and explainability
- Laminar-sensor

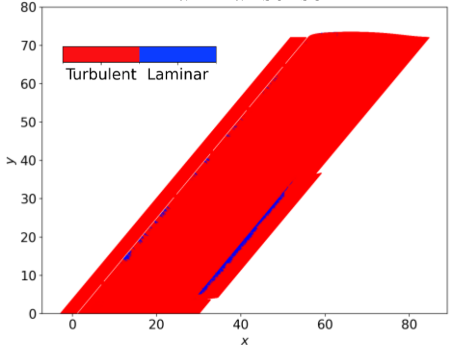
Confidence



Flow classification



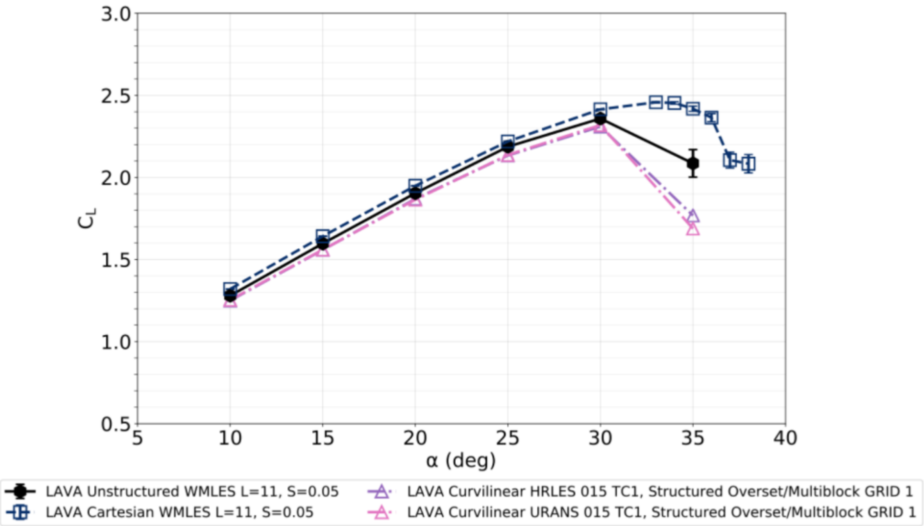
Laminar sensor

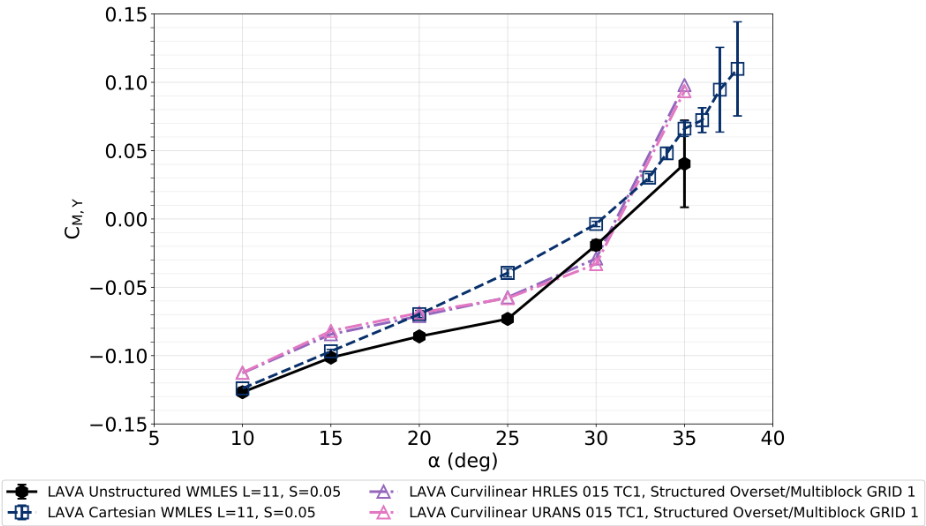


References: *Arranz, Gonzalo, et al. "Building-block-flow computational model for large-eddy simulation of external aerodynamic applications." *Communications Engineering* (2024)

†Ling, Yuenong, et al. "General-purpose data-driven wall model for low-speed flows part I: Baseline model." arXiv preprint arXiv:2511.16511 (2025)

013-015: LAVA Results Highlight for HLPW6 TC1



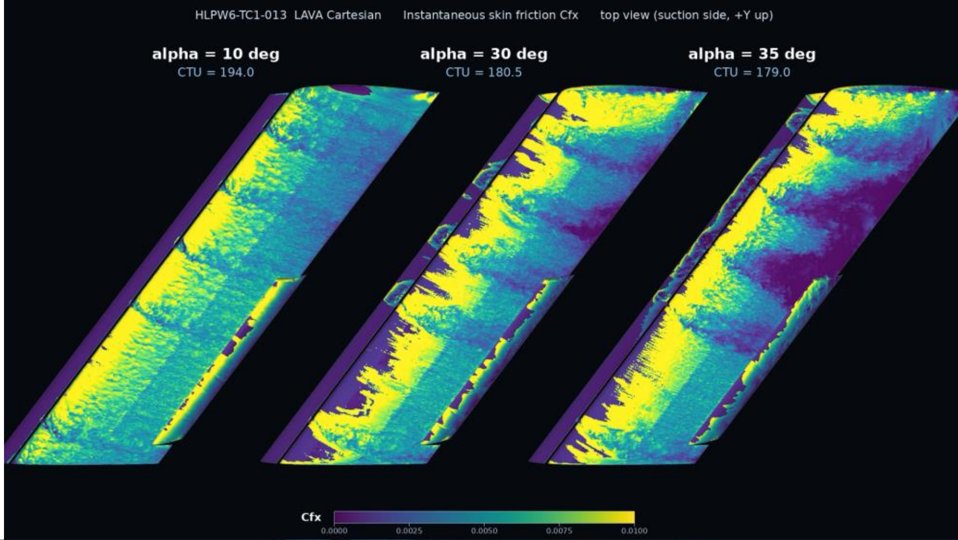


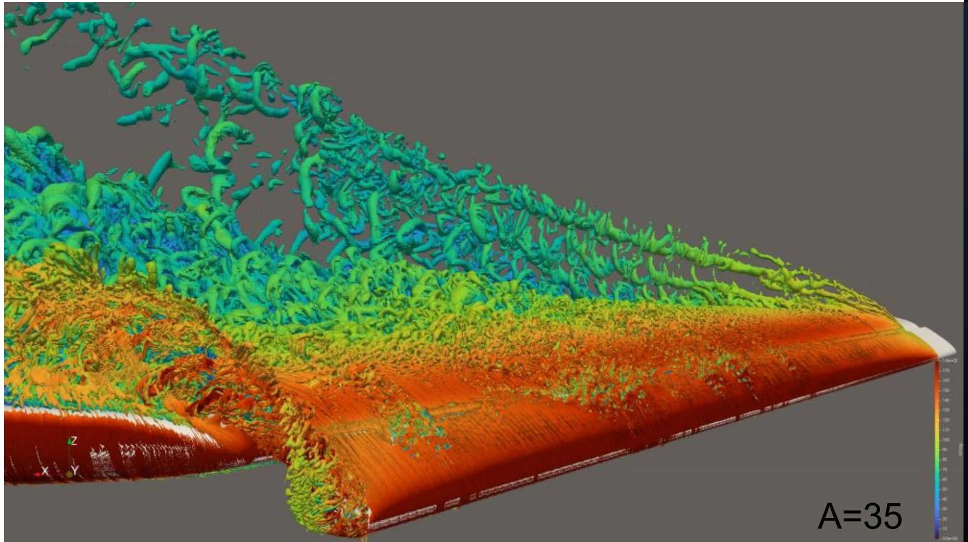
- LAVA group submitted results using Curvilinear, Cartesian and Unstructured solvers.
- Cartesian and Unstructured (Voronoi) submissions use WMLES with wall turbulence sensor-based switching between no-slip and turbulent wall stresses.
- Curvilinear submissions are URANS and HRLES.
- Overall, all 3 LAVA C_L results are consistent until stall, with Cartesian solver predicting a later stall onset
  - Curvilinear and Unstructured do not yet have incremental alpha solutions past 30 degrees to identify stall angle accurately.
- Spread in $C_{M,y}$ is more significant except at low alphas

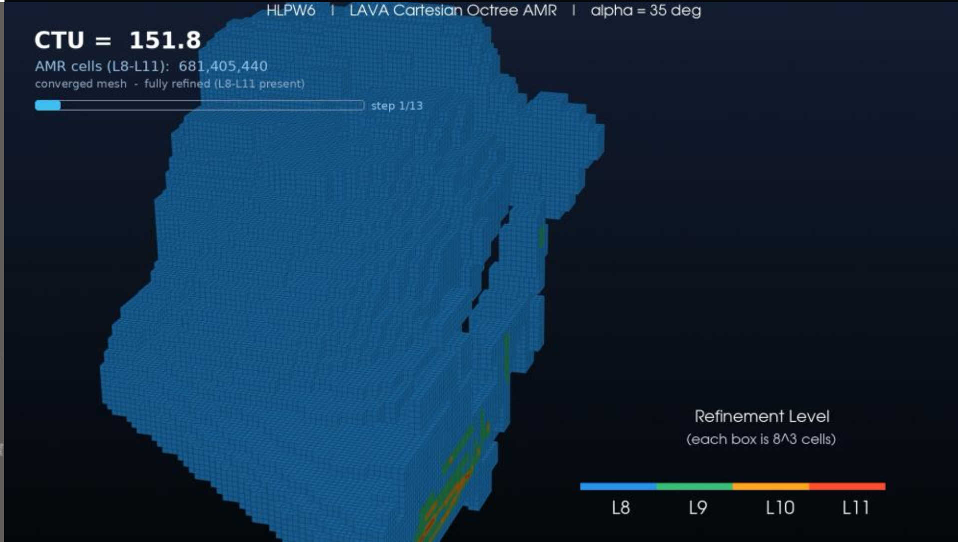
013: LAVA Cartesian WMLES with AMR

Overview:
- All cases run on 32 NVIDIA GH200 NAS Cabeus GPU nodes
- Full grid sensitivity included in single run via AMR refinement (grid-sequenced and small-scale energy based)
- 4th order accurate low-dissipation convective scheme
- WMLES with Sharp Immersed Boundaries
- Using same turbulence sensor as Sozer et al (SciTech 2025), see lower Cfx regions in upper right movie

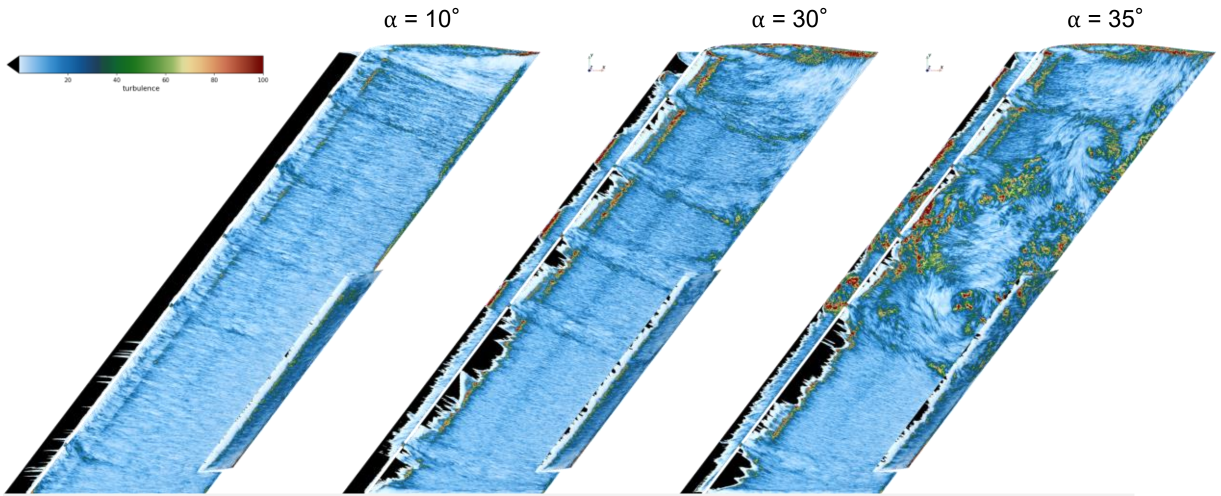
Discussion:
- Like other participants (006, 014), large sensitivity to laminar region treatment
- AMR customizes mesh based on flow conditions (see lower right), yielding targeted high-resolution for critical flow structures (see lower left)
- Lower-alpha lift is converging with mesh resolution. Some other participants appear to be increasing low-alpha lift with resolution



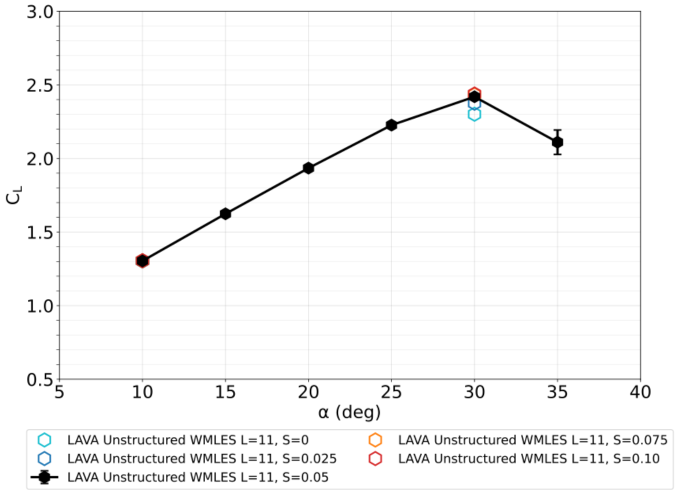




014: LAVA Unstructured Voronoi WMLES – Wall Turbulence Sensor Sensitivity



Wall turbulence sensor distribution



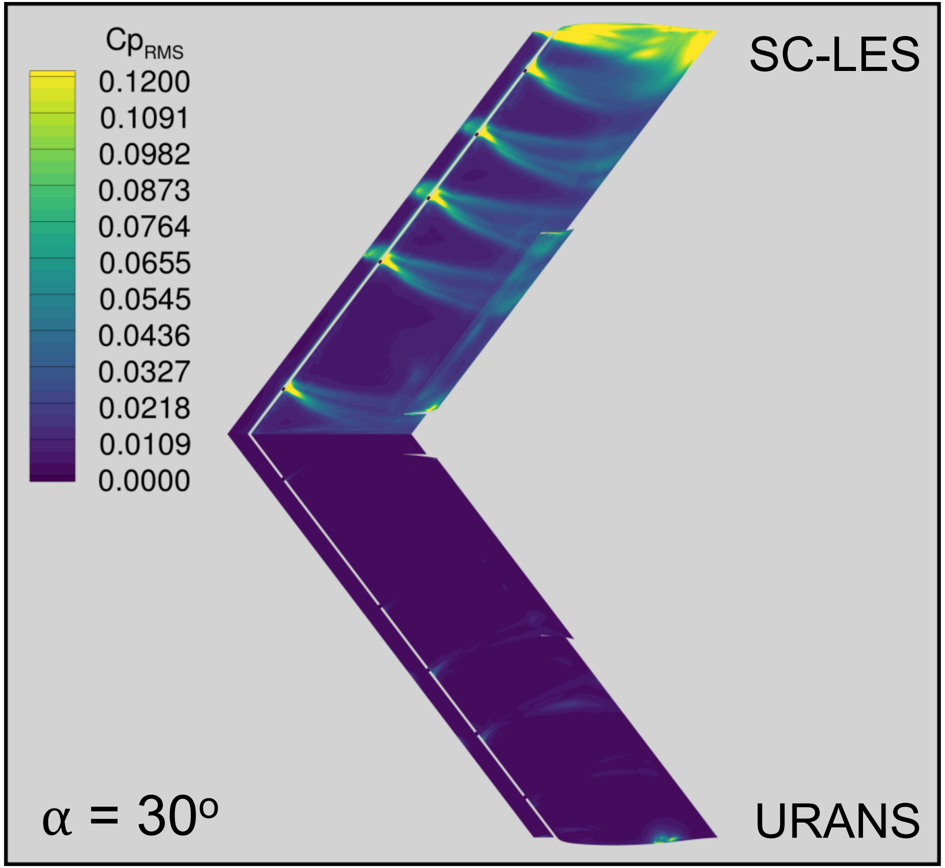
Overview:

- WMLES simulations on Voronoi grids, including a grid sensitivity study with L9, L10 and L11 grid levels.
- 2nd order accurate finite-volume with kinetic energy preserving convective flux with sensor-based blending of upwind dissipation.
- Equilibrium wall model with sensor-based switch to no-slip boundary condition when resolved turbulence level is low.

Discussion:

- Distribution of resolved turbulence over the wing points to potentially significant laminar regions over the leading edges
- At α = 30°, turbulence over the slat seems mainly triggered by upstream influence of the attachment brackets
- The sensor-based switch to no-slip BC involves a threshold choice, currently set as S=0.05
  - Variation of this threshold exhibit sensitivity at low threshold values but the results become nearly insensitive for S>=0.05
  - Near CL,max, use of the sensor has a significant impact on predicted lift
- Consistent with findings from the 5th workshop, these observations point to a need to study laminar-turbulent transition effects in greater detail with either WRLES data or experimental measurements as reference

015: LAVA Curvilinear, HRLES vs URANS

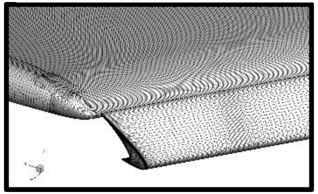


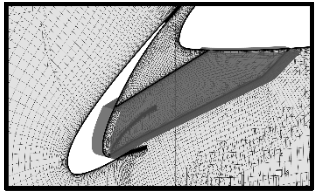
Overview:

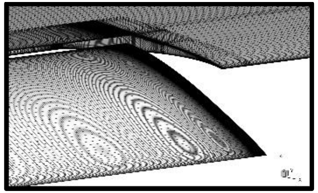
- All cases run on 10 128-core Turin EPYC 9745 CPU nodes
- Structured overset/multiblock grids with 132 million grid points (y+ < 1)
- Low-dissipation blended upwind/centered convective flux discretization
- URANS and HRLES (Stress Corrected LES) using SA-neg turbulence model
- Implicit time-stepping, dt = CTU/200 (URANS) and dt = CTU/1000 (HRLES)
- Immersed boundary (penalty) treatment for attachments

Discussion:

- Similar integrated loads predicted with URANS and SC-LES for alpha 10-30 deg.
- Model sensitivity observed at alpha 35 degrees
- SC-LES captures much larger Cp_{RMS} levels (unsteadiness) than URANS on the same mesh







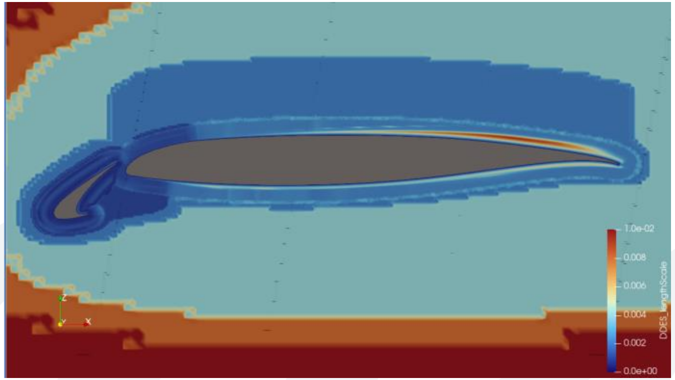
027 – Embraer Flow360

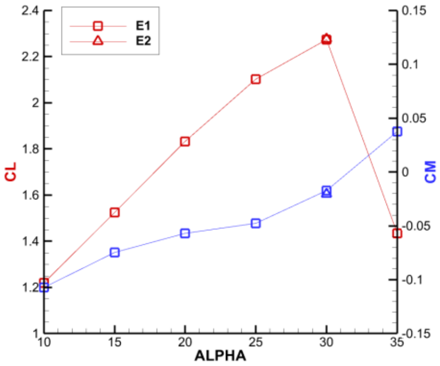
Highlights

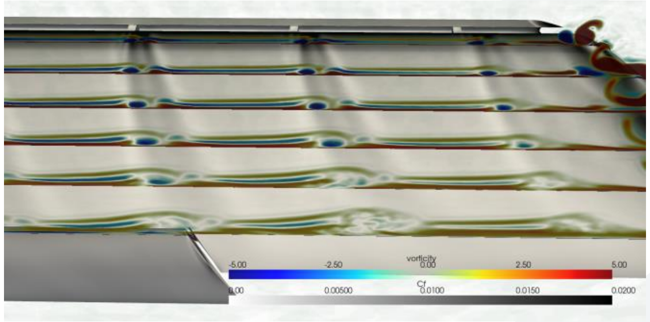
- Two custom grids tailored to DDES were generated:
  - Embraer e1 (standard) and Embraer e2 (finer)
- Simulations performed with Standard DDES with and without Low Dissipation schemes.

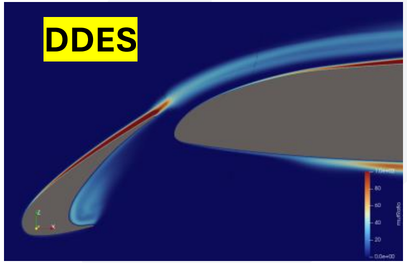
Next steps:

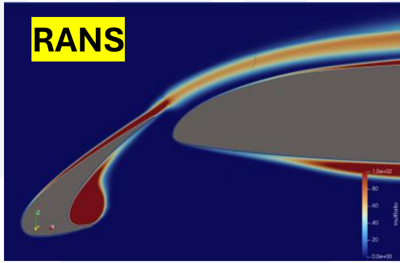
- Address the time step sensitivity.
- Study the influence of Deck-Renard and SLA shielding functions.

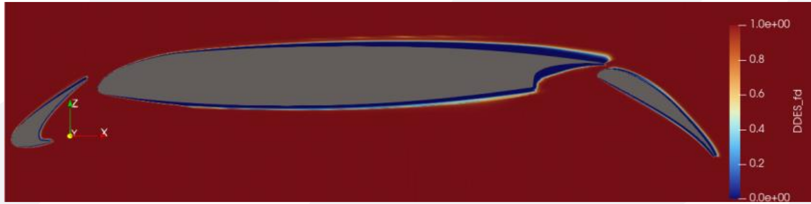












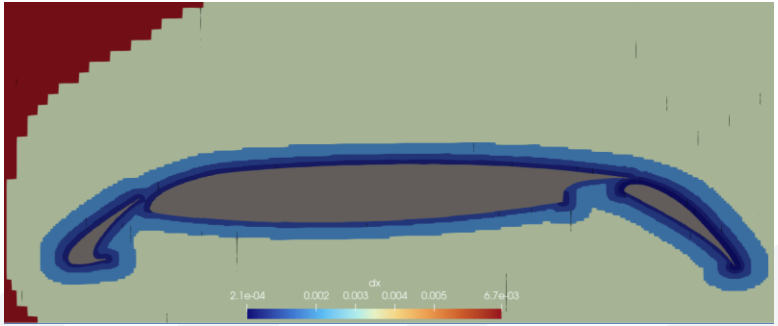
028 – Embraer ScaLES

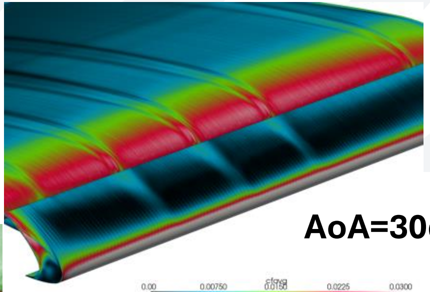
Highlights

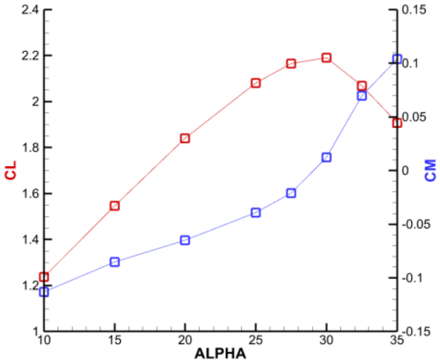
- Cartesian octree equilibrium wall model simulations with immersed boundary technique.
- Additional refinement on the flap upper surface was needed to match CL and CM with RANS at 10deg.

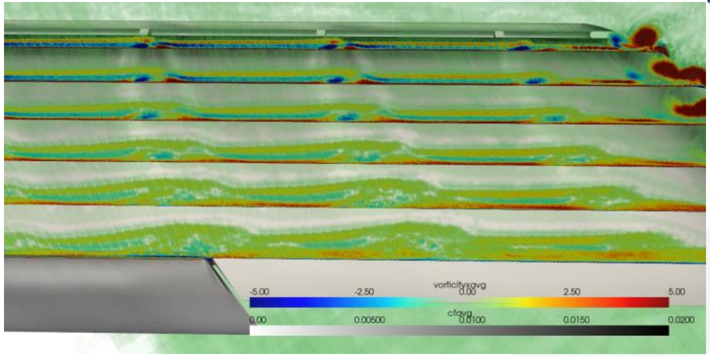
Next steps:

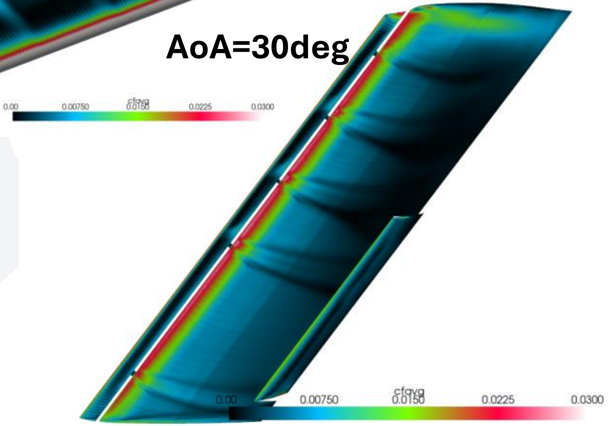
- Address the slat transition sensitivity to different wall-models and exchange locations.



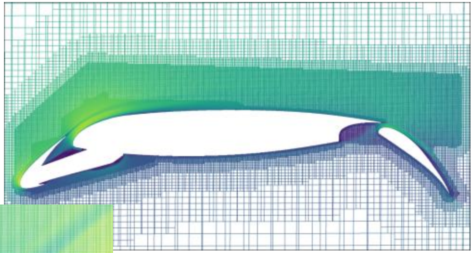


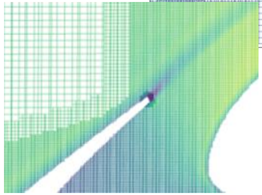






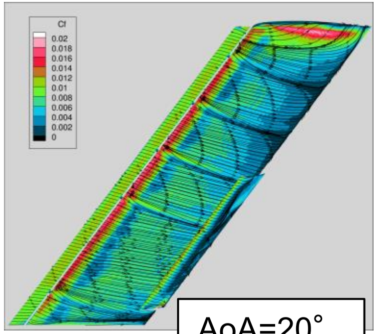
HLPW6 TC1 - 035 ONERA - ProLB Highlight



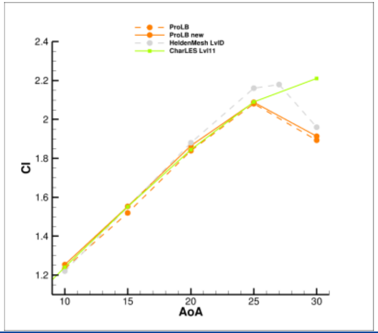


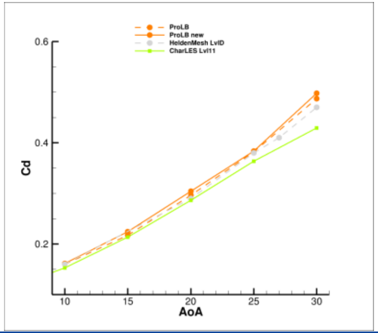
- ProLB Lattice-Boltzmann HPC solver (https://www.prolb-cfd.com) v3.4.2 SP
- WMLES simulation with IBM representation of the walls
- D3Q19 scheme with Hybrid Recursive Regularized collision model

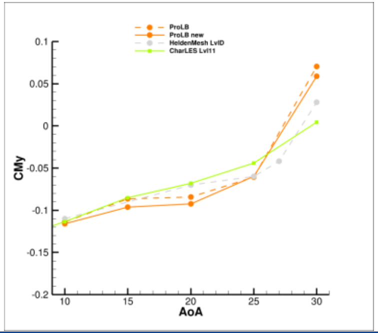
- Minimum cell size = 0.15mm
- Time step = 1.6x10^{-7}s, simulation time = 0.112s, CPU=0.7µs/eq.nodes/iter
- Basic octree mesh 324M int. nodes – 120M equiv fines nodes
  Refined mesh 868M int. nodes – 368M equiv fines nodes
  (refinement boxes around slat brackets and slats wakes)
- Cold start simulation for each AoA (warm restart will be done later in 2026)

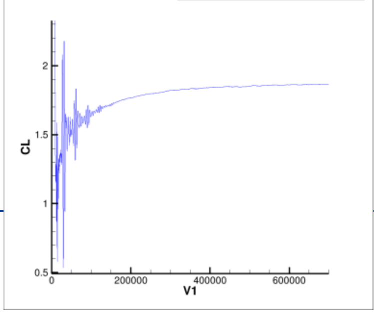


AoA=20°









RÉPUBLIQUE FRANÇAISE
Liberté
Égalité
Fraternité

ONERA
THE FRENCH AEROSPACE LAB

ProLB

Outline

- Background
- CRM-HLS Results
  - Aggregated Results
  - Individual Participant Highlights
- Summary

Key Question-Related Conclusions

- KQ 1: SRS TFG was unable to produce a consensus solution, either at stall or at low alpha and no WRLES/DNS cases were run ahead of mini-workshop 1
- KQ 2: significant sensitivity to laminar-to-turbulent leading-edge transition was exposed, but the correct behavior is impossible to confirm without high-fidelity data (experimental or simulation)

SRS TFG Recommendations

- **Experimental data** is needed to determine where $C_{L,max}$ occurs
- Desire for **WRLES** results
  - Including detailed post-processing (e.g., turbulence index on slat)
- Desire for more **HRLES** results
  - Determine whether low scatter is due to few submissions or higher accuracy of the method, especially at low AoA
- Request a consensus RANS solution at $\alpha = 10° - 20°$
- Deeper dive into **transition sensor results**
  - We will be requesting BL profiles to further diagnose differences

AMERICAN INSTITUTE OF
AERONAUTICS AND ASTRONAUTICS

BACKUP

Forces/Moments – All Participants