Predicting High-Lift Aerodynamics on NASA Common Research Model

Cetin C. Kiris, Aditya S. Ghate, Jared C. Duensing, Oliver M. F. Browne, Jeff A. Housman,

Gerrit-Daniel Stich, Gaetan K. Kenway, Luis S. Fernandes, Leonardo G. Machado

Computational Aerosciences Branch

NASA Ames Research Center

CadenceLIVE Silicon Valley 2022

Santa Clara Convention Center, June 8-9th, 2022

Objective

Investigate best-practices for aerodynamic predictions of high-lift configurations through a full angle-of-attack sweep including C_{Lmax} and stall

- On validity of RANS for C_{Lmax}
- Does HRLES improve RANS?
- Is WMLES a capable tool for C_{Lmax} and stall?
- Comparison of free-air results between methods
- Wind Tunnel vs Free Air Simulations
- Cost comparisons

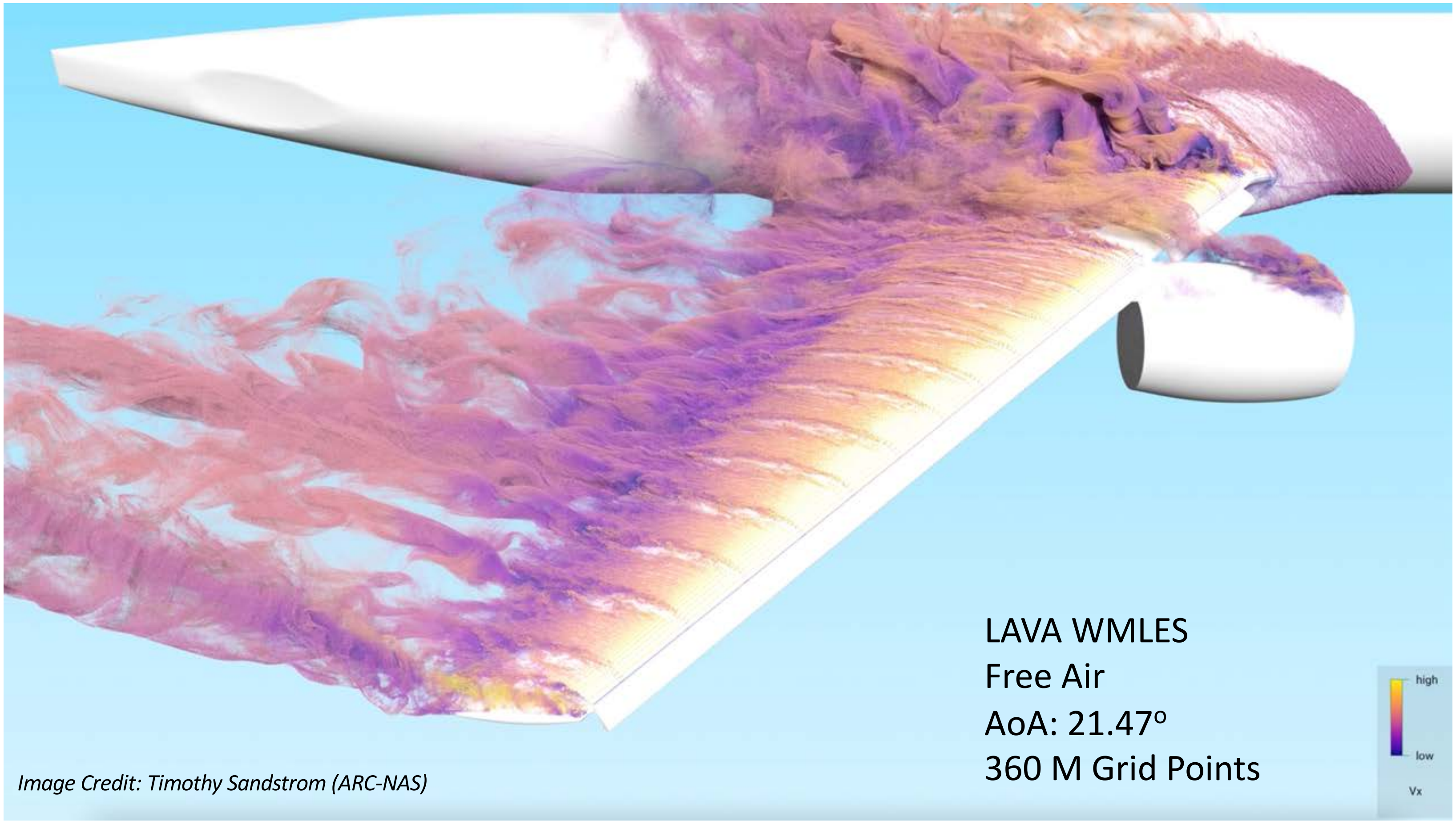


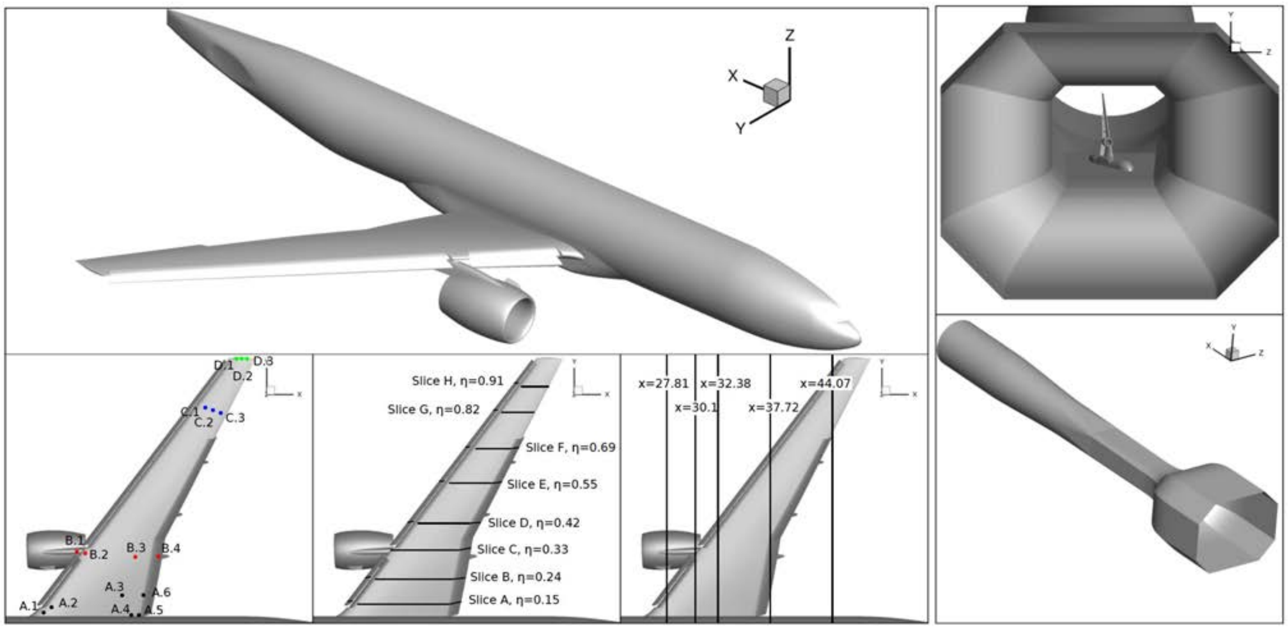
Image Credit: Timothy Sandstrom (ARC-NAS)

High Lift Prediction Workshop 4 (HLPW4)

https://hiliftpw.larc.nasa.gov/

NASA Ames LAVA group participated in the RANS, HRLES and WMLES Technical Focus Groups (TFGs) and submitted data for each to the workshop in December 2021.

NASA 10% Semispan High-lift Common Research Model (CRM-HL) – Case 2a and 2b for HLPW4



(a) Free Air (Case 2a) (b) Wind Tunnel (Case 2b)

LAVA Papers from HLPW4:

AIAA SciTech Forum2022:

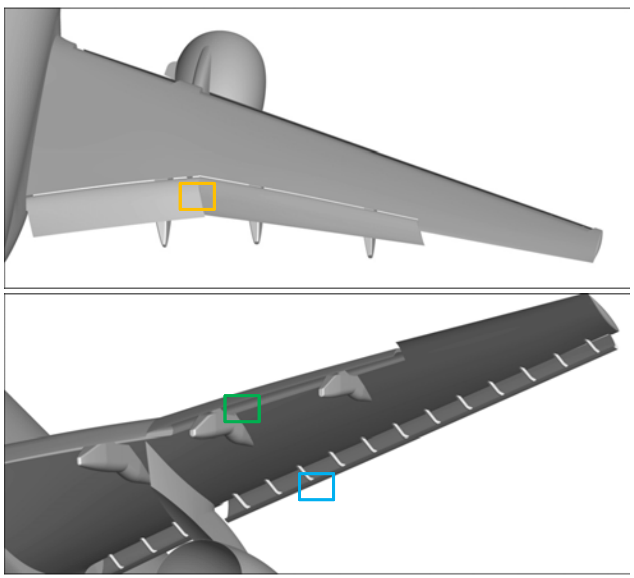
- *Kiris, C. C., Ghate, A. S., Duensing, J. C., Browne, O. M., Housman, J. A., Stich, G.-D., Kenway, G., Dos Santos Fernandes, L. M., and Machado, L. M., "High-Lift Common Research Model: RANS, HRLES, and WMLES perspectives for CLmax prediction using LAVA," AIAA SciTech 2022 Forum, AIAA Paper 2022-1554, 2022. doi:10.2514/6.2022-1554*

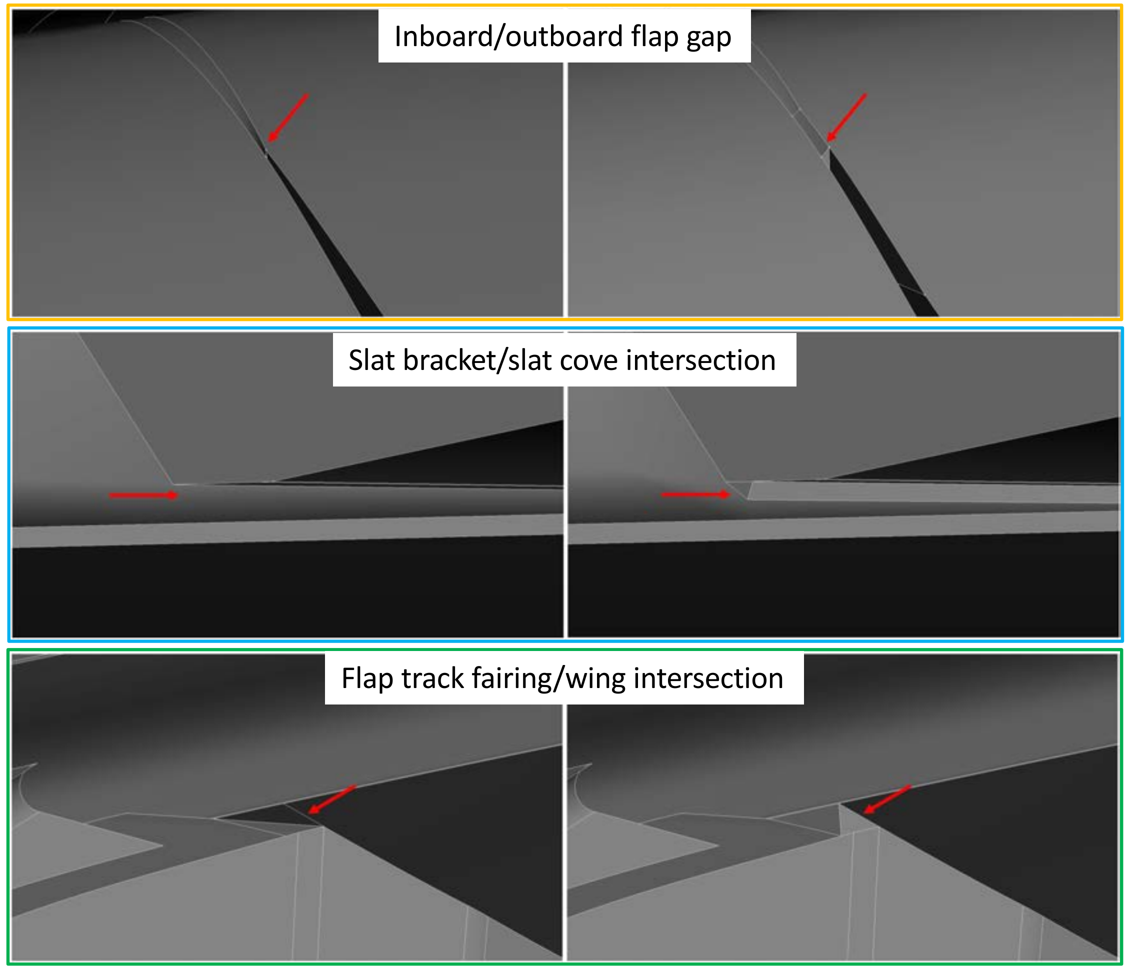
AIAA Aviation Forum 2022:

- *Duensing, J. C., Housman, J. A., Dos Santos Fernandes, L. M., Machado, L. M., and Kiris, C., "A Reynolds-Averaged Navier-Stokes Perspective for the High Lift-Common Research Model Using the LAVA Framework," AIAA Aviation Paper to appear, 2022.*
- *Browne, O., Housman, J., Kenway, G., Ghate, A., and Kiris, C., "A Hybrid RANS-LES Perspective for the High Lift Common Research Model Using LAVA," AIAA Aviation Paper to appear, 2022.*
- *Ghate, A., Stich, G.-D., Kenway, G., Housman, J., and Kiris, C., "A Wall-Modeled LES Perspective for the High Lift Common Research Model Using LAVA," AIAA Aviation Paper to appear, 2022.*

Geometric Modifications for Structured Grid Generation

- Minor updates to the underlying geometry were necessary to allow *structured overset* mesh generation
- All modifications performed using the ANSA CAD software
- Sharp concave corners below a certain tolerance (~15º) removed to enable volume mesh extrusion
- Tight gaps widened to enable surface mesh topologies of acceptable quality

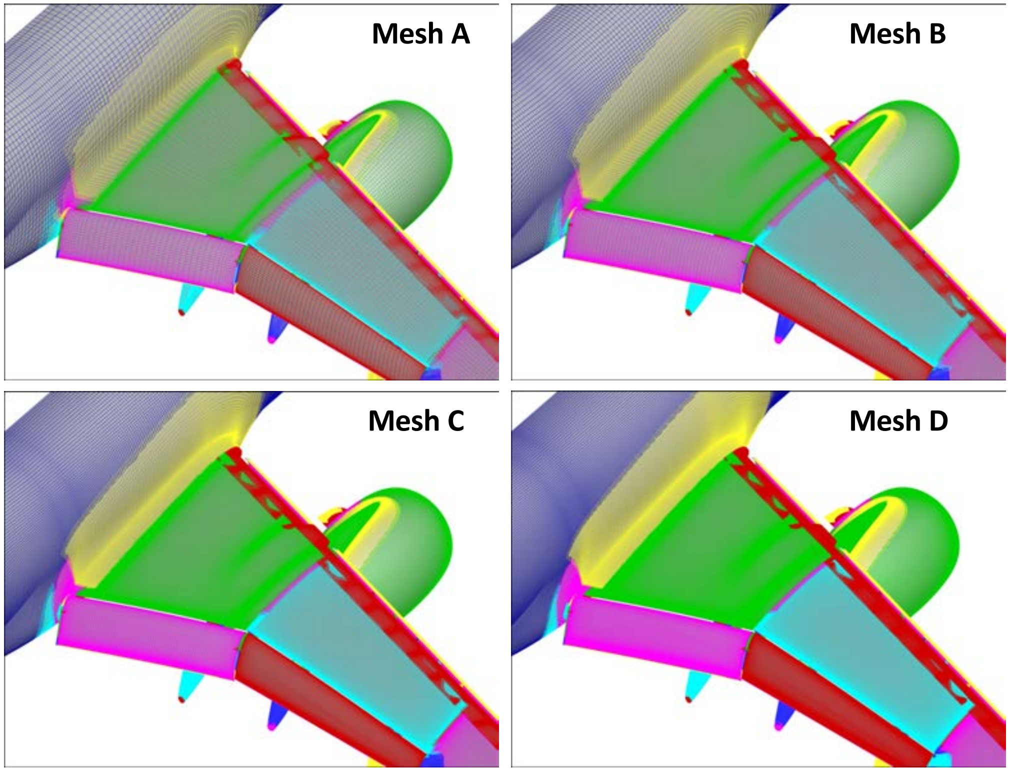




Computational Approach: RANS Grid Generation

- Mesh generation completed using Pointwise and Chimera Grid Tools (CGT)
- Meshing strategy based on provided Geometry and Mesh Generation Workshop (GMGW-3) guidelines
- Point distributions and local refinement regions were adjusted based on initial CFD simulations
- Computational grids would serve as the official committee-provided structured overset mesh family

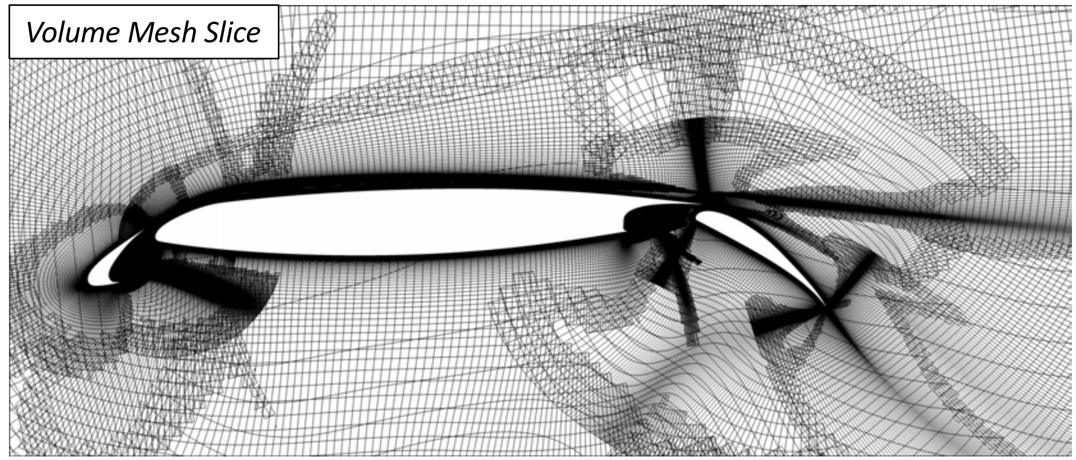
Mesh Level	Total Solve Points (M)	Target y^+	Max. Stretching Ratio
A	20.15	2.25	1.25
B	64.71	1.50	1.16
C	223.5	1.00	1.10
D	550.2	0.75	1.07

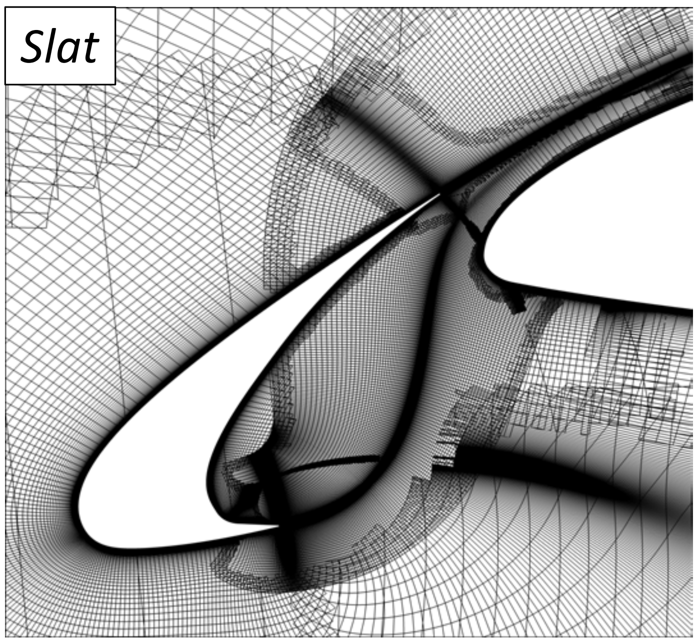


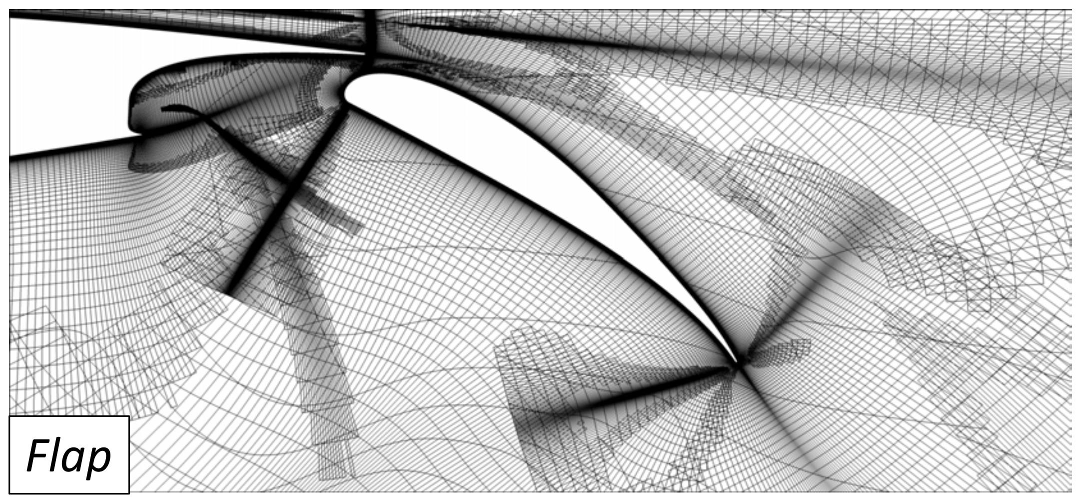
Free-air nominal configuration grid systems

Computational Approach: RANS Grid Generation

- Wake refinement regions generated to better resolve higher gradients and separated flow regions
- Regions were refined downstream of all three wing element trailing edges (slats, wing, and flaps)
- Spatial extent and shaping of refinement regions determined based on preliminary RANS simulations

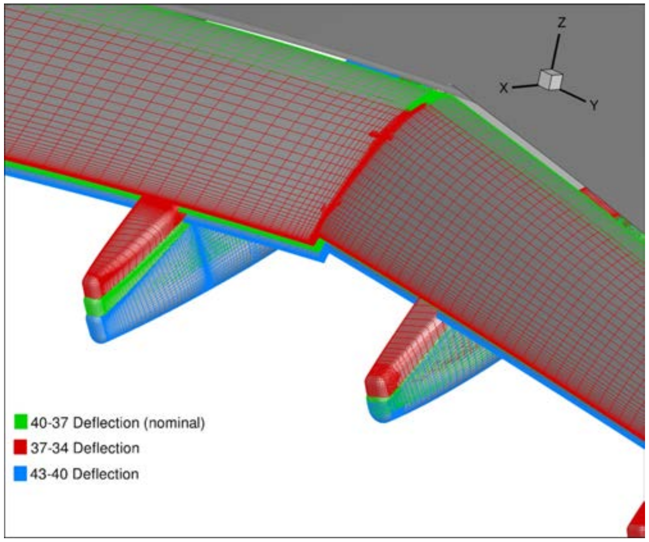




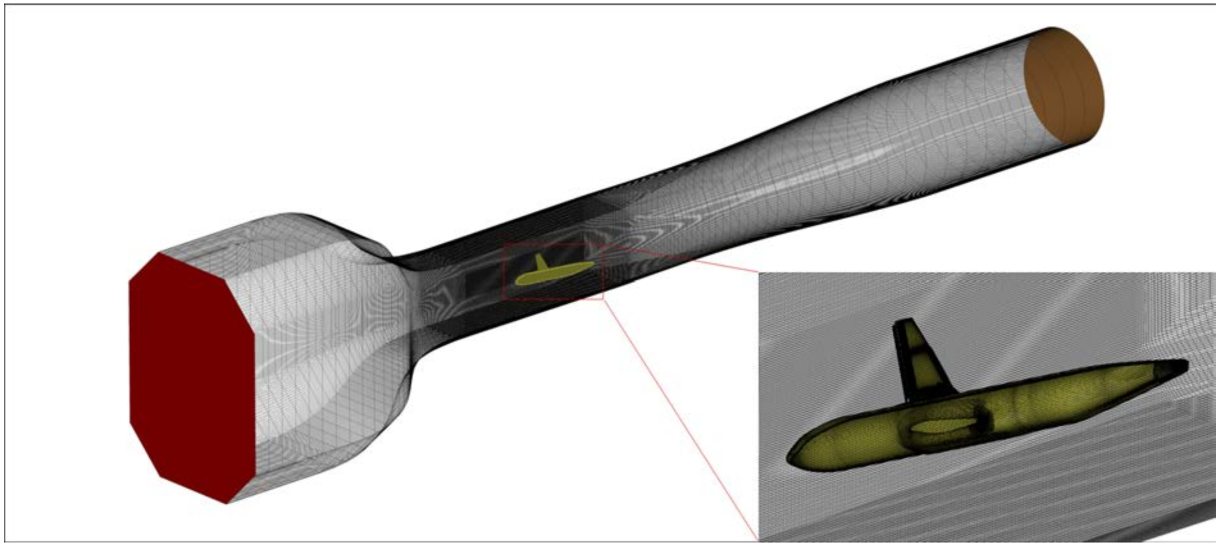


Computational Approach: RANS Grid Generation

- Additional grid systems generated for HLPW4 workshop studies extending beyond nominal CRM-HL configuration
  - Flap deflection study grid systems (all refinement levels)
  - Wind tunnel modeling studies (mesh C equivalent refinement)
  - Reduced y^+ grid systems for coarsest refinement levels
- Unique grids required for each angle of attack for wind tunnel simulations



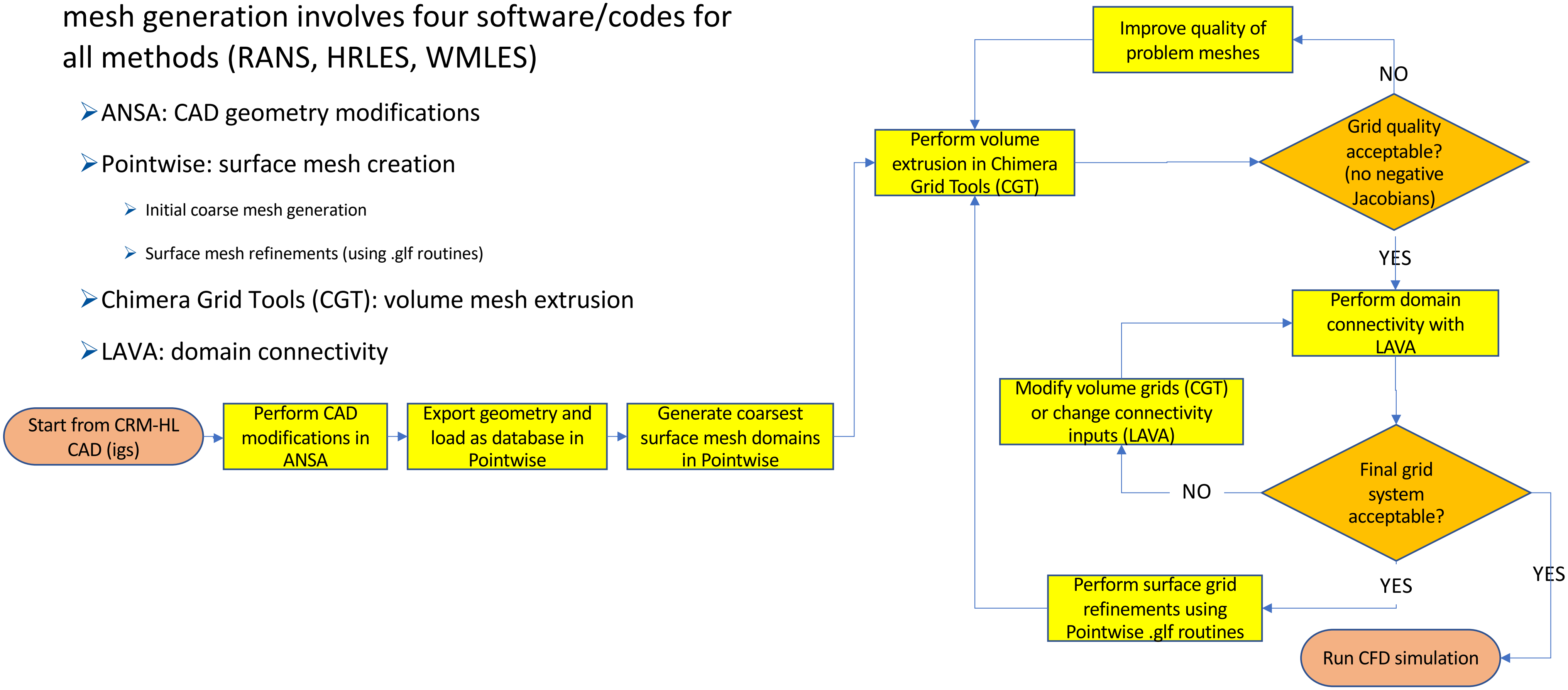
Flap deflection study grid systems



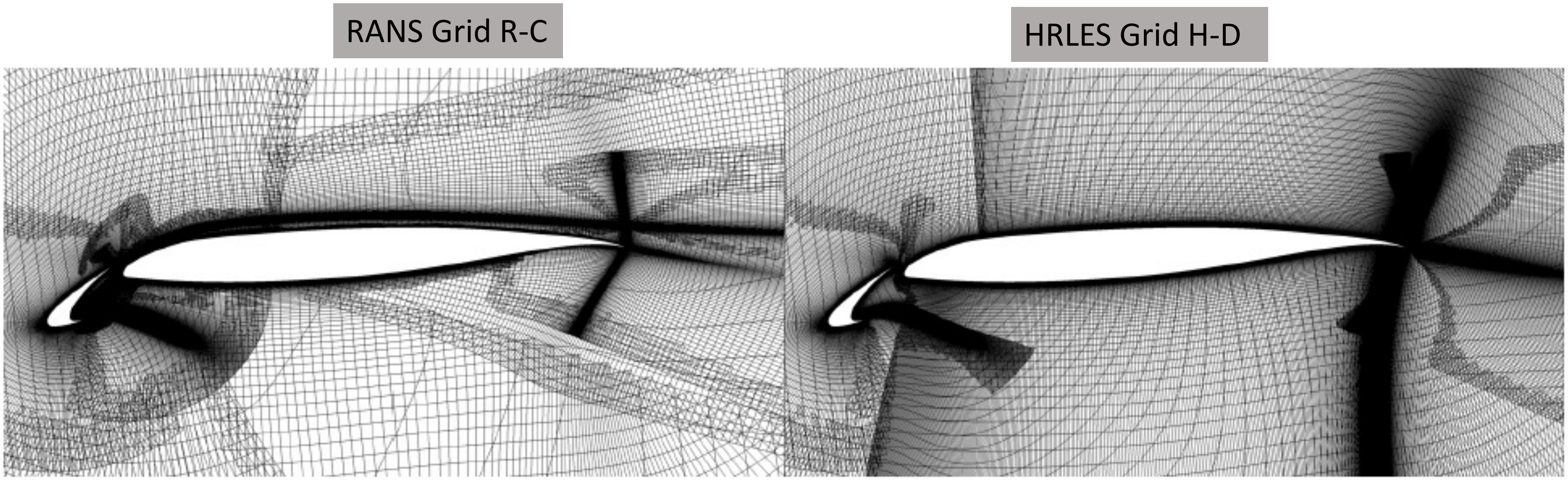
Wind tunnel modeling study grid system

Grid Generation Process Summary (All Methods)

- Complete process used for structured curvilinear mesh generation involves four software/codes for all methods (RANS, HRLES, WMLES)
  - ANSA: CAD geometry modifications
  - Pointwise: surface mesh creation
    - Initial coarse mesh generation
    - Surface mesh refinements (using .glf routines)
  - Chimera Grid Tools (CGT): volume mesh extrusion
  - LAVA: domain connectivity



Computational Approach: HRLES Grid Generation



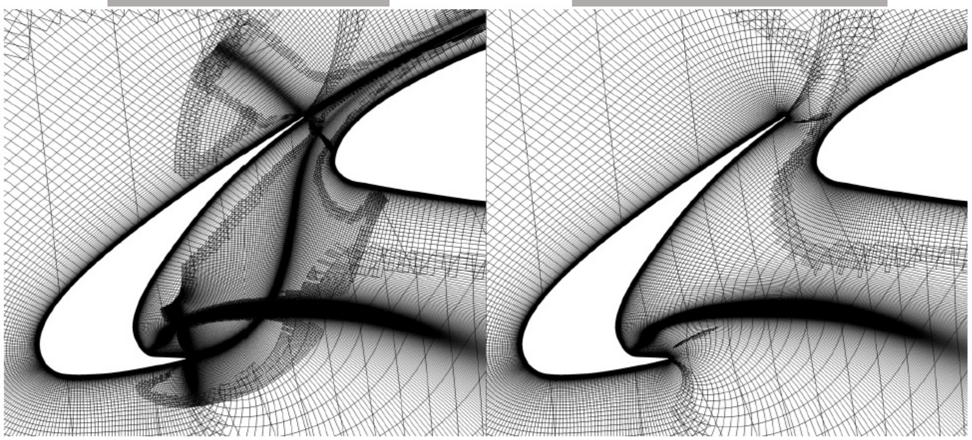
(a) Outboard wing (y = 24 m.)

Main modifications to RANS Grids for HRLES:

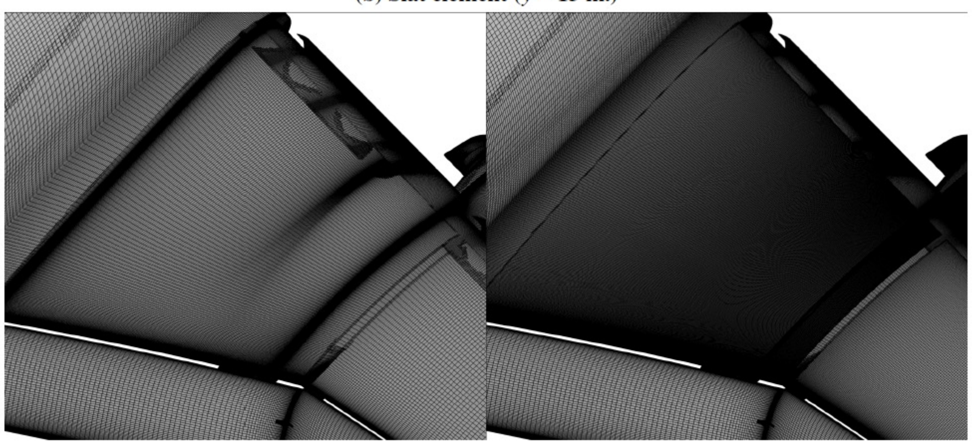
- To prevent excessive outboard separation, the outboard region of the wing was significantly refined for HLRES Grid H-D – 8x streamwise and 16x spanwise when compared to Grid R-C.

Computational Approach: HRLES Grid Generation

RANS Grid R-C | HRLES Grid H-D



(b) Slat element (y = 15 m.)



(c) Inboard wing upper surface

Main modifications to RANS Grids for HRLES:

- The grid points in the slat wake were redistributed to ensure lower aspect ratio cells were in the slat wake which are more appropriate for resolving the fluctuations in the slat wake.

- The inboard section on the wing was also refined in Grid H-D 4x in stream and span and the grid points were redistributed in the spanwise direction to reduce the clustering at the wing-collar juncture and the wake of the chine vortex.

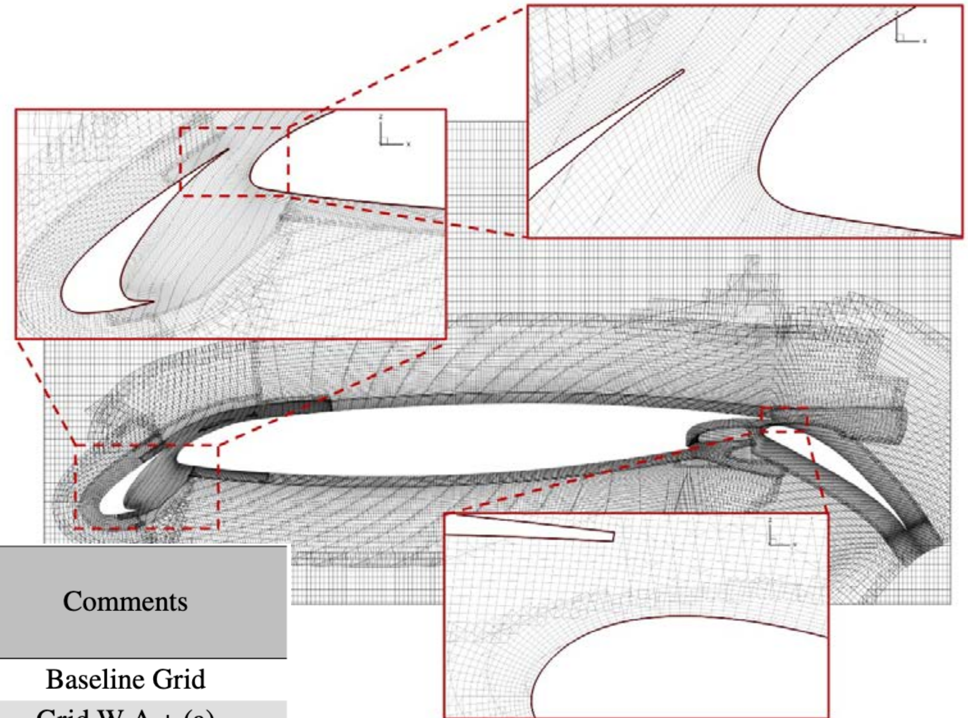
Name	Solve Points	Target y^+	Max Stretching Ratio	Comments
Grid R-C	224M	1.0	1.10	
Grid H-A	365M	1.0	1.10	inboard + outboard refinement
Grid H-B	325M	1.0	1.10	modified slat wake grid + outboard refinement
Grid H-C	421M	1.0	1.10	outboard refinement
Grid H-D	571M	1.0	1.10	inboard + midboard + nacelle refinement

Computational Approach: WMLES Grid Generation

WMLES mesh was built from scratch using Pointwise, Chimera Grid Tools as well as custom tool for hyperbolic marching of multi-block topologies (pyHyp). RANS/HRLES mesh could not be re-used!

Four sets of meshes (A-D) were created which adhered to the following meshing criteria:

1. Do not violate minimum cell size constraint (see table off-wall spacing)
2. Keep nominal aspect ratio as close to 1 as possible
3. Minimize oversets especially in areas of strong velocity gradients (BL) and shear-layers

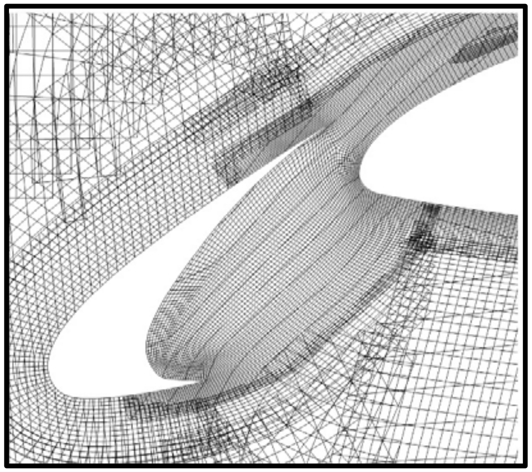


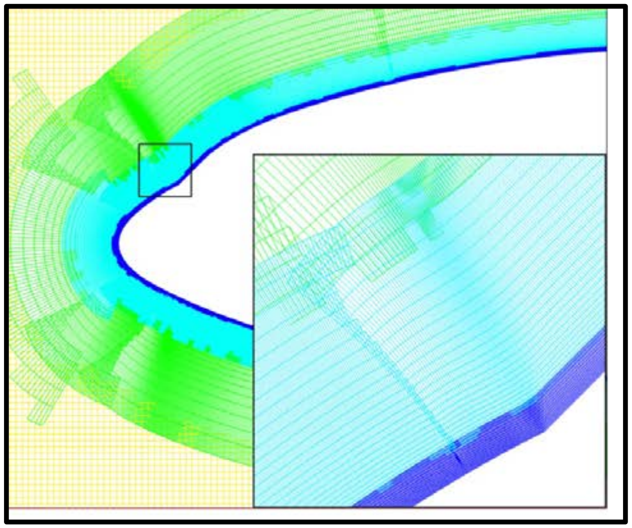
Name	Solve Points	Off-wall spacing	Nominal Aspect Ratio	Comments
Grid W-A	275M	5mm (2.5mm near LE and flaps)	6-8	Baseline Grid
Grid W-B	360M	5mm (2.5mm near LE and flaps)	6-8	Grid W-A + (a)
Grid W-C	650M	5mm (2.5mm near LE and flaps)	2-3	Grid W-B + (b)
Grid W-D	1100M	2.5mm (5mm on wing pressure side)	4-6	Grid W-C + (c)

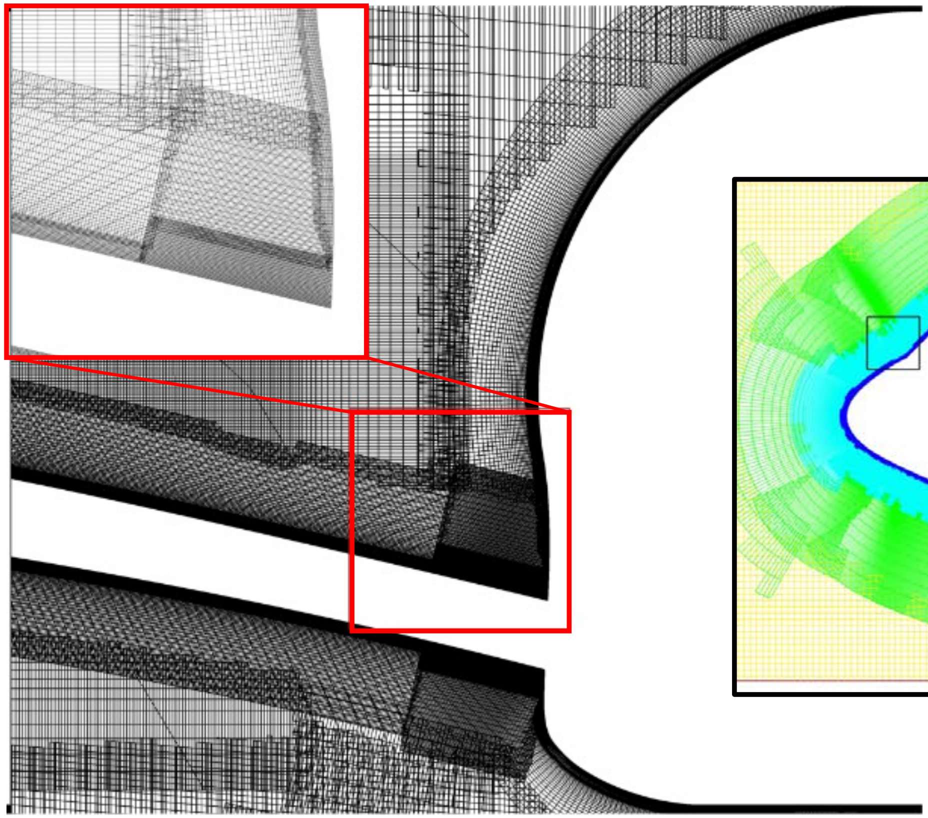
(a) off-body refinement around the second overset layer off the wall and refinement block around the chine vortex; (b) surface mesh was refined in stream-wise and span-wise direction on wing suction side and fuselage; (c) additional factor 2 refinement of wall-normal spacing on wing suction side as well as parts of the fuselage mesh.

Computational Approach: WMLES Grid Generation

- Complex multi-block slat cove mesh to avoid oversets and improve mesh quality



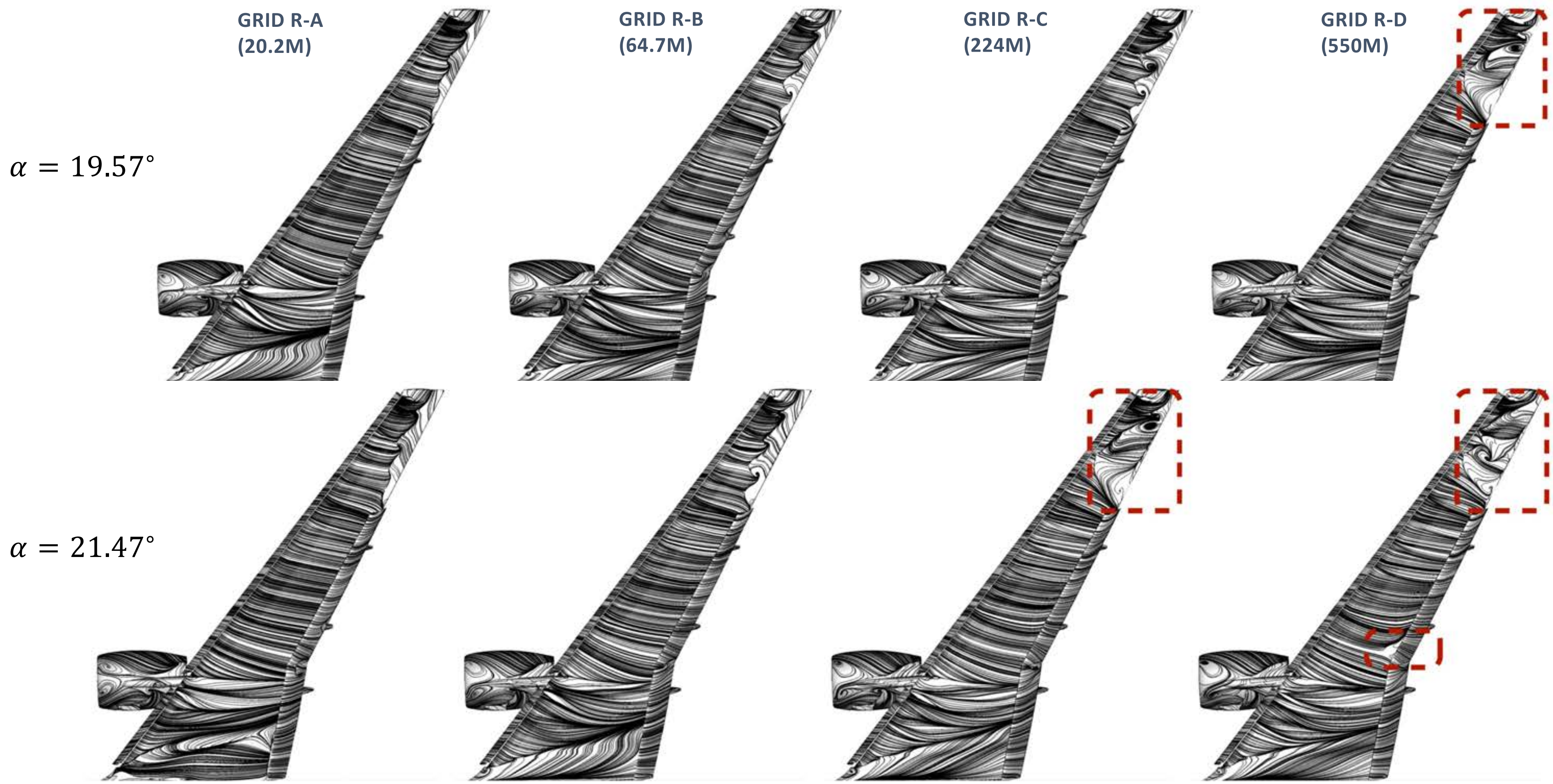




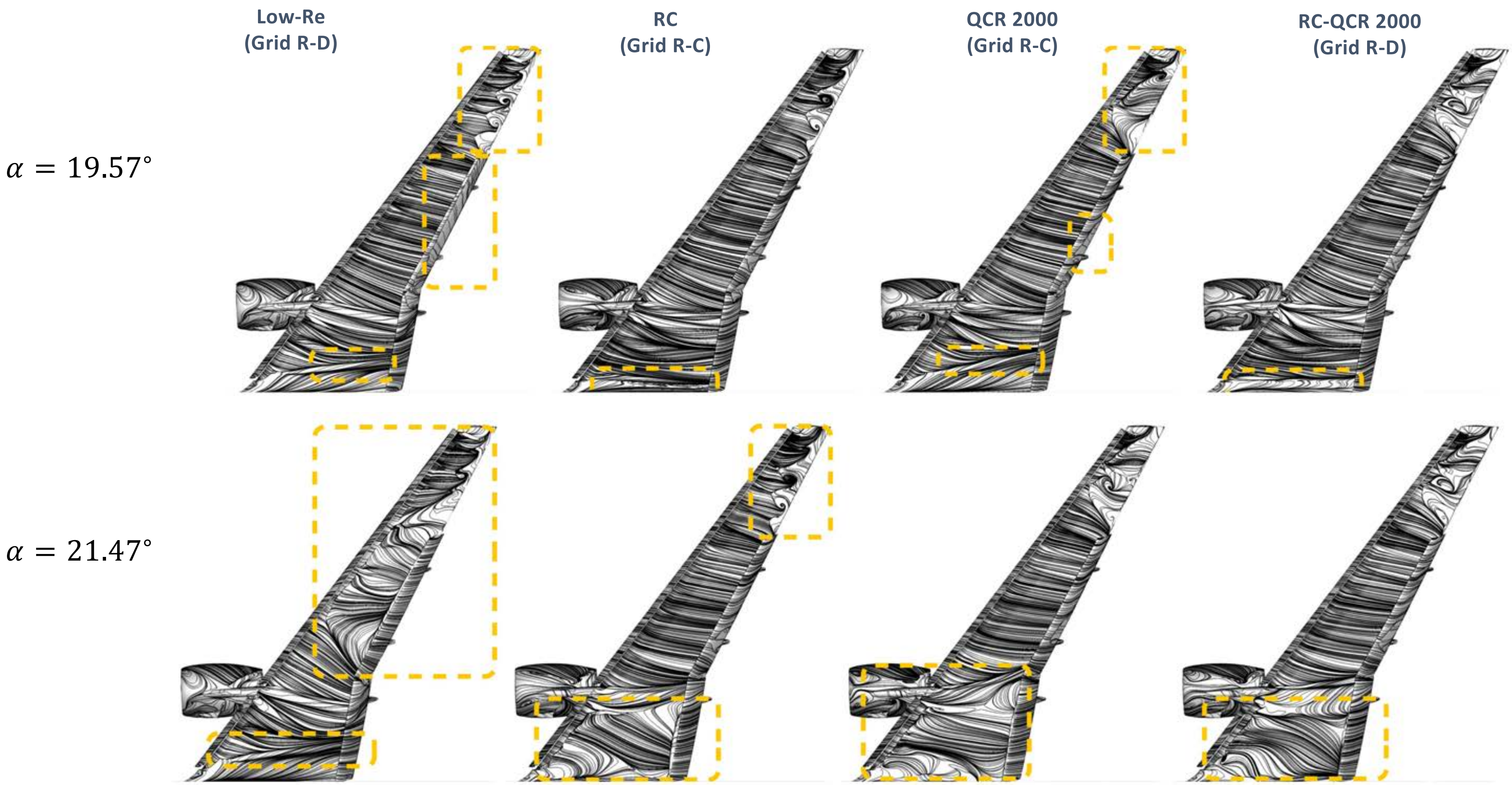
- Special refined juncture flow mesh with refined streamwise and spanwise spacings

- Multi-layer volume mesh approach: Grow volume in several layers with factor 2 coarsening in stream and span to relax high near-wall mesh requirements

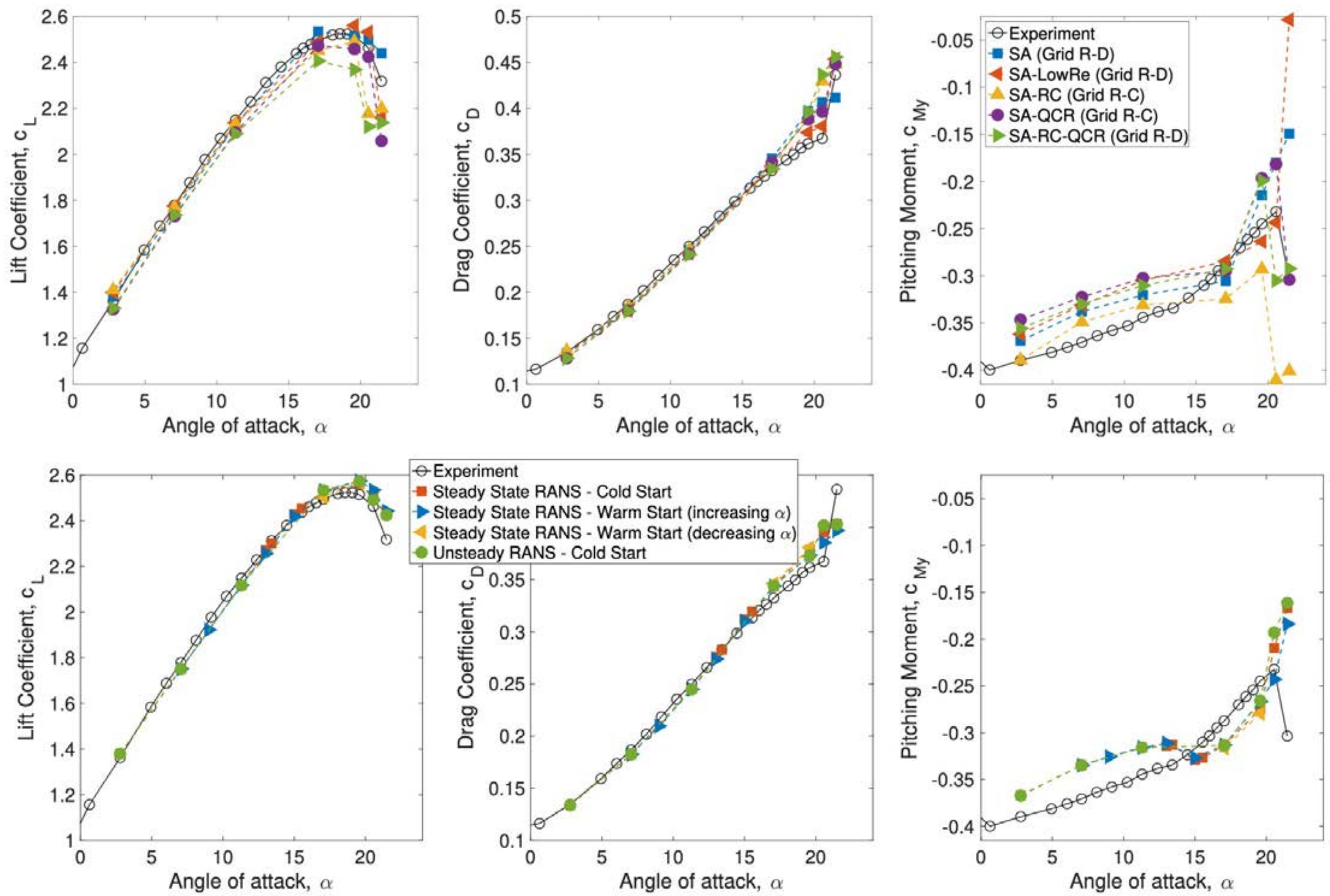
RANS Simulations (Baseline SA) – Grid sensitivity



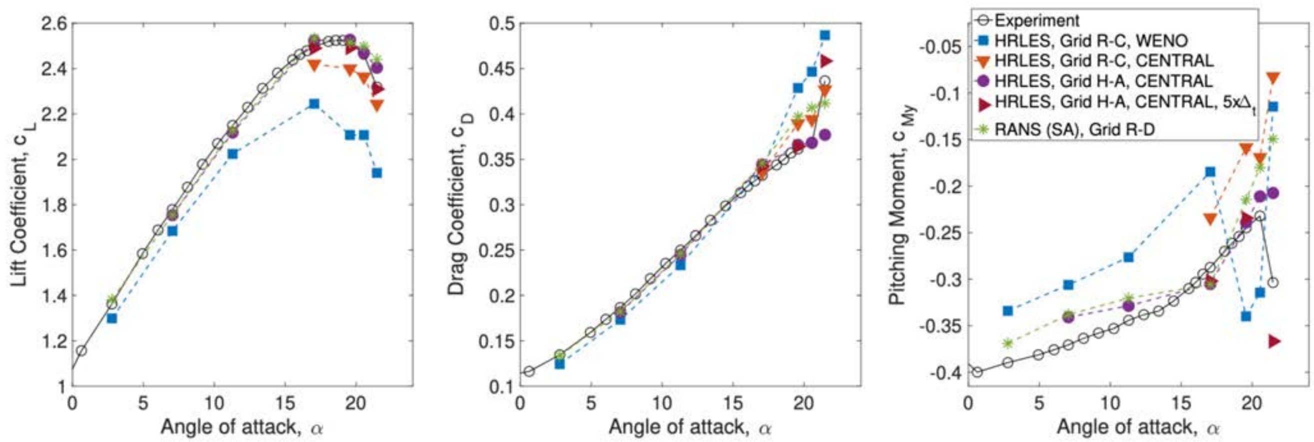
RANS – SA Correction Terms

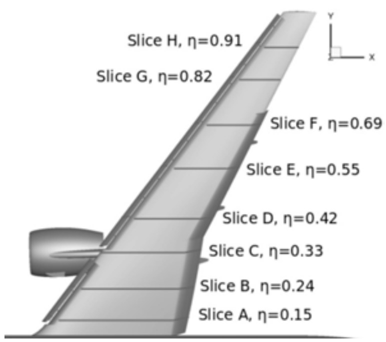


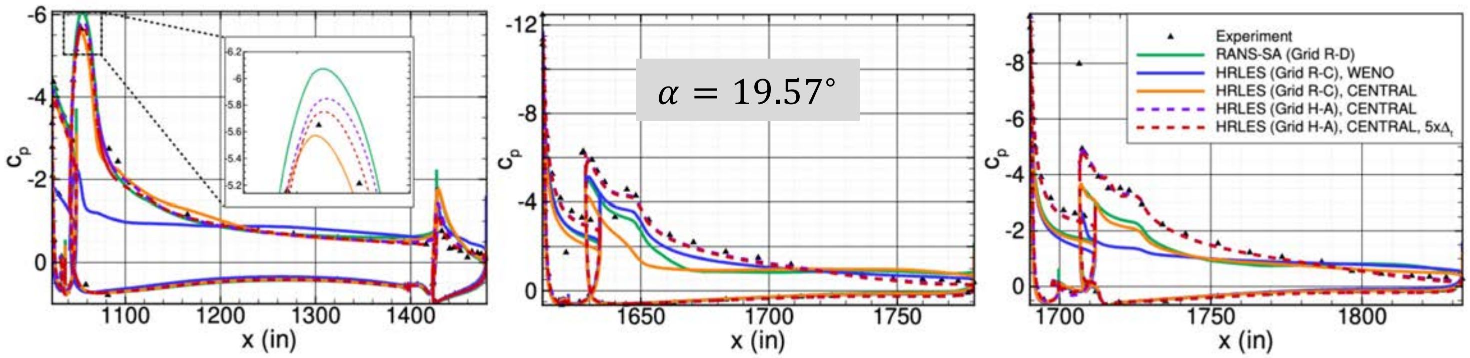
RANS – SA Variations and Simulation Procedure



HRLES – Improvements over RANS

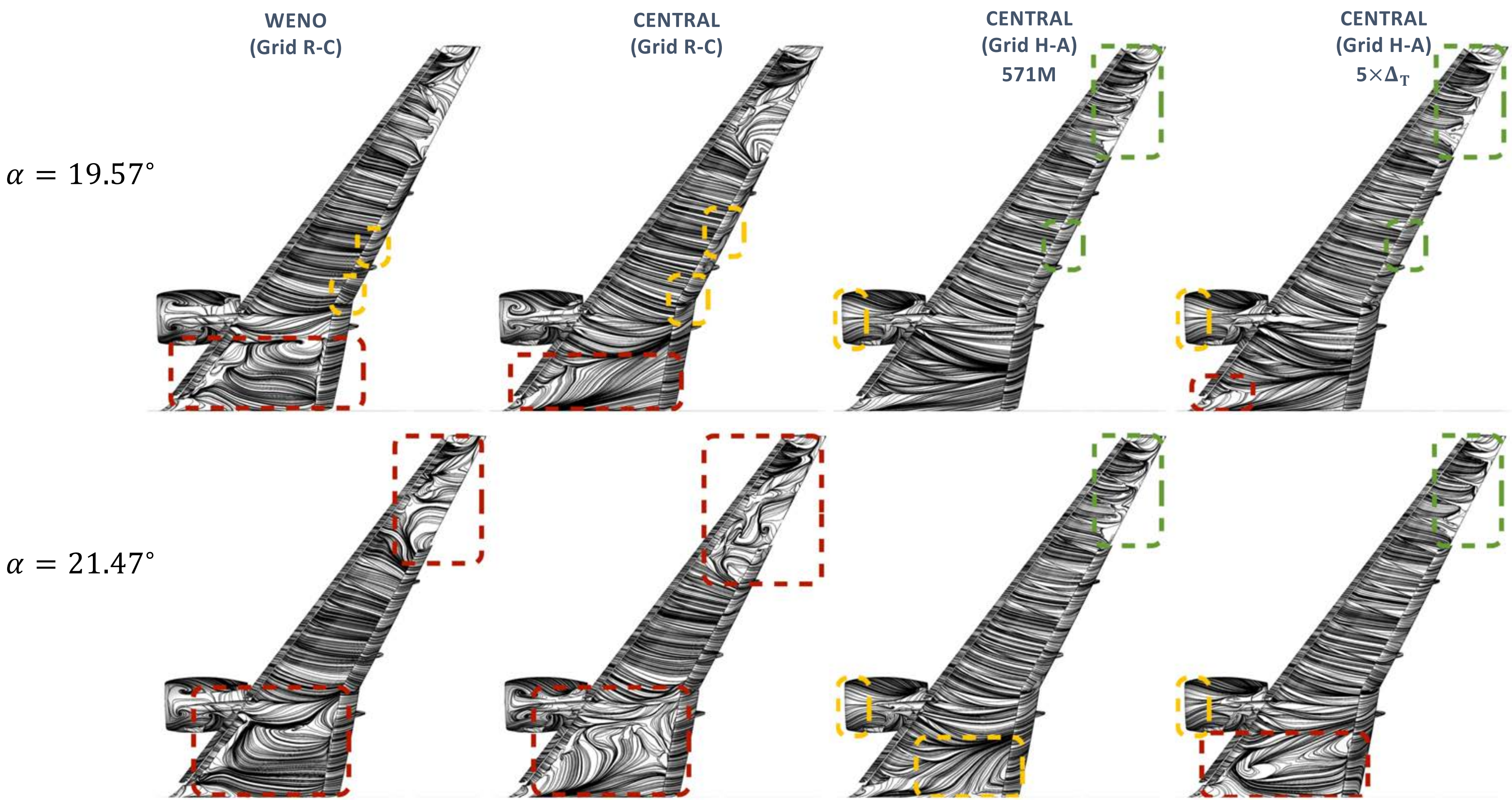




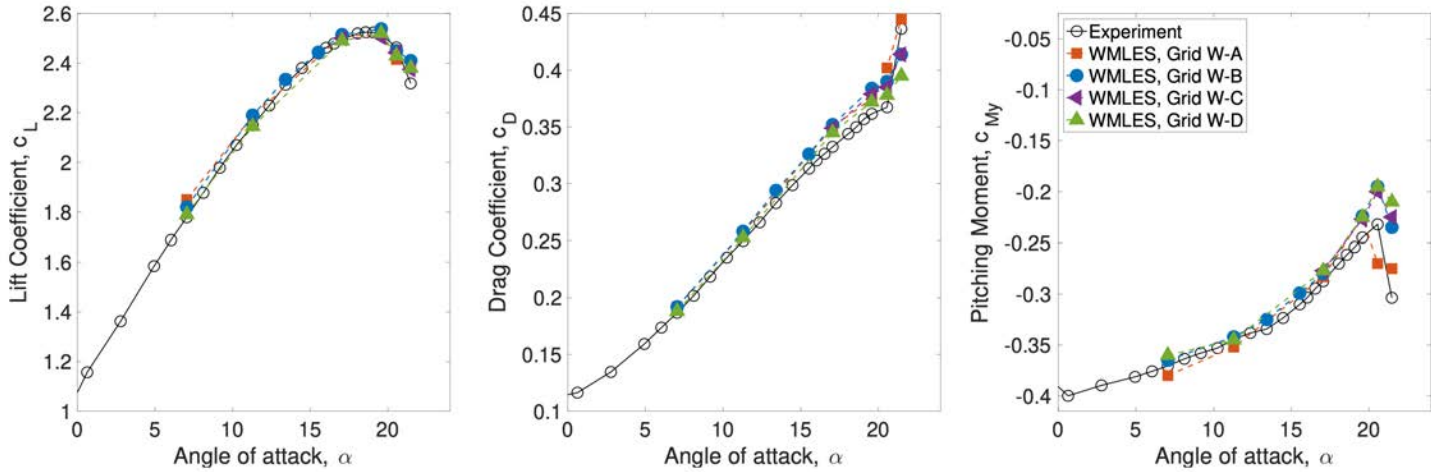


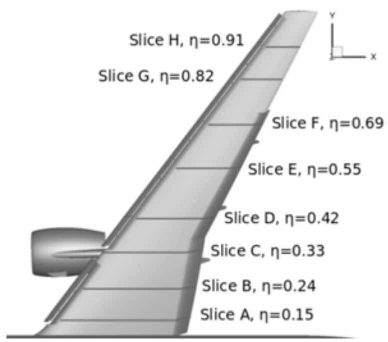
(a) Slice A, $\eta = 0.15$ (b) Slice G, $\eta = 0.82$ (c) Slice H, $\eta = 0.91$

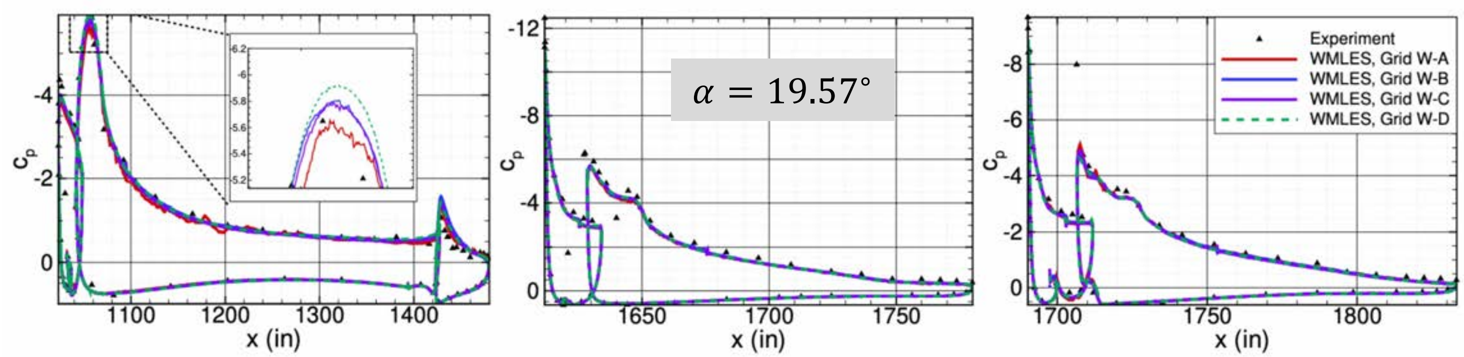
HRLES – Improvements over RANS



WMLES – Grid Sensitivity and "Convergence"





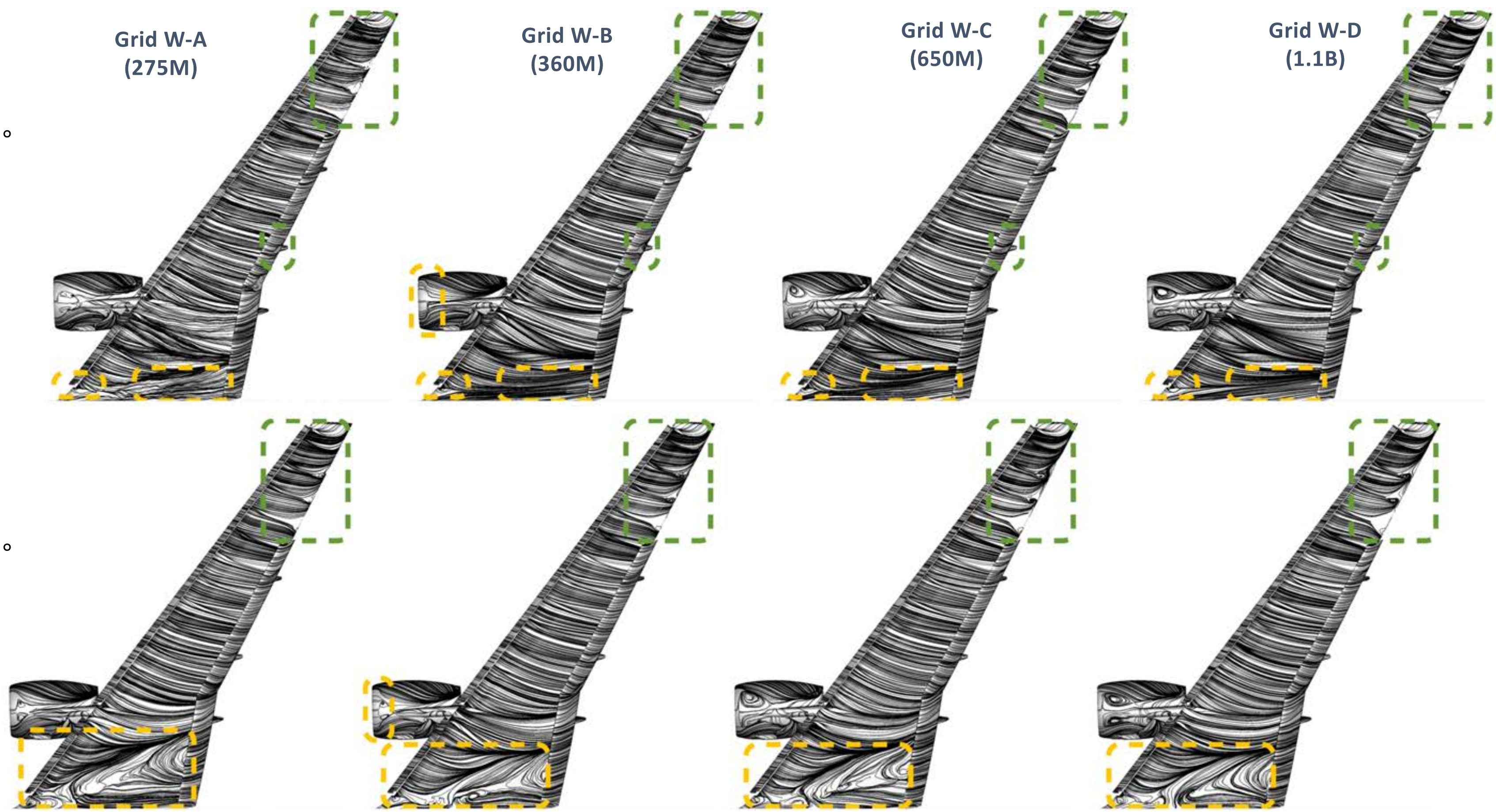


(a) Slice A, $\eta = 0.15$ (b) Slice G, $\eta = 0.82$ (c) Slice H, $\eta = 0.91$

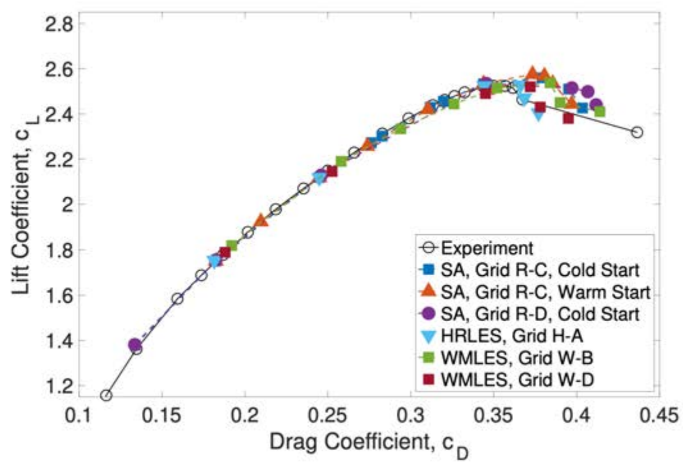
WMLES – Grid Sensitivity and Convergence

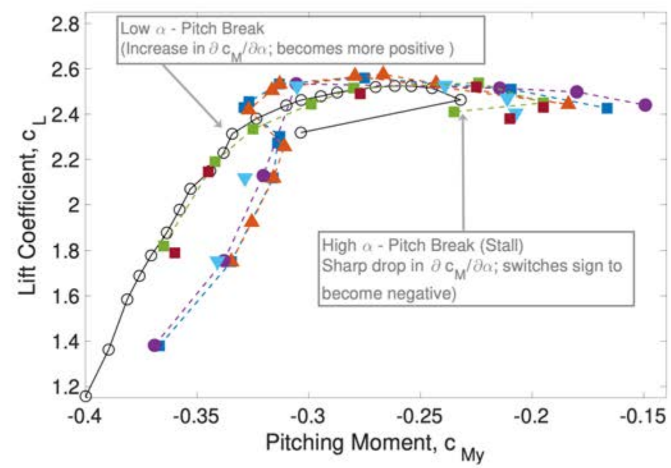
$\alpha = 19.57°$

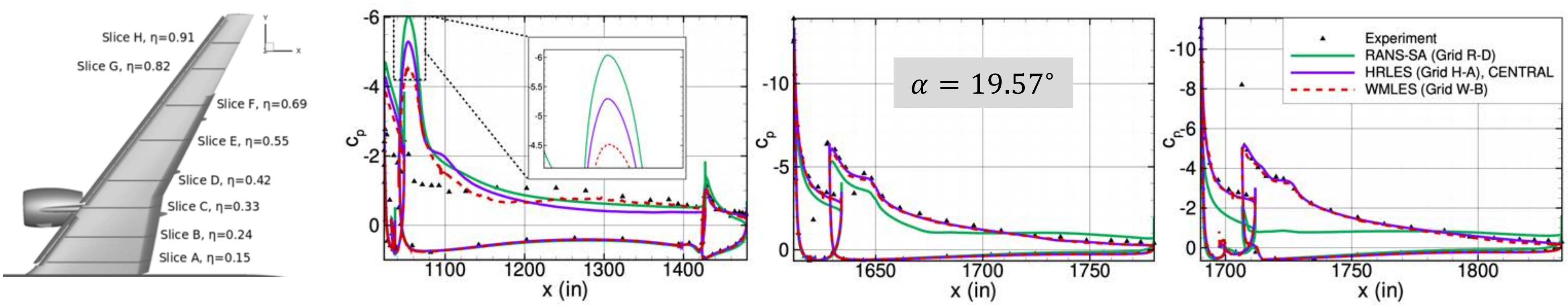
$\alpha = 21.47°$



Comparison Between Methods (Free-Air)





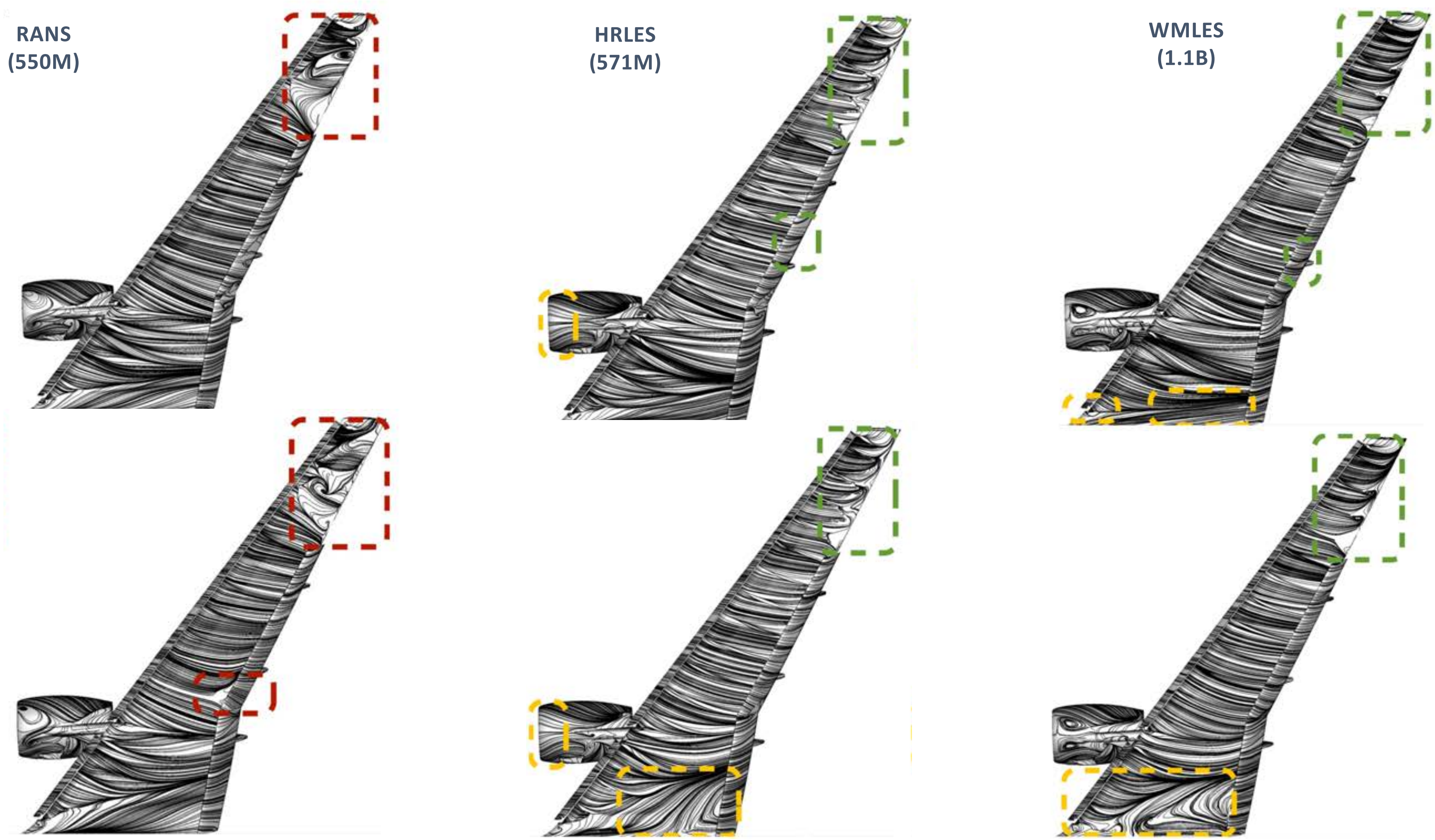


(a) Slice A, $\eta = 0.15$ (b) Slice G, $\eta = 0.82$ (c) Slice H, $\eta = 0.91$

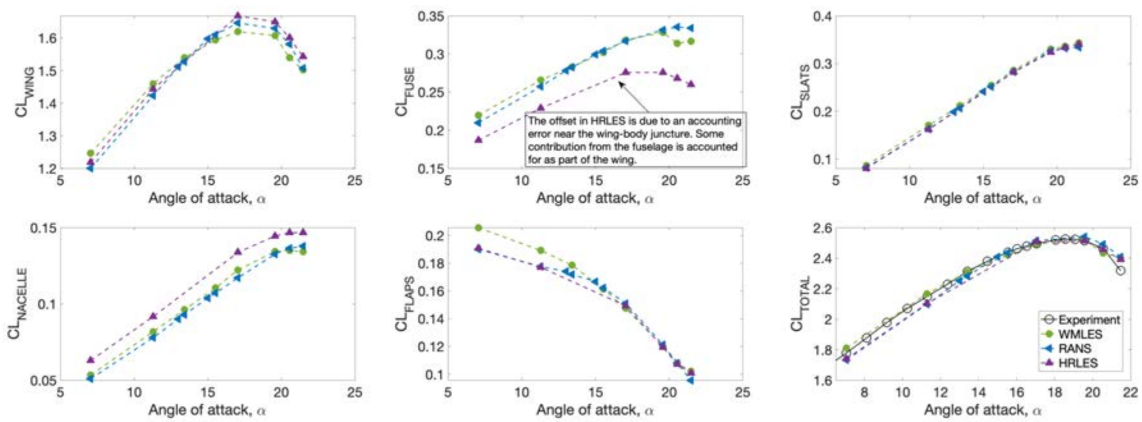
Comparison Between Methods (Free-Air)

$\alpha = 19.57^\circ$

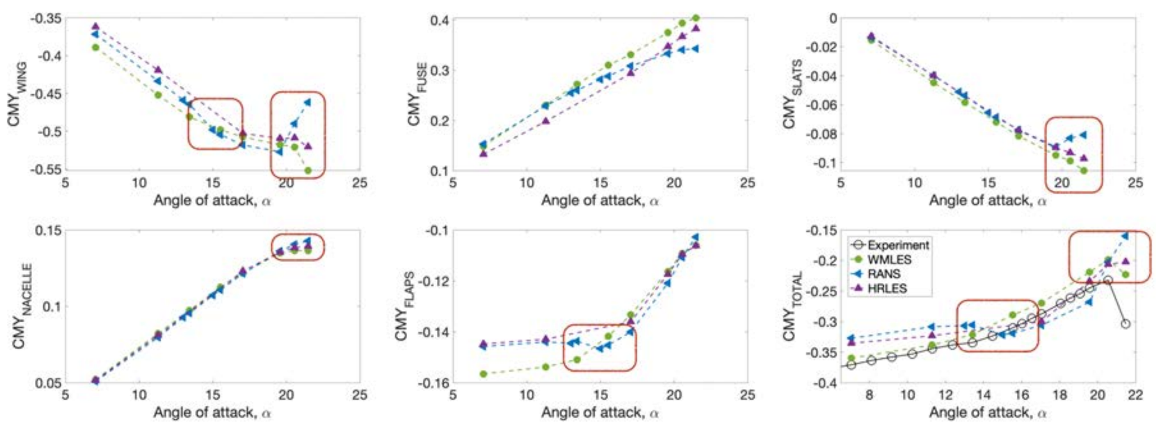
$\alpha = 21.47^\circ$



Comparison Between Methods (Free-Air)



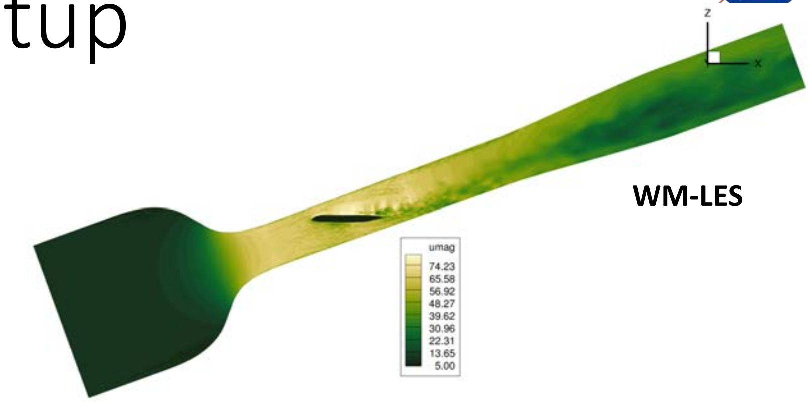
(a) Lift coefficient



(b) Pitching moment coefficient

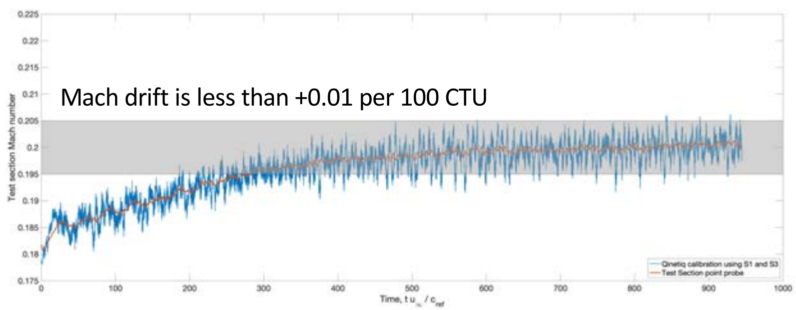
- Both WMLES and HRLES predict a high-alpha pitch break in the wing-integrated moments
- RANS predicts an opposite high-alpha break due to onset of large-scale spurious outboard separation
- The low-alpha pitch break seem to occur due to sudden loss-of-lift on the flaps; WMLES appears to predict the correct trend, but RANS shows abnormal behavior
- All methods clearly over-predict lift after CLmax is reached

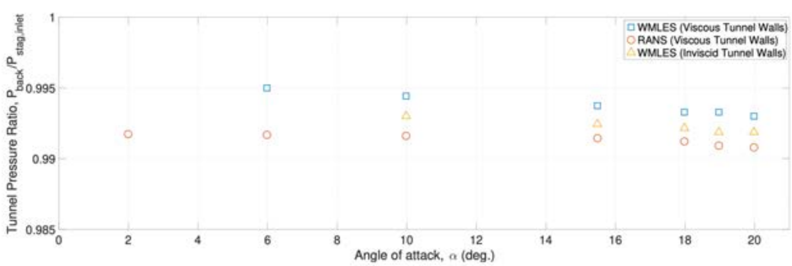
Tunnel – initialization and setup

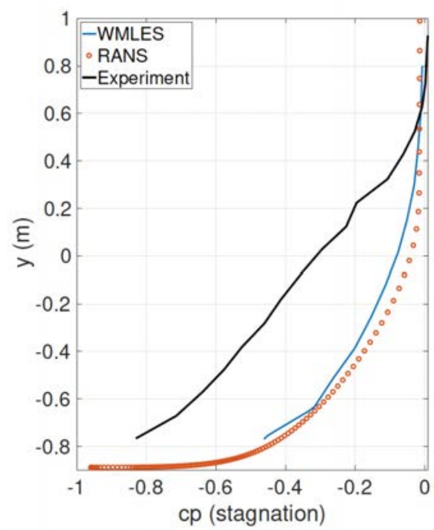


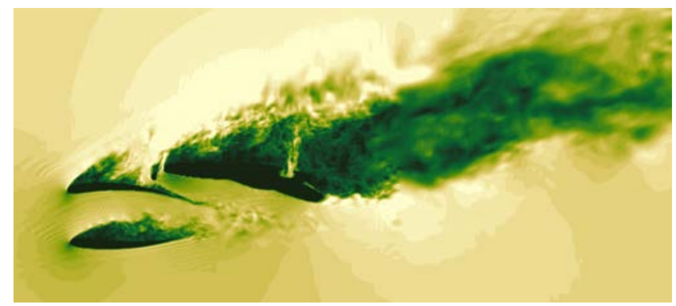
Two precursor simulations: WM-RANS + WM-LES (coarse)

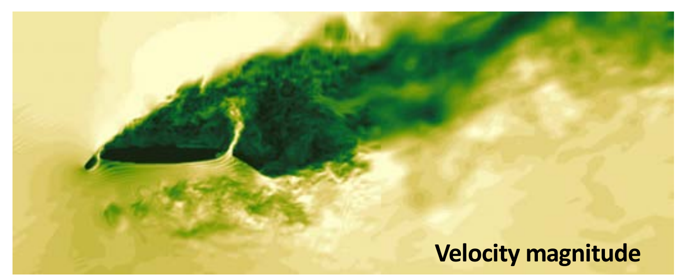
- "Coarse-representation" of model geometry to capture blocking effect
- Full grid is approximately 77M compute points; time step is 25x larger than GridB WMLES
- Roughness treatment used in upstream convergent section to "thicken" test section BL
- Fixed back-pressure (obtained from WM-RANS, with BL calibration)
- Precursor computational costs are approx. 10% that of a 50-CTU gridB simulation



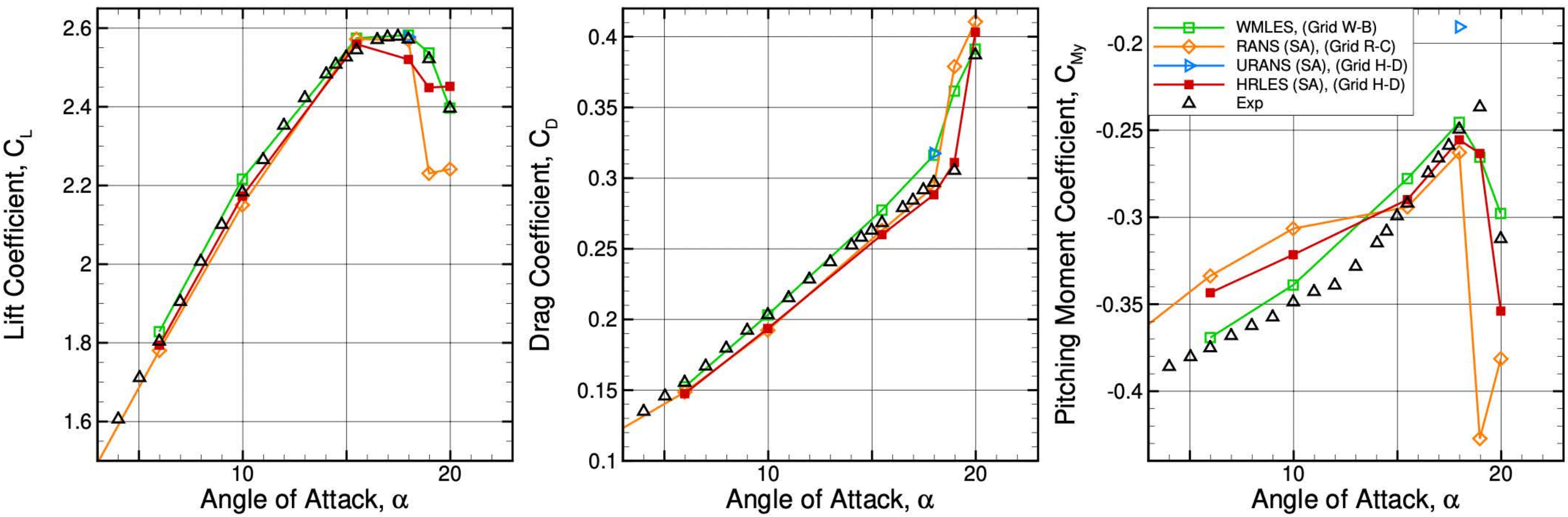




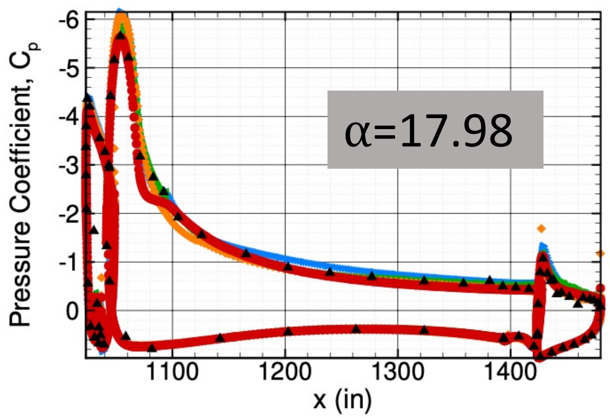




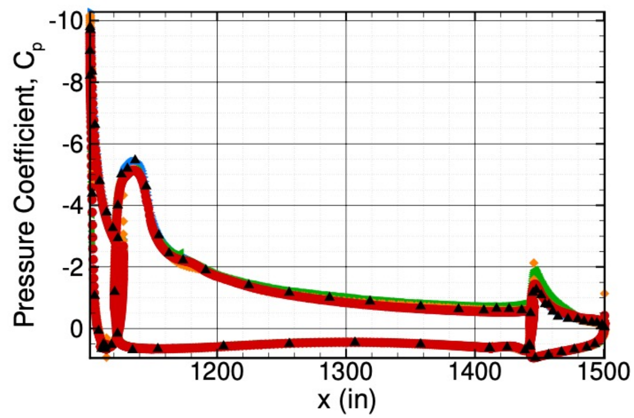
Tunnel – Loads compared with experiment



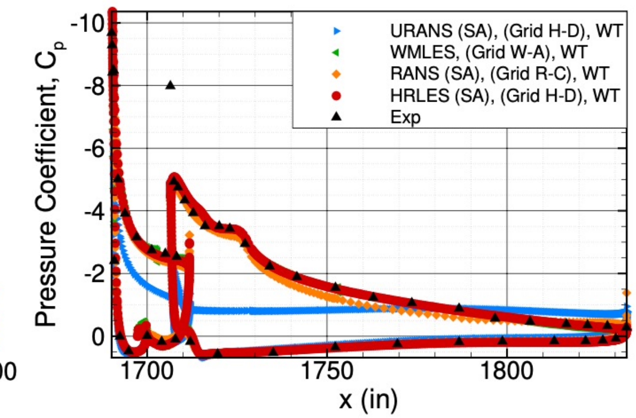
Surface Pressure, Cp – WT



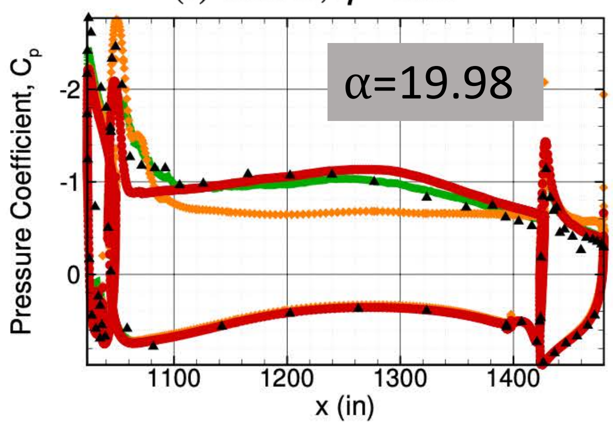
(a) Slice A, $\eta = 0.15$



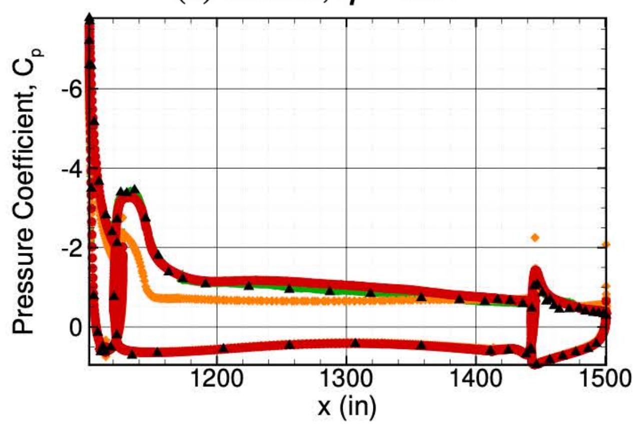
(b) Slice B, $\eta = 0.24$



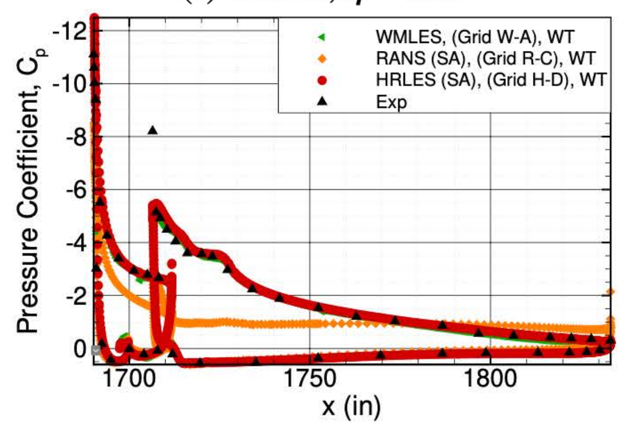
(c) Slice H, $\eta = 0.91$



(a) Slice A, $\eta = 0.15$



(b) Slice B, $\eta = 0.24$

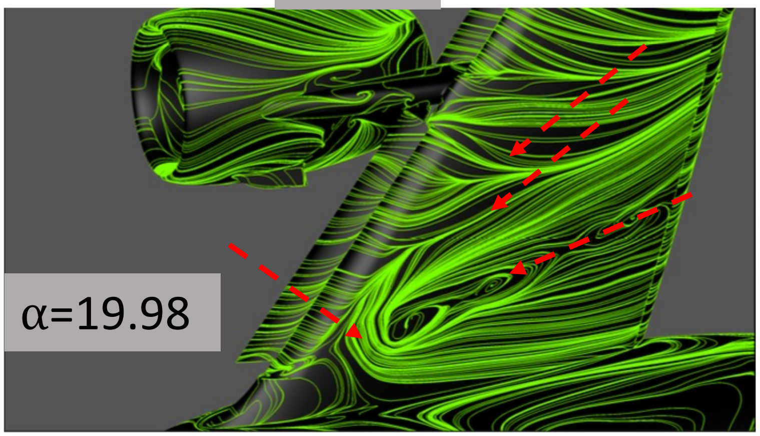


(c) Slice H, $\eta = 0.91$

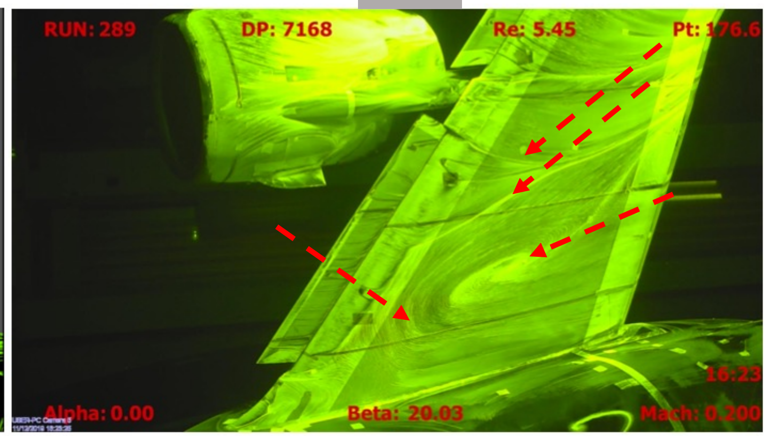
Streamline HRLES/RANS vs Oil-Flow Comparison – WT

HRLES

WT

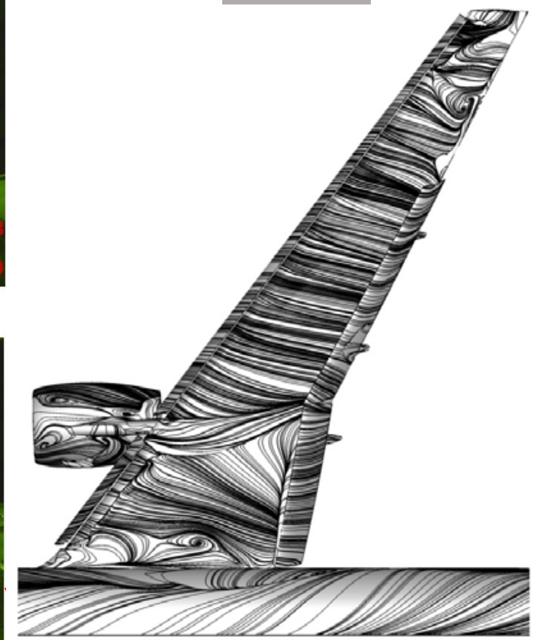


(a) HRLES

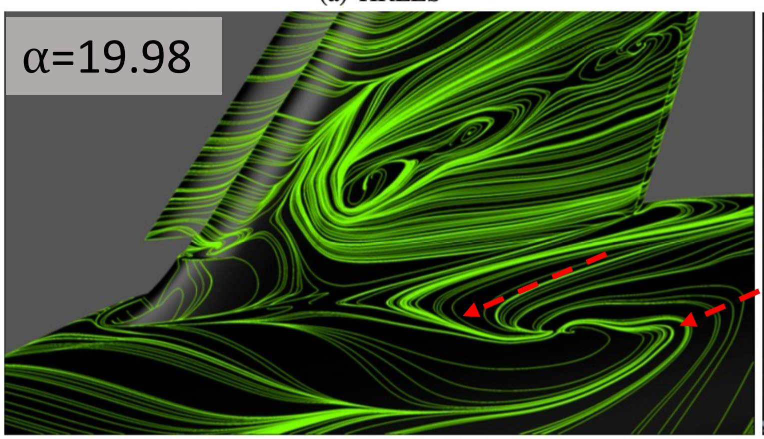


(b) Oil Flow

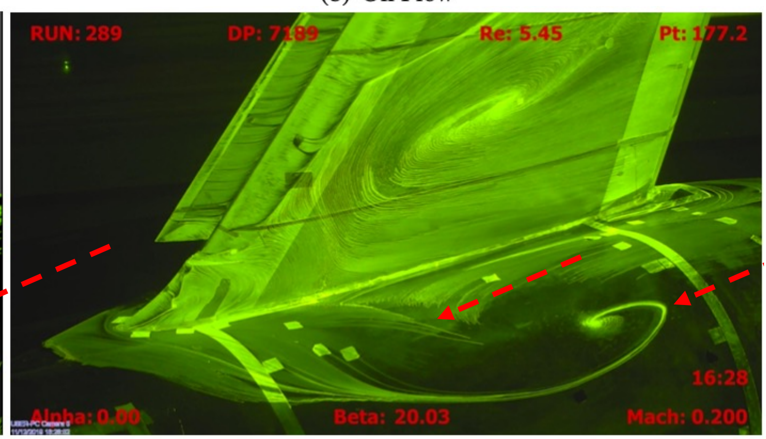
RANS



(d) RANS (SA), α = 19.98°

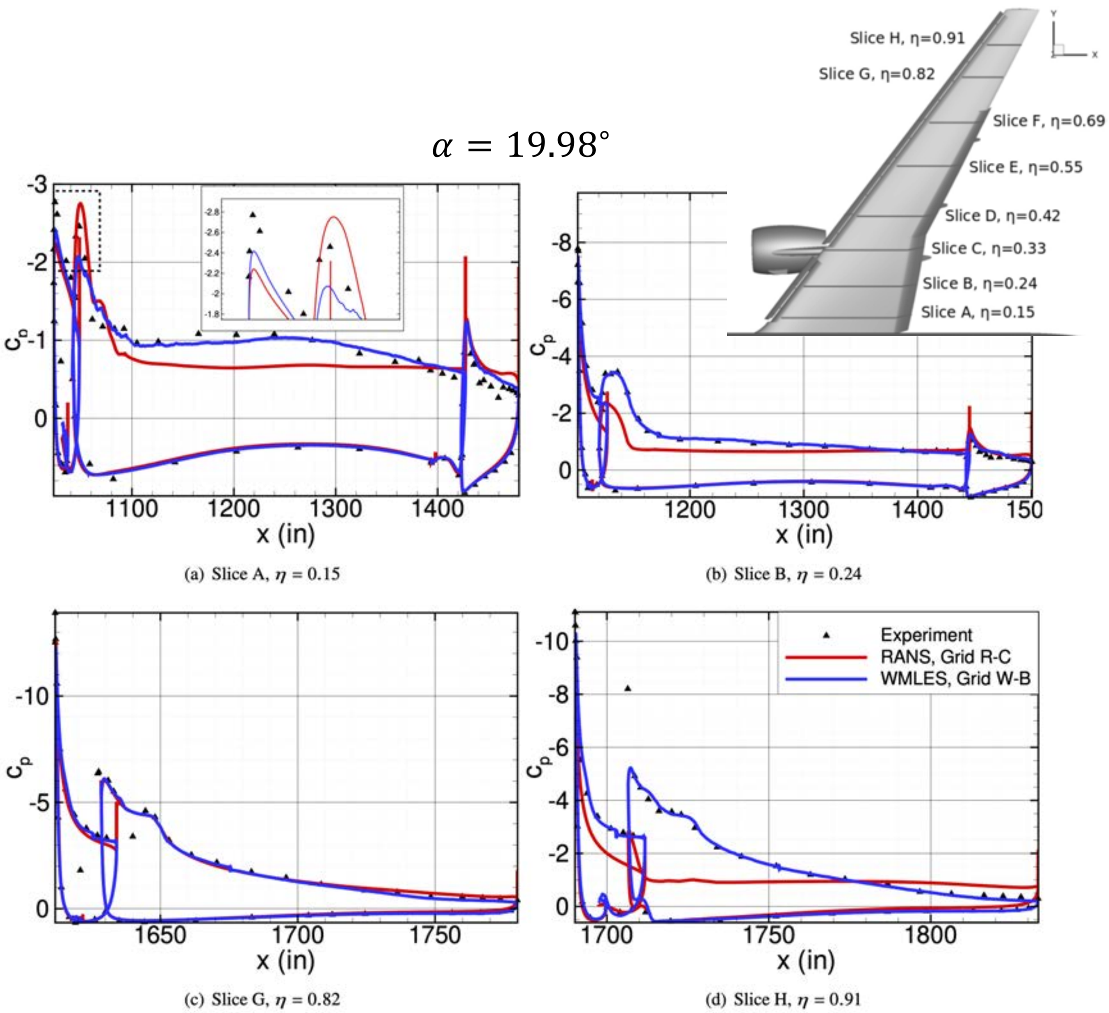


(a) HRLES



(b) Oil Flow

Streamline WMLES/RANS vs Oil-Flow Comparison – WT

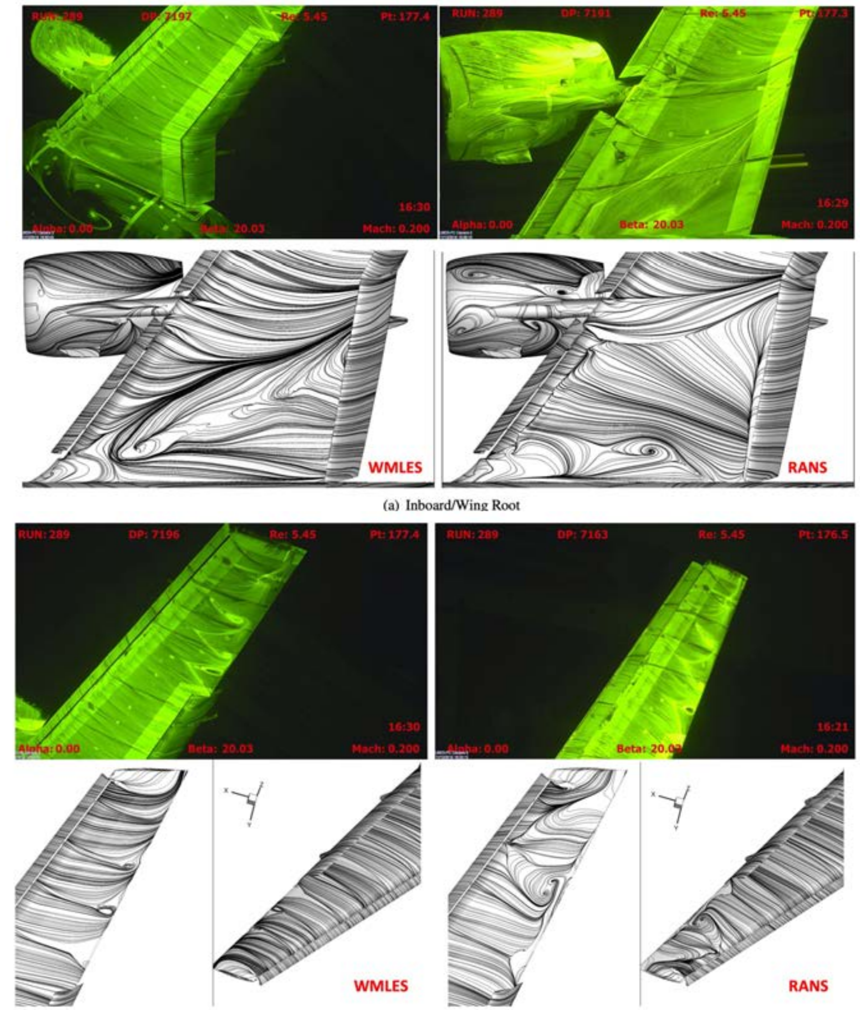


(a) Slice A, $\eta = 0.15$

(b) Slice B, $\eta = 0.24$

(c) Slice G, $\eta = 0.82$

(d) Slice H, $\eta = 0.91$



(a) Inboard/Wing Root

(b) Outboard Wing

Oil flow images https://hiliftpw.larc.nasa.gov

Cost – Are scale resolving methods competitive?

Attribute	Simulation Methodology: RANS (Steady) Grid R-C	RANS (Steady) Grid R-D	RANS (Unsteady) Grid R-C	HRLES Grid H-A	WMLES Grid W-B
Solve Points	223M	550M	223M	571M	360M
Timestep size	-	-	$2.57 \times 10^{-3}s$	$2.0 \times 10^{-4}s$	$3.5 \times 10^{-6}s$
Nodes used for benchmark	35 Skylakes (40 cores/node)	100 Broadwells (28 cores/node)	70 Broadwells (28 cores/node)	200 Skylakes (40 cores/node)	100 AMD Romes (128 cores/node)
Core-time per compute point per timestep	-	-	$354.36\mu s$	$139.5\mu s$	$2.03\mu s$
Timesteps per CTU	-	-	40	514	29338
Core-time per CTU	-	-	901 hours	11360 hours	5970 hours
Simulation time needed for $\alpha = 19.57°$	-	-	150 CTU	50 CTU	50 CTU
Core-time needed for $\alpha = 19.57°$	21,000 hours	44,800 hours	135,150 hours	560,000 hours	298,500 hours
NAS SBUs needed for $\alpha = 19.57°$	**835**	**1,600**	**3,560**	**22,120**	**9,470**
Relative Cost over typical RANS	**1.0**	**1.9**	**4.25**	**26.4**	**11.3**

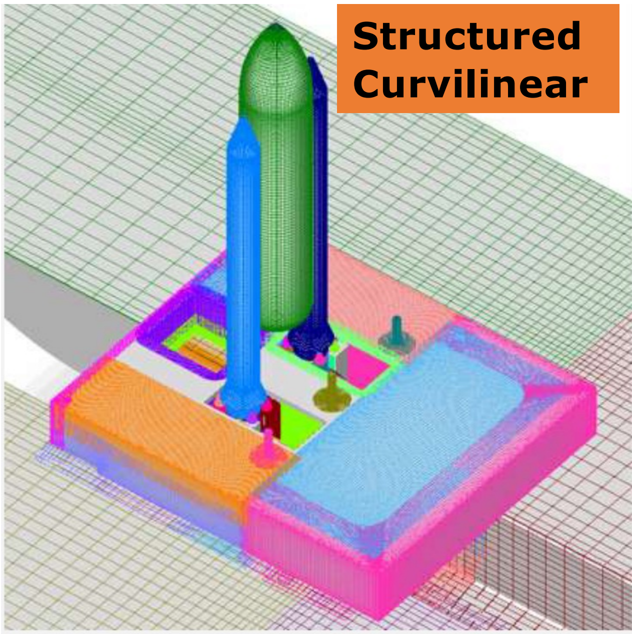
Summary from Turbulence Closure Studies

- **Shortcomings of RANS for CLmax**
  - Drag polar is accurate at low-angles of attack, but abnormal trends observed in pitching moments – possible incorrect flow topologies on flaps?
  - At C_{Lmax} – strong sensitivity to both grid (on the outboard wing) and SA model corrections (inboard wing) seen
  - In-tunnel simulations show excess inboard and outboard separation inconsistent with oil-flow and CP data from experiments
- **Does HRLES mitigate challenges of RANS?**
  - HRLES does show measurable improvements over RANS near C_{Lmax} in terms of improved outboard flow-topologies and pitching moment predictions in both the free air and wind tunnel configuration,
  - Improvements over RANS only achieved when an LES-appropriate grid and an LES-appropriate discretization is utilized
  - Sensitivity is also reported for time-step size post C_{Lmax} with excessively large time steps resulting in unphysical wing-root separation in the free-air
- **Is WMLES suitable for C_{Lmax} problems?**
  - WMLES offers substantial benefits over RANS in terms of a) Robustness (low sensitivity to parameters), b) Cost (competitive turn-around time) and c) Accuracy (both flow physics and engineering metrics)
  - Acceptable grid convergence is in CP and aerodynamic loading is observed at most angles, although: CMY shows sensitivity at both the highest and the lowest angles
- **Can free-air simulations reproduce the stall physics observed in the tunnel experiments?**
  - Both HRLES and WMLES show corner-flow separation in free-air but both predict a much weaker pitch break going from C_{Lmax} to the stall state.
  - WMLES in-tunnel simulations show quite accurate predictions of pitch break with both wing root and outboard flow topologies showing promising agreement with experiment.
  - WMLES with slip-wall treatment for the tunnel side-walls highlight potential sensitivity of the post C_{Lmax} stall onset phenomenon to the tunnel side-wall boundary layers
- **Future directions (will be addressed at Aviation 2022):**
  - Issues associated with thin leading edge boundary layers are the likely culprits with the WMLES problems. Further investigations will be performed.
  - Installations effects involving a) tunnel blockage, b) standoff/mount and c) side-wall boundary layers need to be investigated further using WMLES.
  - Further grid refinement studies in HRLES will be performed
  - Scalability in grid generation needs to be addressed: Use of octree-immersed boundary treatments for WMLES

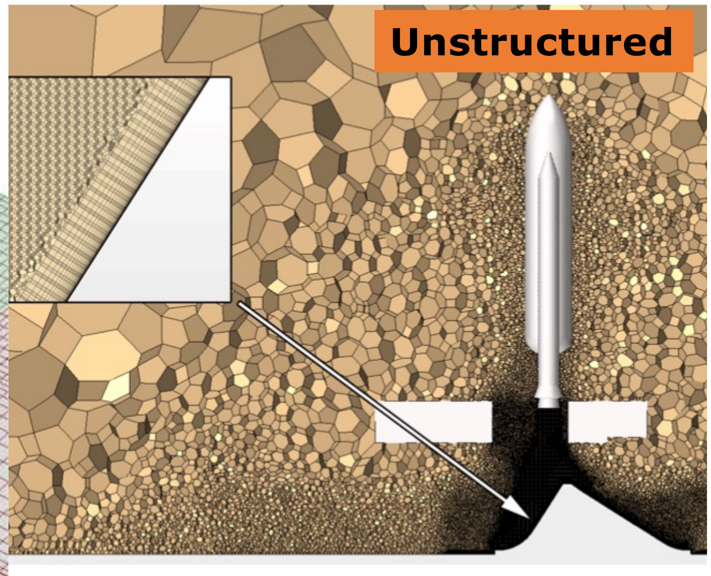
Summary from Turbulence Closure Studies

- **Shortcomings of RANS for CLmax**
  - Drag polar is accurate at low-angles of attack, but abnormal trends observed in pitching moments – possible incorrect flow topologies on flaps?
  - At C_{Lmax} – strong sensitivity to both grid (on the outboard wing) and SA model corrections (inboard wing) seen
  - In-tunnel simulations show excess inboard and outboard separation inconsistent with oil-flow and CP data from experiments
- **Does HRLES mitigate challenges of RANS?**
  - HRLES does show measurable improvements over RANS near C_{Lmax} in terms of improved outboard flow-topologies and pitching moment predictions in both the free air and wind tunnel configuration,
  - Improvements over RANS only achieved when an LES-appropriate grid and an LES-appropriate discretization is utilized
  - Sensitivity is also reported for time-step size post C_{Lmax} with excessively large time steps resulting in unphysical wing-root separation in the free-air
- **Is WMLES suitable for C_{Lmax} problems?**
  - WMLES offers substantial benefits over RANS in terms of a) Robustness (low sensitivity to parameters), b) Cost (competitive turn-around time) and c) Accuracy (both flow physics and engineering metrics)
  - Acceptable grid convergence is in CP and aerodynamic loading is observed at most angles, although: CMY shows sensitivity at both the highest and the lowest angles
- **Can free-air simulations reproduce the stall physics observed in the tunnel experiments?**
  - Both HRLES and WMLES show corner-flow separation in free-air but both predict a much weaker pitch break going from C_{Lmax} to the stall state.
  - WMLES in-tunnel simulations show quite accurate predictions of pitch break with both wing root and outboard flow topologies showing promising agreement with experiment.
  - WMLES with slip-wall treatment for the tunnel side-walls highlight potential sensitivity of the post C_{Lmax} stall onset phenomenon to the tunnel side-wall boundary layers
- **Future directions (will be addressed at Aviation 2022):**
  - Issues associated with thin leading edge boundary layers are the likely culprits with the WMLES problems. Further investigations will be performed.
  - Installations effects involving a) tunnel blockage, b) standoff/mount and c) side-wall boundary layers need to be investigated further using WMLES.
  - Further grid refinement studies in HRLES will be performed
  - Scalability in grid generation needs to be addressed: Use of octree-immersed boundary treatments for WMLES (NEXT STEP)

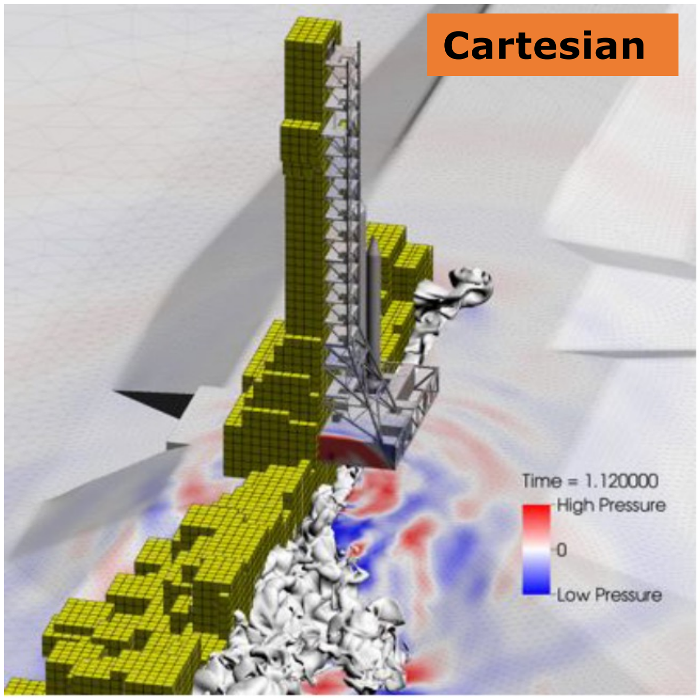
CFD Grid Paradigms



- Logically rectangular grids are efficient, high-order methods common
- Grid generation usually labor intensive, judging grid quality may require expertise



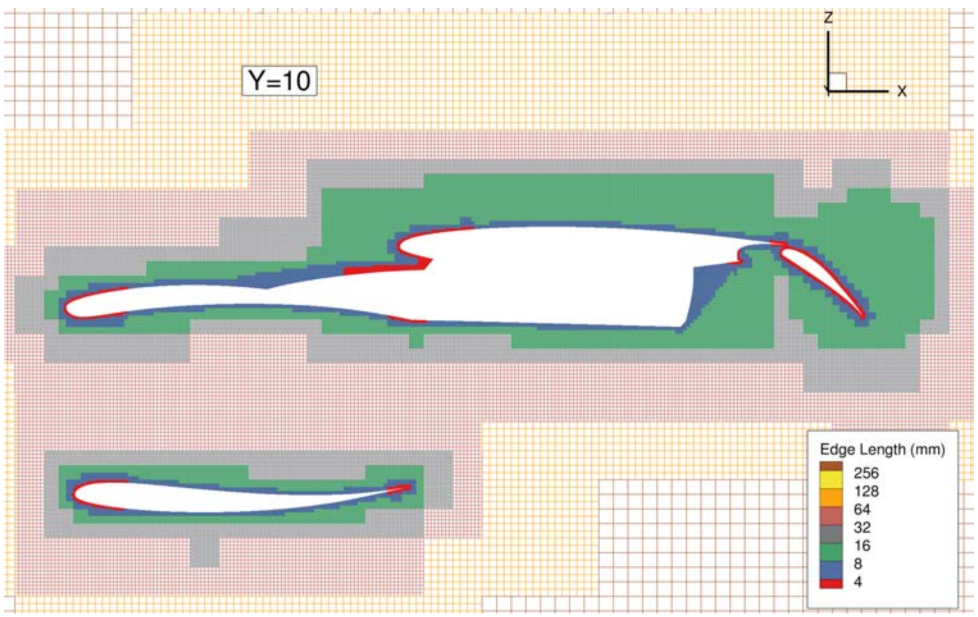
- Robust grid generation for complex geometry
- High-order methods non-trivial, computationally expensive

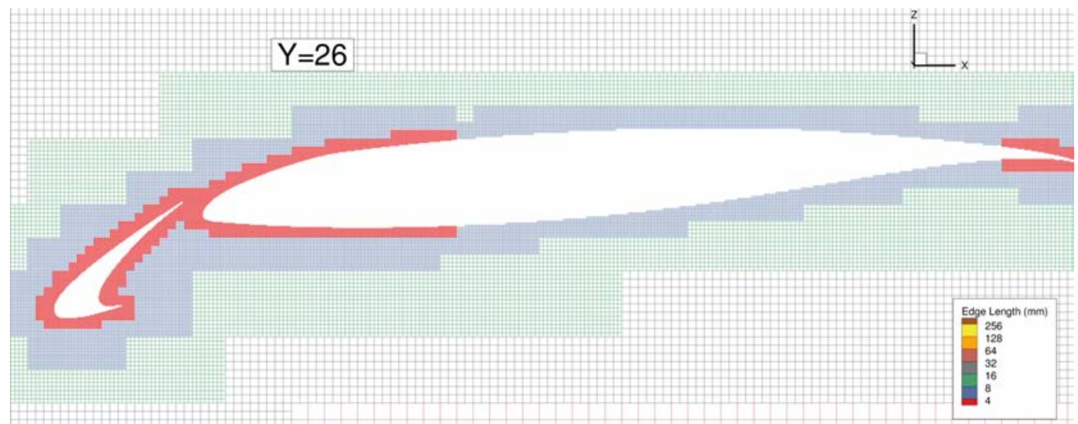


- Automatic volume grid generation
- High-order methods are efficient and mature
- Isotropic grid cells nonideal for boundary layer resolution
- Wall Modeling is a key

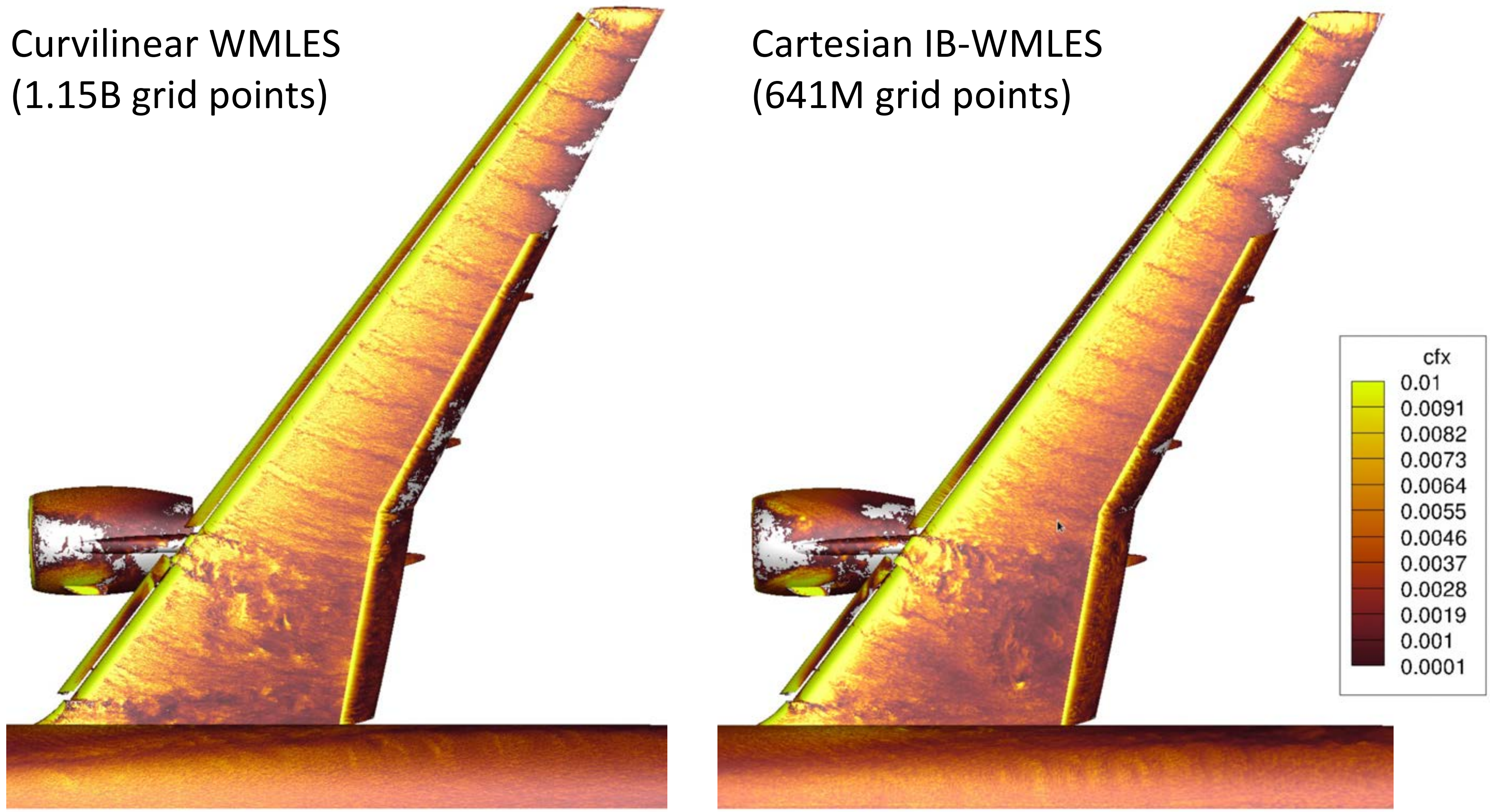
Cartesian Mesh Dramatically Reduces Mesh Generation Time

- Surface mesh triangulation (ANSA): 3 hours
- Manual specification of surface/volume refinement regions : 2 hours
- Volume Mesh (1 Skylake node) : 1.25 min
- Fast-turn around enables interactive specification of refinement regions and criteria (next page)
- Approximately 600 million compute nodes (minimum grid spacing is 4mm)
- Volume refinement regions to capture side-of-body vortex, chine vortex, tip vortex and flap wakes

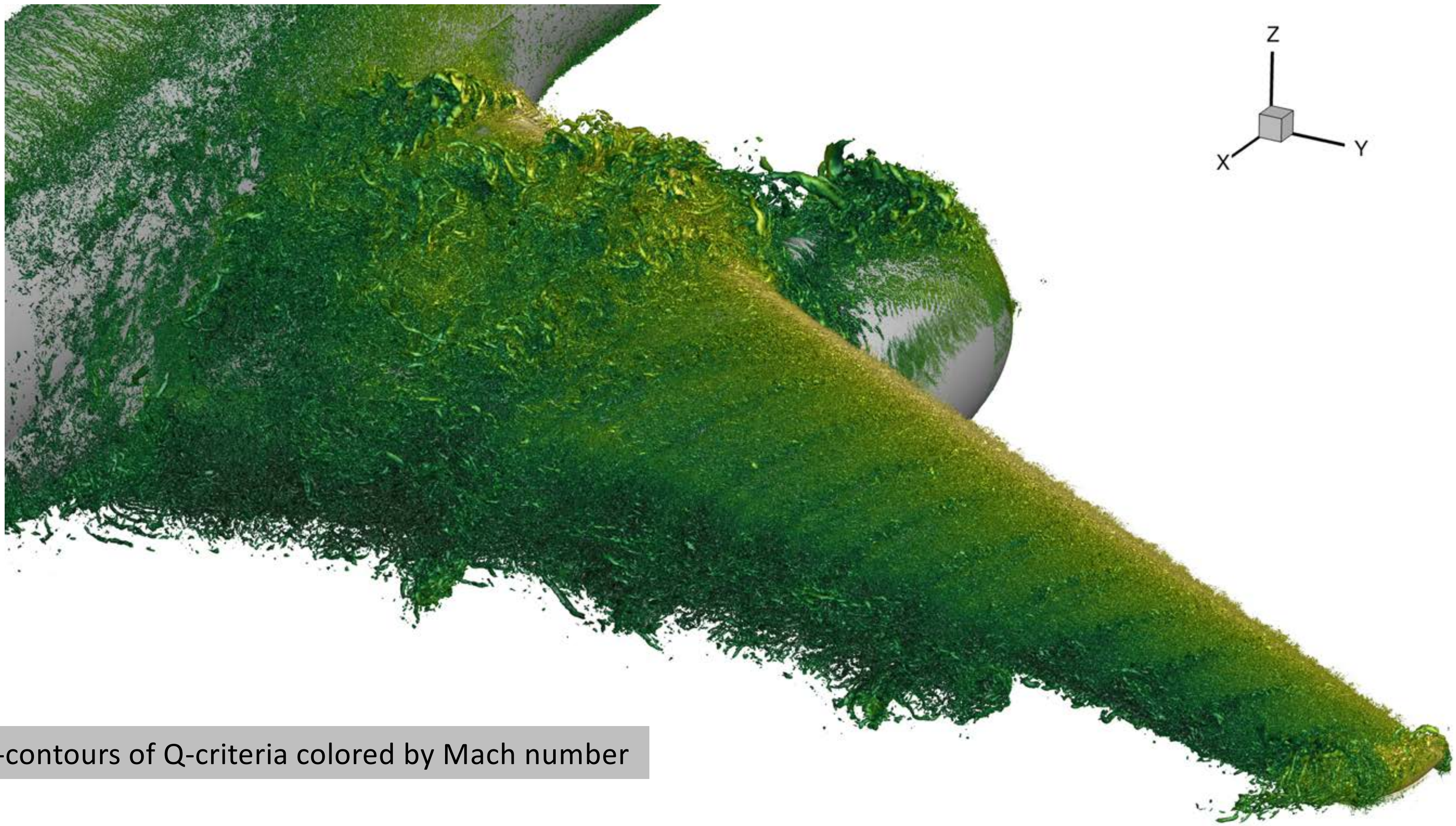




Instantaneous surface skin friction (c_{f_x}) at CLmax ($\alpha = \mathbf{19.57}°$)



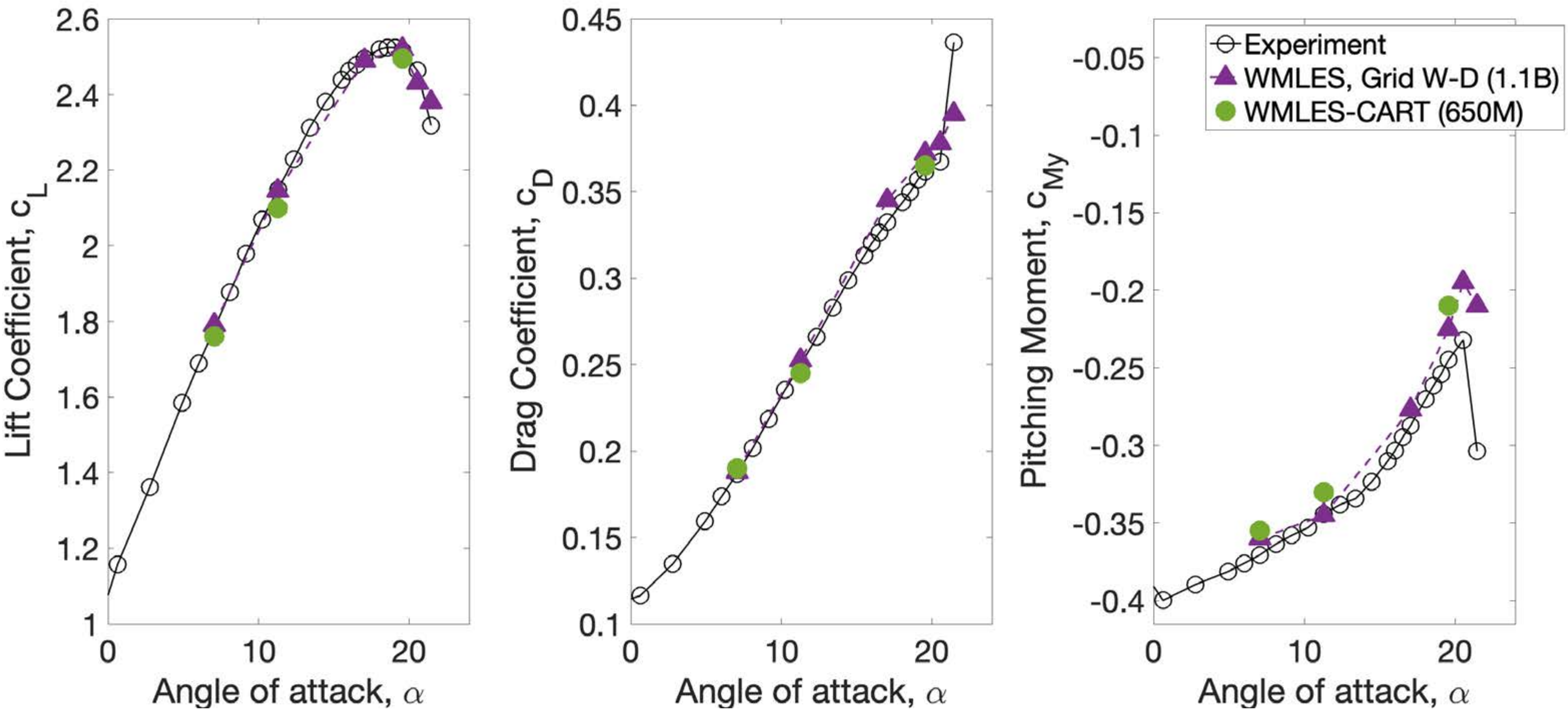
Flow Visualization for Free-Air case at CLmax ($\boldsymbol{\alpha = 19.57°}$)



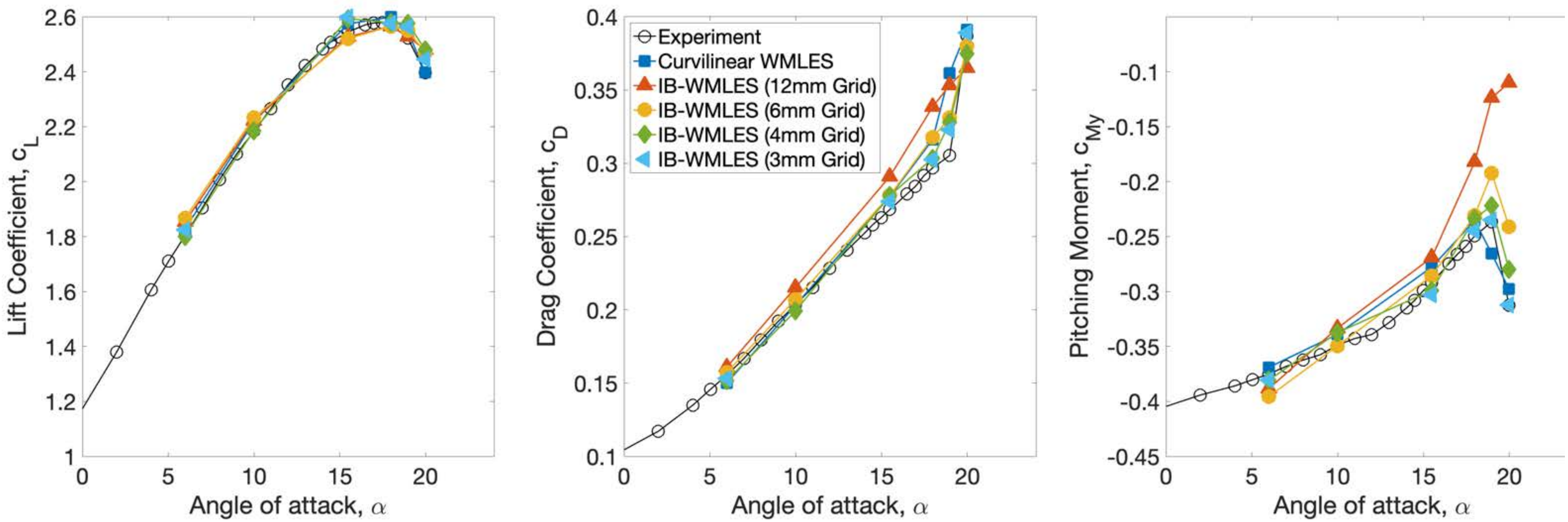
Iso-contours of Q-criteria colored by Mach number

Cartesian WMLES Loads

Comparison with curvilinear WMLES (Free-Air)



Loads – LAVA Cartesian WMLES (Wind Tunnel Installed)



Curvilinear WMLES	571 M
IB-WMLES (12mm Grid)	110 M
IB-WMLES (6mm Grid)	400M
IB-WMLES (4mm Grid)	1.1 B
IB-WMLES (3mm Grid)	2.25 N

Cost and Timing Comparisons – Computational performance

Attribute	Simulation Methodology				
	RANS (Steady) Grid R-C	RANS (Steady) Grid R-D	WMLES Grid W-B	HRLES Grid H-A	CART-WMLES Grid C-A
Solve Points	223M	550M	360M	571M	641M
Timestep size	-	-	$3.5 \times 10^{-6} s$	$2.0 \times 10^{-4} s$	$4.4 \times 10^{-6} s$
Nodes used for benchmark	35 Skylakes (40 cores/node)	100 Broadwells (28 cores/node)	100 AMD Romes (128 cores/node)	200 Skylakes (40 cores/node)	70 Skylakes (40 cores/node)
Core-time per compute point per timestep	-	-	$2.03\mu s$	$139.5\mu s$	$0.91\mu s$
Timesteps per CTU	-	-	29,338	514	23,321
Core-time per CTU	-	-	5970 hours	11360 hours	3780 hours
Simulation time needed for $\alpha = 19.57°$	-	-	50 CTU	50 CTU	50 CTU
Core-time needed for $\alpha = 19.57°$	21,000 hours	44,800 hours	298,500 hours	560,000 hours	189,000 hours
NAS SBUs needed for $\alpha = 19.57°$	**835**	**1,600**	**9,470**	**22,120**	**7,604**
Relative Cost over typical RANS	**1.0/0.52**	**1.91/1.0**	**11.3 / 5.9**	**26.4 / 13.8**	**9.1 / 4.7**
Grid Generation (Human Effort)	**2-4 months**	**2-4 months**	**2-4 months**	**2-4 months**	**4-6 hours**

Isotropy requires more grid points

Better quality grid leads to larger time-step

Much more efficient algorithm

Slightly cheaper than curvilinear

5 – 10x more expensive than RANS

Negligible human effort for cartesian octree grids (scalable process)

Cartesian WMLES (miniapp) on GPUs

- Miniapp that replicates the main computational kernel accounting for 66% of runtime
- Directive-based OpenMP/OpenACC approaches do not give adequate performance
- CUDA Fortran version is 1.5X more performant and code structure is closer to CPU version
- Relevant metrics:
  - MUPS: Millions of UPdates per Second → Higher is better
  - MUPS/W: MUPS per unit of Power → Higher is better
- A100 has 4X higher power efficiency than Skylake and 2.4X higher than Rome
- Significant fraction of peak FLOPS on all CPUs/GPUs → All implementations are well optimized

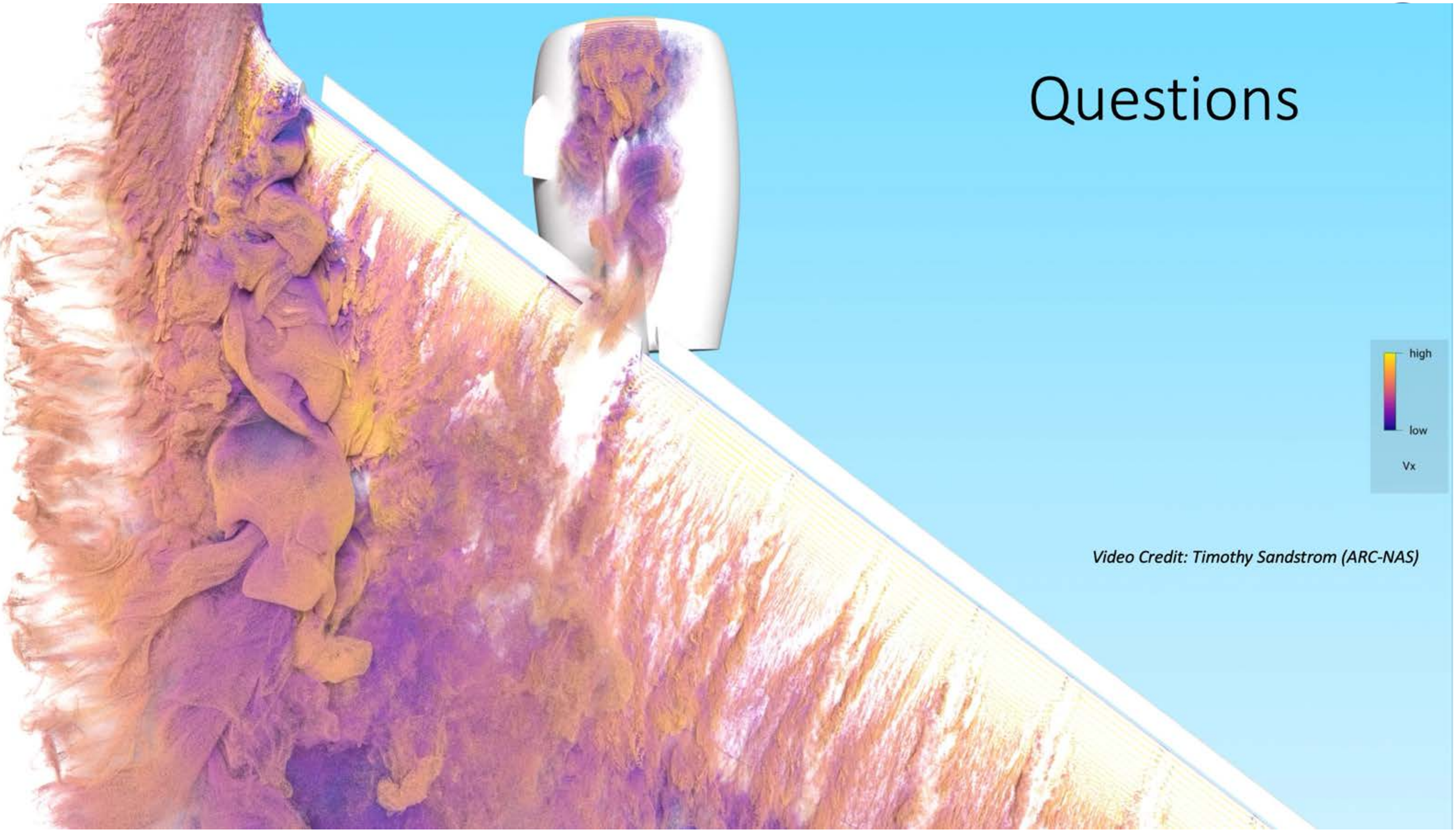
Architecture	Type	MUPS	Power, TDP (W)	MUPS/ W	Theoretical Peak DP Flops (TF)	Estimated Fraction of Configured Peak Achieved (%)
2x Intel Skylake 6148	CPU	103	300	0.34	3.1	22
2x AMD Rome 7742	CPU	254	450	0.56	4.6	34
1x Nvidia A100 (OpenACC)	GPU	360	400	0.90	7.5 (underclocked)	24
1x Nvidia A100 (CUDA)	GPU	540	400	1.35	7.5 (underclocked)	36

Acknowledgements

- This work was funded by NASA Aeronautics Research Mission Directorate's (ARMD) Transformational Tools and Technologies (T^3) project.
- Computer time has been provided by the NASA Advanced Supercomputing (NAS) facility at NASA Ames Research Center. A small subset of the simulations presented in the paper utilized NAS allocation on Amazon Web Services (AWS).

- Special thanks to
  - Chris Rumsey (NASA LaRC), Jeff Slotnick (Boeing), and Carolyn Woeber (Cadence) for their support during the AIAA HLPW4 activities.
  - The AIAA HLPW4 participants for valuable discussions.

Questions



Video Credit: Timothy Sandstrom (ARC-NAS)