



Advancements in Scale Resolving Simulations for Certification by Analysis

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NASA ARMD T³ Project Revolutionary Computational Aerosciences (RCA)

Technical Challenge for C_{Lmax} Prediction

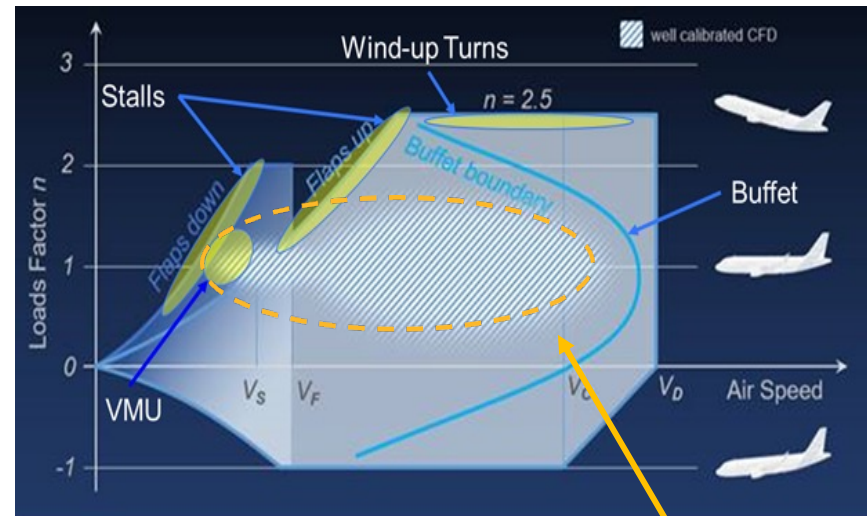


POC: Mujeeb Malik (NASA-LaRC)

RCA TC: “Develop and demonstrate computationally efficient, eddy-resolving modeling tools that predict maximum lift coefficient (C_{Lmax}) for transport aircraft with the same accuracy as certification flight tests.”

- High-Lift (HL) certification flight tests account for roughly 2/3 of flight certification test points
- 50% of HL flight tests replaced by computations would save hundreds of million dollars from aircraft development programs

- **ARMD:** Aeronautics Research Mission Directorate
- **T³:** Transformational Tools and Technologies

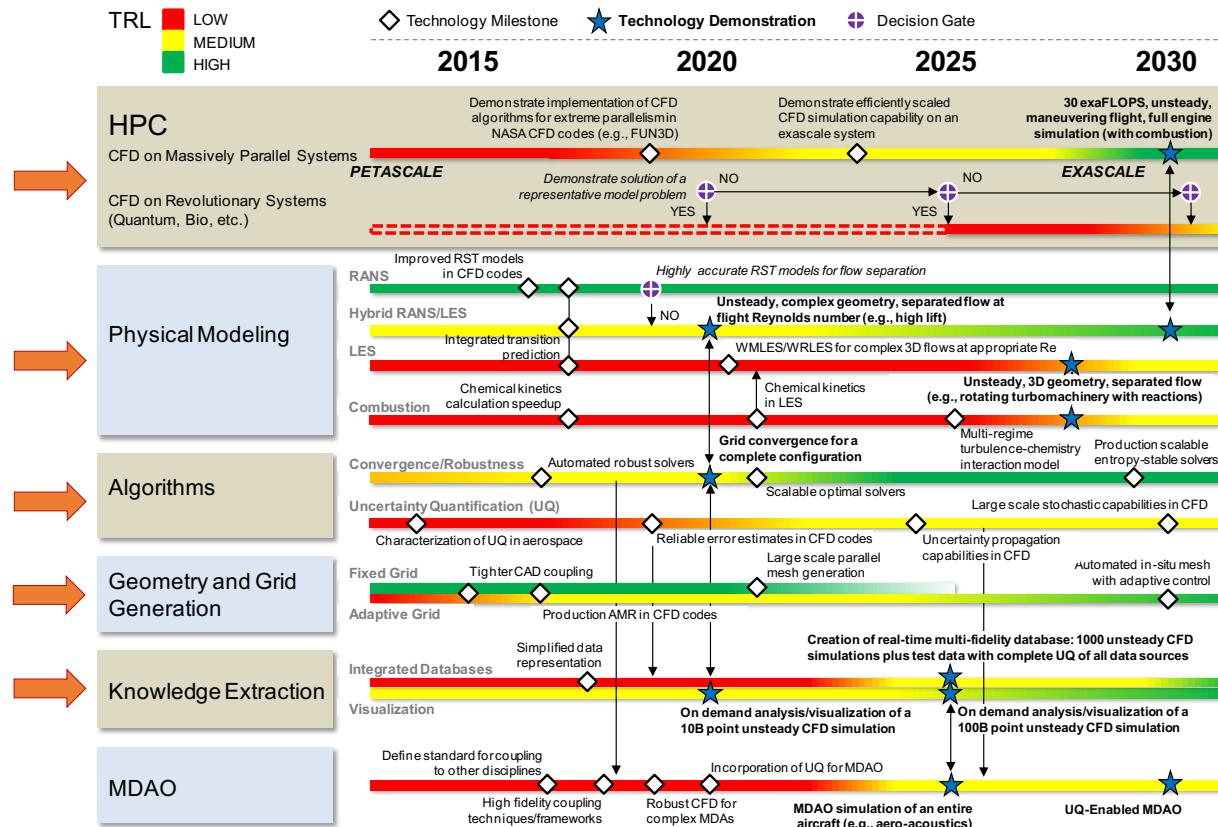


“Continued advances are required to address full-flight envelope predictions and propulsion system operating conditions, reduce design cost and cycle time, reduce ground and flight-testing, and enable product certification through analysis...”

Recommendation of CFD Vision 2030 Study

Limits of
current CFD

CFD 2030 Technology Development Roadmap

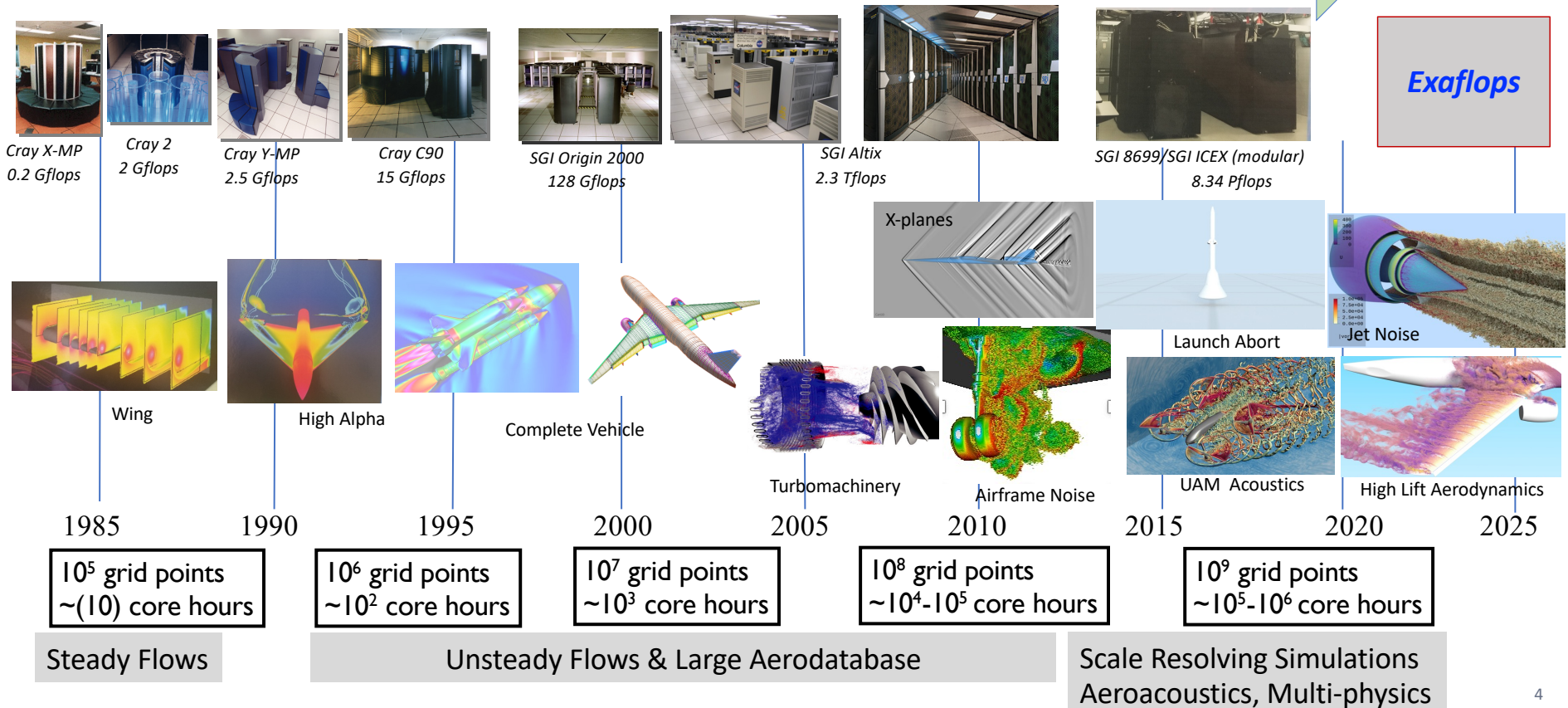


CFD Vision 2030 Study report published in 2014

Computational Aerosciences with HPC



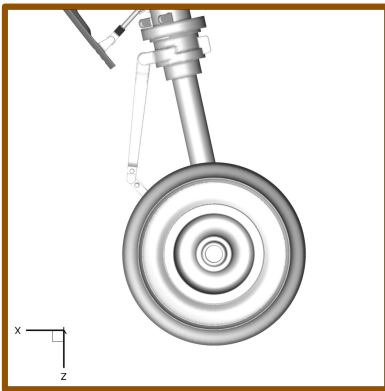
Exponential Growth of Compute Power



Computational Fluid Dynamics (CFD) Process

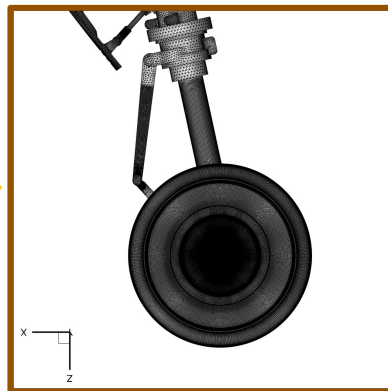


Geometry Definition



Meshing:

Split up space into mesh consisting of small cubes



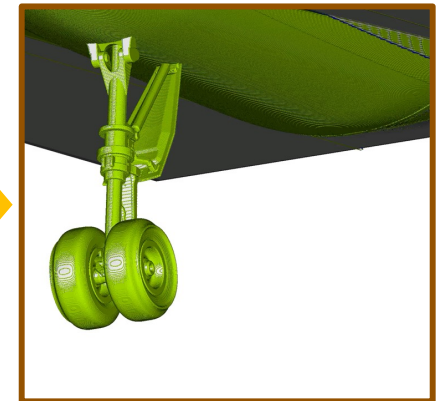
Solver:

Solve mathematical equations on small cubes (HPC)



Analysis:

Post-processing, big data, machine learning (ML)



- The success of the ML models in computational aerosciences
 - **Availability** of big data (parametric studies & space-time resolving datasets)
 - **Accuracy** of the CFD solutions
 - **Robustness** of the solution process
 - **Cost** of the simulations (labor and computations)

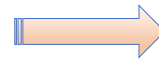


When is CFD Credible?

Verification

Reduce numerical error

- Grid paradigms and grid quality
- Grid resolution studies
- Effects of numerical dissipation
-



Validation

Reduce modeling error

- Turbulence closure
- Transition
- Multi-physics modeling
-

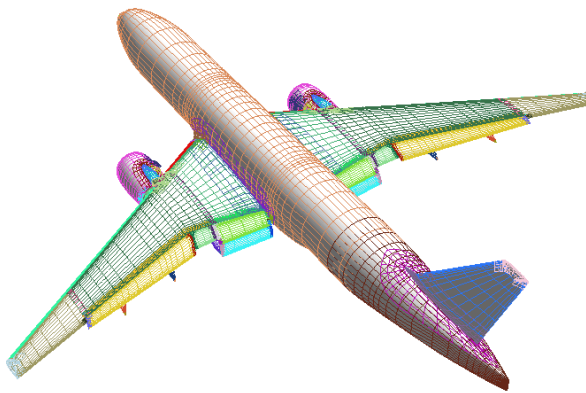
Reducing Numerical Error

Reducing Modeling Error



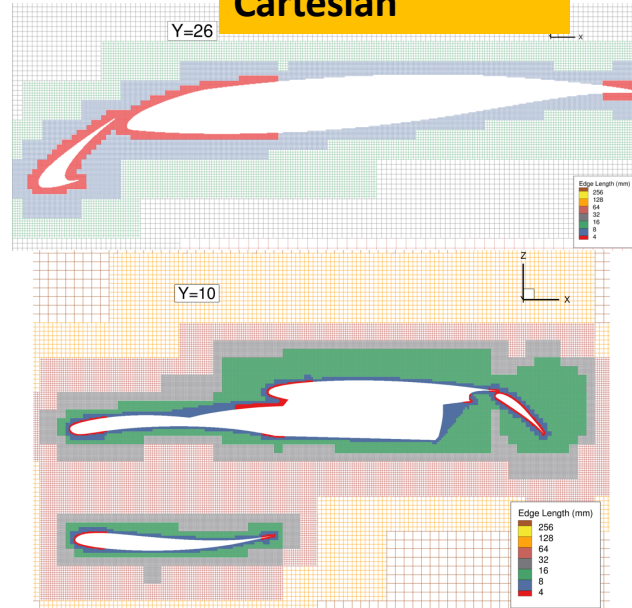
CFD Grid Paradigms

Structured Curvilinear



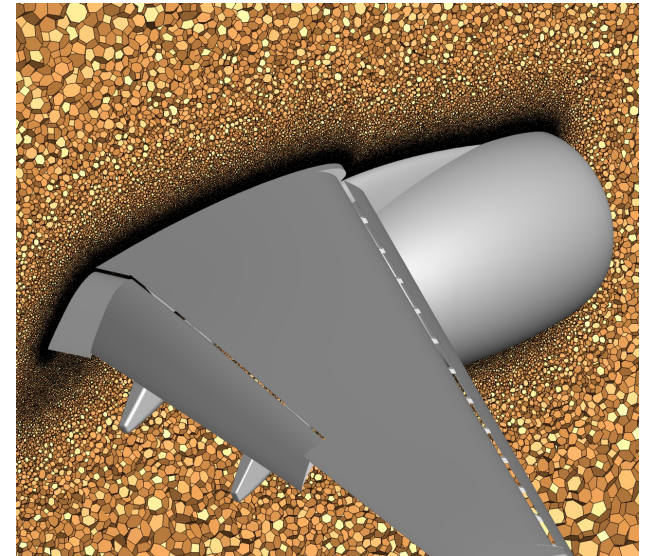
- High quality body fitted grids
- Low computational cost
- Reliable higher order methods
- Grid generation largely manual and time consuming

Cartesian



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

Unstructured

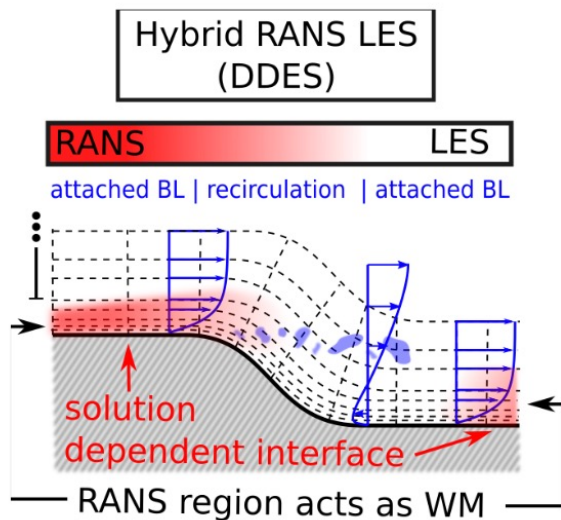


- Partially automated grid generation
- Body fitted grids
- Grid quality can be challenging
- High computational cost
- Higher order methods yet to fully mature

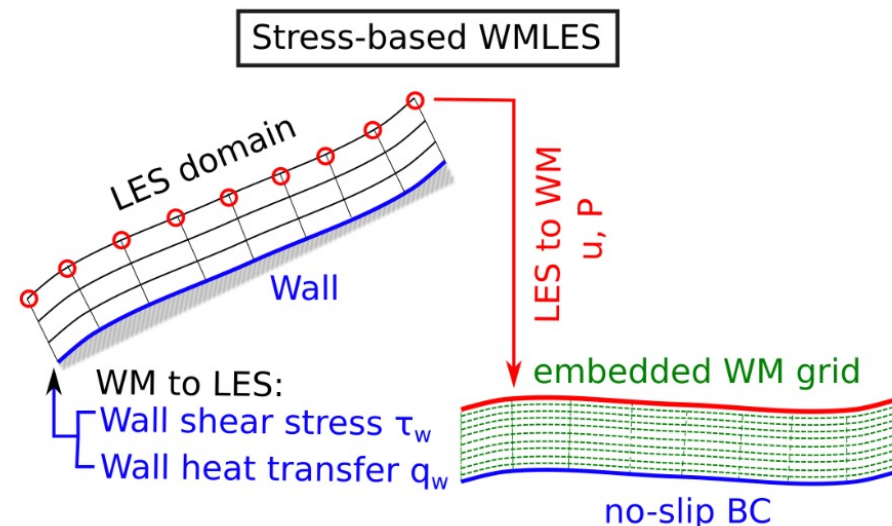
Turbulence Closure in Scale Resolving Simulations



- **Hybrid RANS Large Eddy Simulations (HRLES):** A scalar field, referred to as “shielding function” is computed as a function of the flow-solution (typically instantaneous solution) and other mesh-parameters (such as cell-size and aspect ratios) to detect a switch between LES and RANS closure models. Typical shielding functions are designed to keep the PDE in RANS state for attached flows and switch to an LES state in separated flows.



- **Equilibrium Wall-Modeled Large Eddy Simulations (WMLES):** Tangential gradients of pressure and convective stress are assumed to be in exact balance (instantaneously). This eliminates wall-parallel connectivity, and the wall-model can be posed as an ordinary differential equation in wall-normal coordinate exclusively. All participants used Equilibrium wall-modeling.





CFD Turbulence Closure Methods

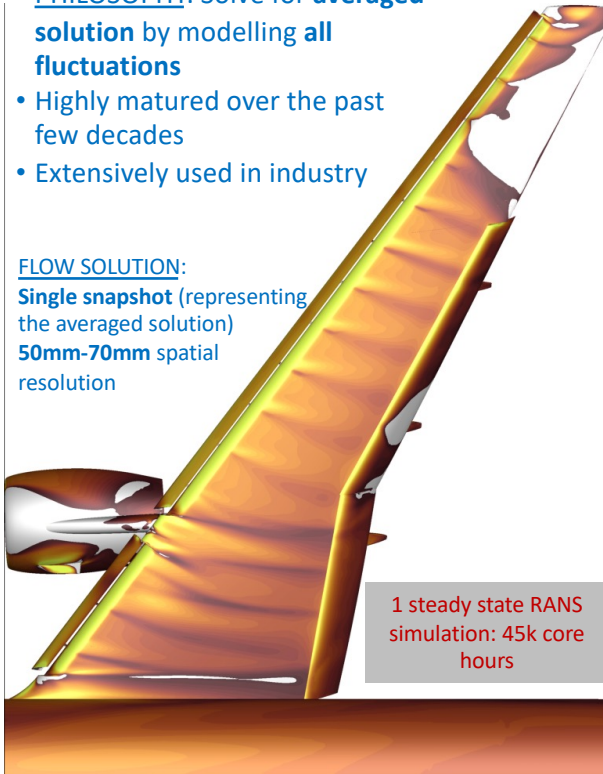
REYNOLDS AVERAGED NAVIER STOKES (RANS)

1980s - Present

- **PHILOSOPHY:** Solve for **averaged solution** by modelling **all fluctuations**
- Highly matured over the past few decades
- Extensively used in industry

FLOW SOLUTION:

Single snapshot (representing the averaged solution)
50mm-70mm spatial resolution



1 steady state RANS simulation: 45k core hours

DELAYED DETACHED EDDY SIMULATIONS (DDES)

1990s - Present

- **PHILOSOPHY:** **Model all fluctuations** except for those in **separated regions**
- Incremental changes requires to existing RANS tools
- High maturity level – very popular in industry

FLOW SOLUTION:

2E-4s of Temporal resolution
13mm-50mm of spatial resolution



Cost of 1 DDES = 13 RANS simulations

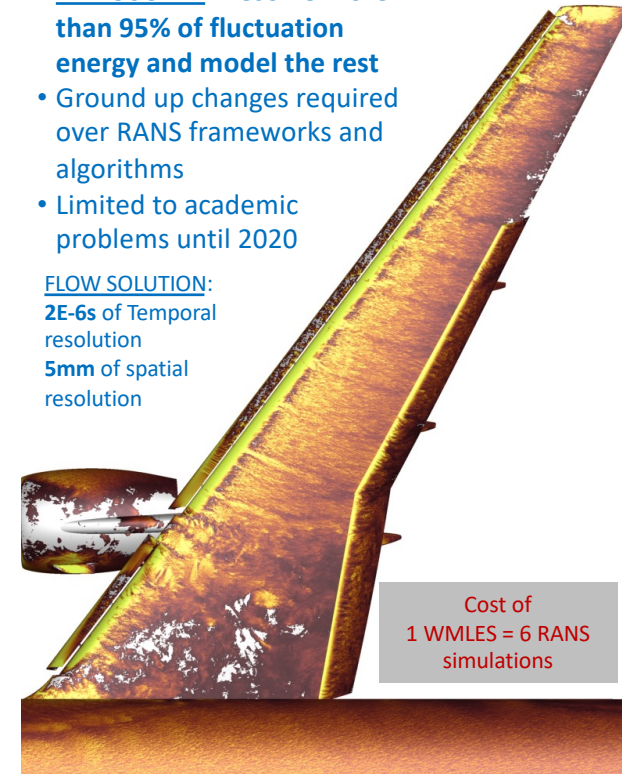
LARGE EDDY SIMULATIONS (WMLES)

2020 - Present

- **PHILOSOPHY:** **Resolve more than 95% of fluctuation energy and model the rest**
- Ground up changes required over RANS frameworks and algorithms
- Limited to academic problems until 2020

FLOW SOLUTION:

2E-6s of Temporal resolution
5mm of spatial resolution

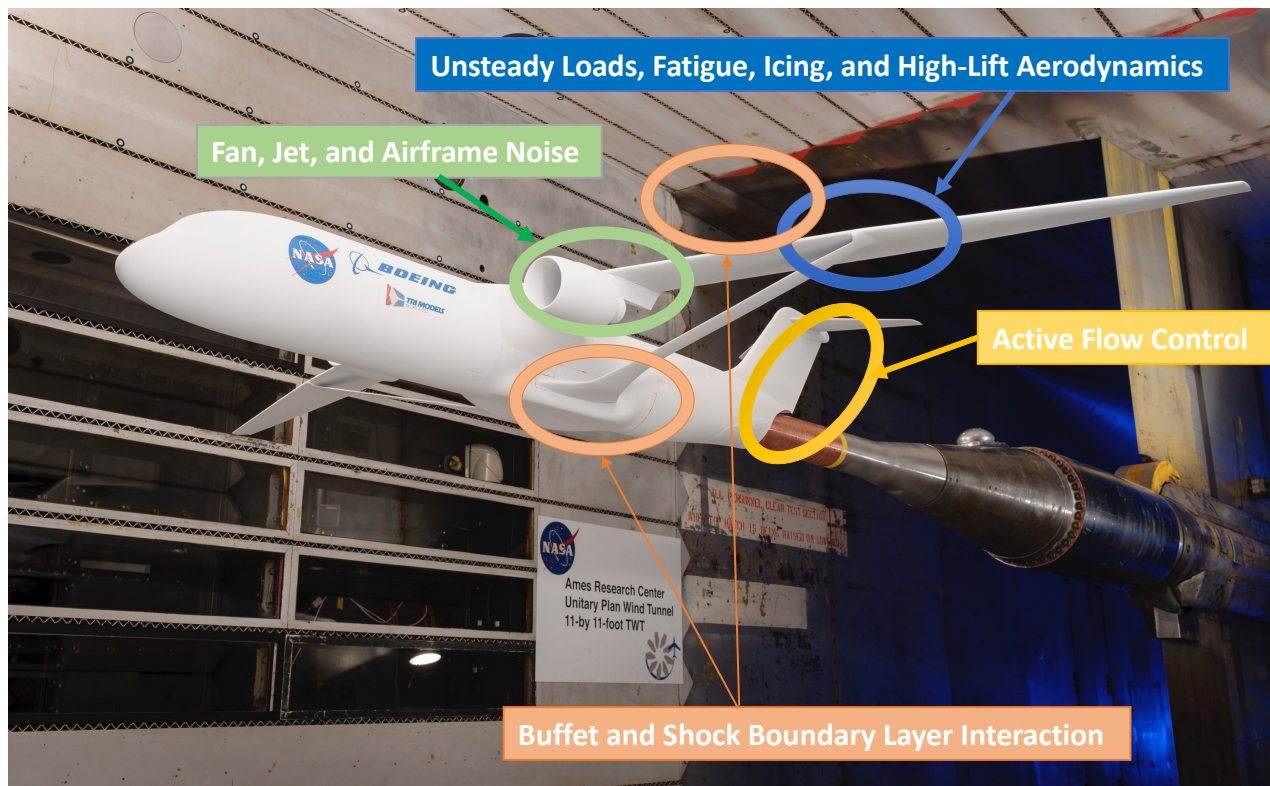


Cost of 1 WMLES = 6 RANS simulations

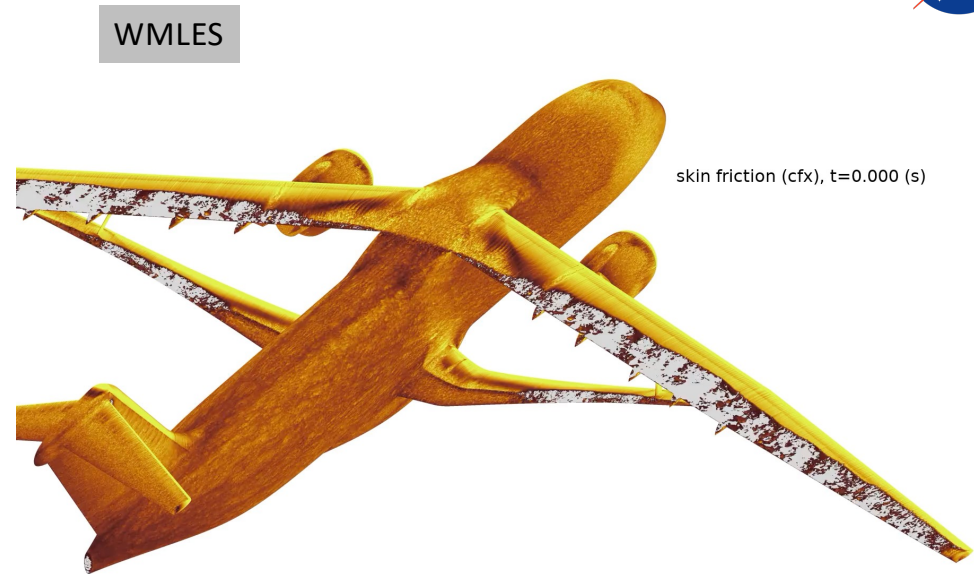
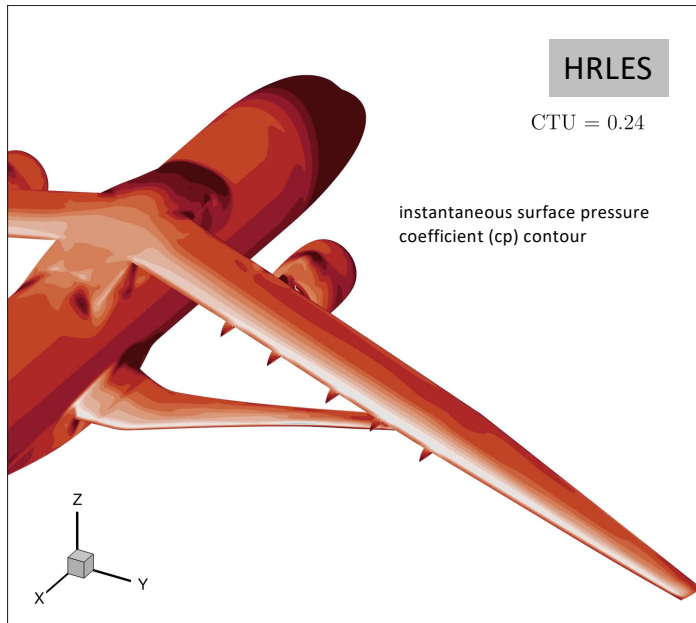
Next Generation Vehicles & Challenges



- ✓ **Increase predictive use of computational aerosciences capabilities for next generation vehicles**
 - The next frontier is to use scale resolving simulations to predict:



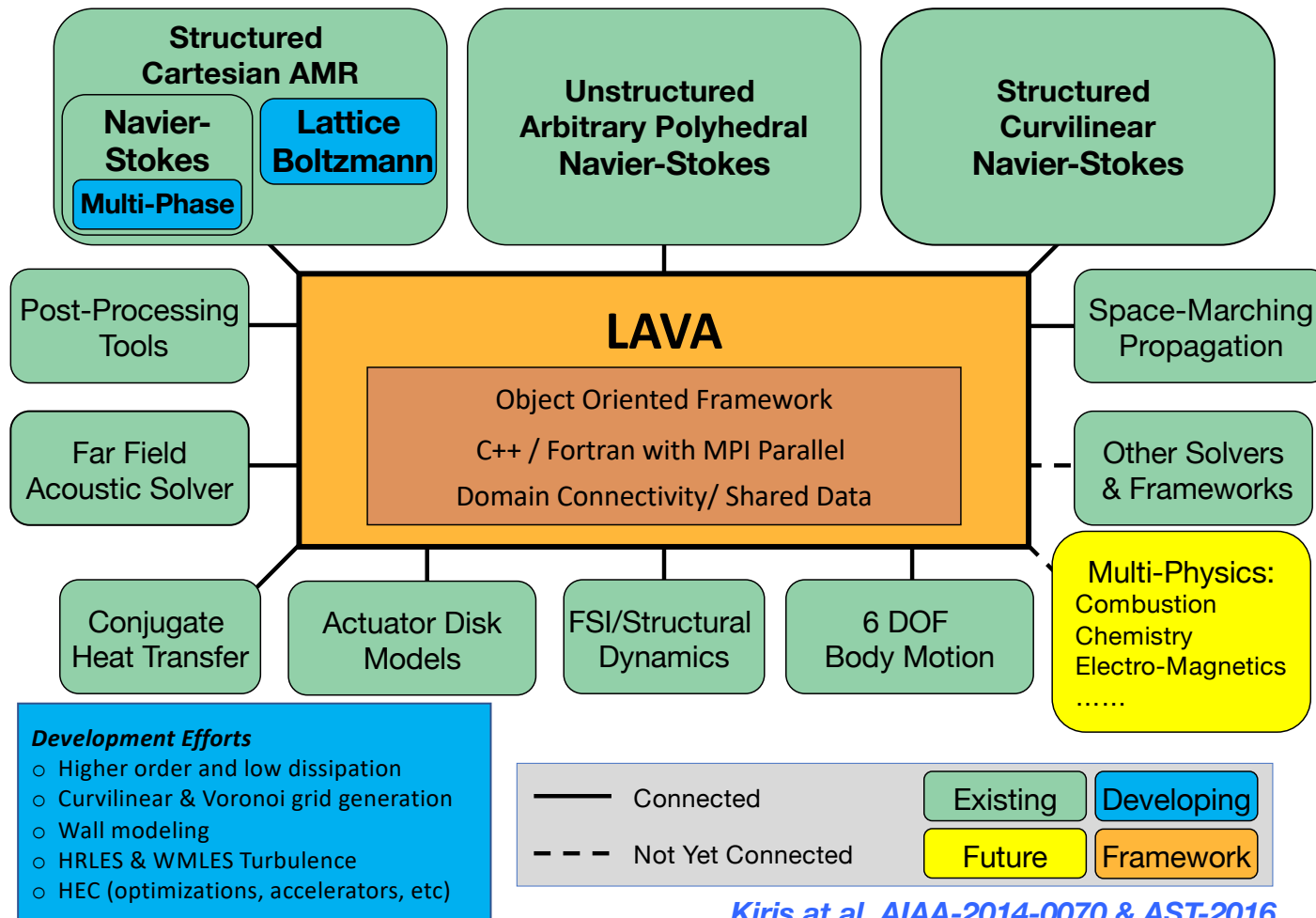
Buffet Onset Predictions for Transonic Truss Braced Wing (TTBW)



Examples of Scale Resolving Simulations – pathway to best practices

- **High-Lift Common Research Model: C_{Lmax} prediction (AIAA 4th High Lift Prediction Workshop)**
- Transonic Buffet: Shock Induced Flow Separation (AIAA Drag Prediction Workshops)
- NASA Juncture Flow Model
- Icing
- Landing Gear Acoustics
- Jet Noise Predictions

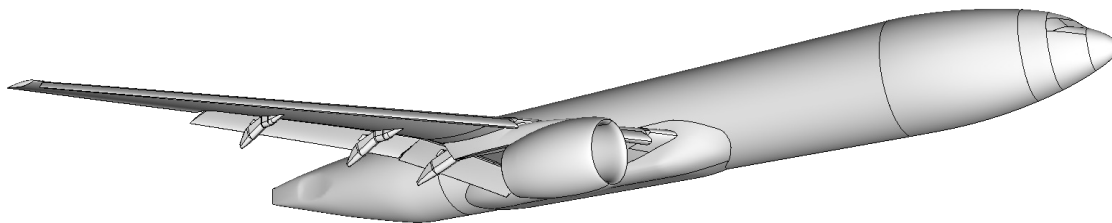
Launch, Ascent, and Vehicle Aerodynamics (LAVA) Framework



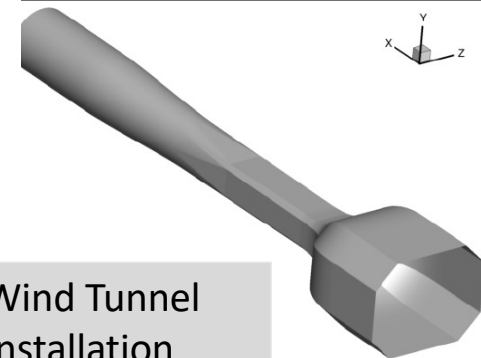
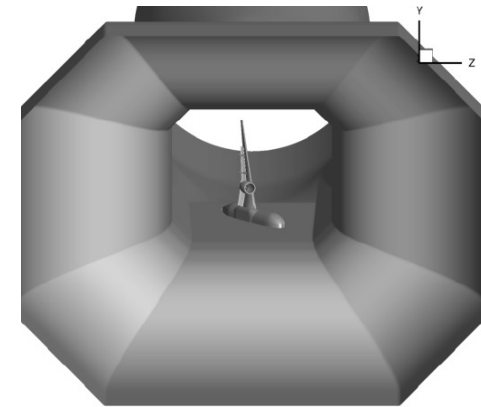
High-Lift Common Research Model: $C_{L_{max}}$ Prediction



- Participated the AIAA High-Lift Prediction Workshop-4 (HLPW4) Wall-Modeled Large Eddy Simulation (WMLES) Technology Focus Group.
- Extensive validation studies were performed for Free Air and Wind Tunnel installed case



Free Air



Wind Tunnel
Installation

High-Lift Common Research Model: C_{Lmax} Prediction



- ***“High-Lift Common Research Model: RANS, HRLES and WMLES perspectives for C_{Lmax} prediction using LAVA”*** by Kiris et. al. AIAA Scitech Forum 2022 DOI: [10.2514/6.2022-1554](https://doi.org/10.2514/6.2022-1554)
- ***“A Reynolds-Averaged Navier-Stokes Perspective for the High Lift-Common Research Model Using the LAVA”*** by Duensing et. al. AIAA Aviation Forum 2022. DOI: [10.2514/6.2022-3742](https://doi.org/10.2514/6.2022-3742) and AMS Seminar <https://www.nas.nasa.gov/pubs/ams/2022/05-26-22.html>
- ***“A Hybrid RANS-LES Perspective for the High Lift-Common Research Model Using the LAVA”*** by Browne et. al. AIAA Aviation 2022 Forum . DOI: [10.2514/6.2022-3523](https://doi.org/10.2514/6.2022-3523) and AMS Seminar <https://www.nas.nasa.gov/pubs/ams/2022/06-02-22.html>
- ***“A Wall Modeled LES Perspective for the High Lift-Common Research Model Using the LAVA”*** by Ghate et. al. AIAA Aviation 2022 Forum . DOI: [10.2514/6.2022-3434](https://doi.org/10.2514/6.2022-3434) and AMS Seminar <https://www.nas.nasa.gov/pubs/ams/2022/06-09-22.html>
- ***“Investigation of a Hybrid RANS-LES Approach for $C_{L,max}$ Prediction on NASA High Lift Common Research Model”*** by Browne et. al. Accepted for publication in AIAA Journal

CRM-HL at the stalled state

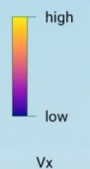
Particle traces colored by Mach number
Curvilinear WMLES at the post CLmax Stalled State
1100M point grid (W-D)
Timestep Size: $3.4\mu\text{s}$
Video Credit: Timothy Sandstrom

Slowest Time-scale Motion: At least 1.5s
Largest Relevant Length Scale: At least 7m (size of inboard separated region)

Smallest Geometric Length Scale: Approx. 2.5mm (blunt trailing edges)

Fastest Time-scale Motion: Approx. $600\mu\text{s}$
(shedding time-scale, $St=0.2$, for slat brackets)

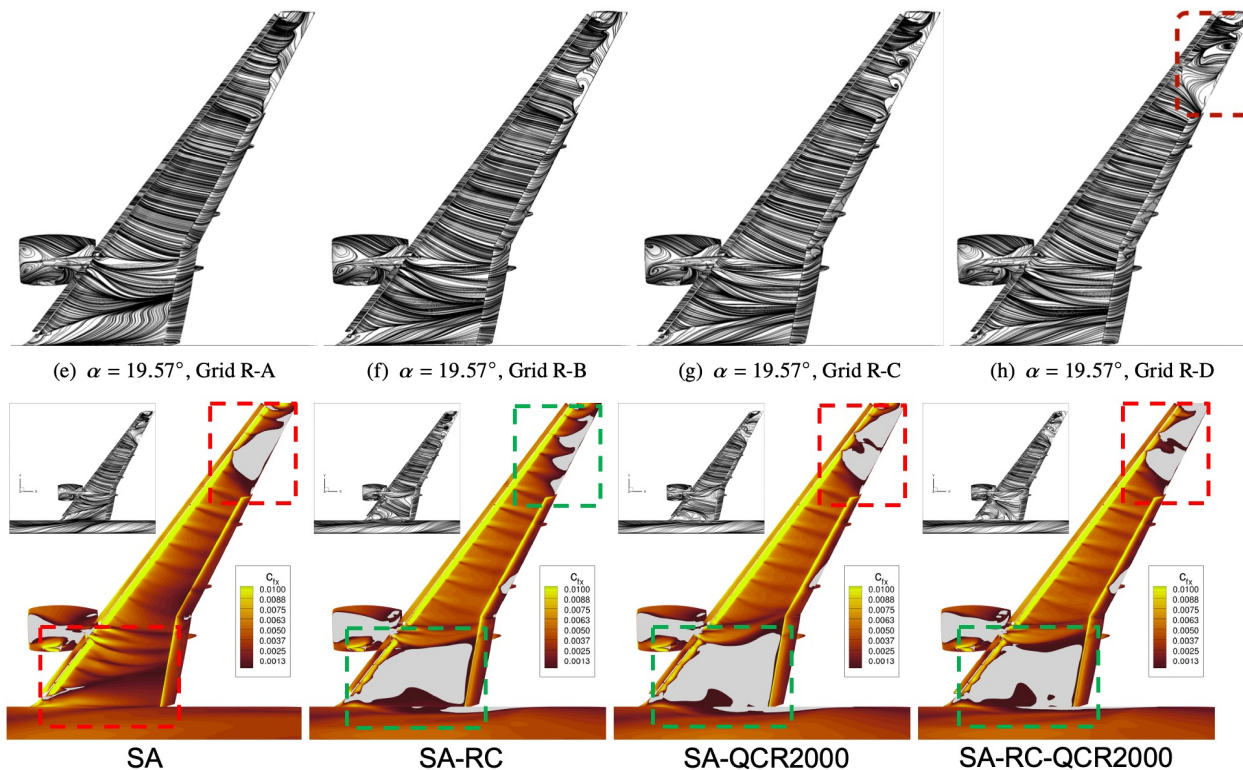
Peak Mach (mean-flow) number: Approaching $M = 1$ (outboard slats)
Peak suction: $c_p \approx -15$ (outboard slats)



Problems with RANS



1st Problem: Excess Spurious Separation on Outboard Wing:



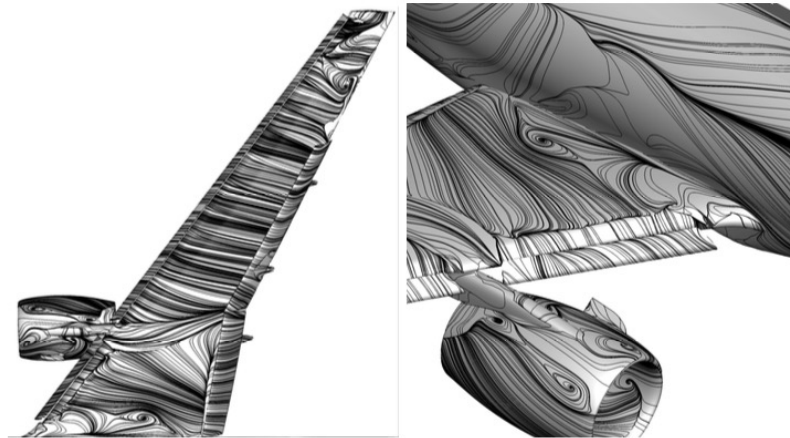
Solution worsens
with grid
refinement using
baseline SA

Solution worsens
with SA corrections

Problems with RANS

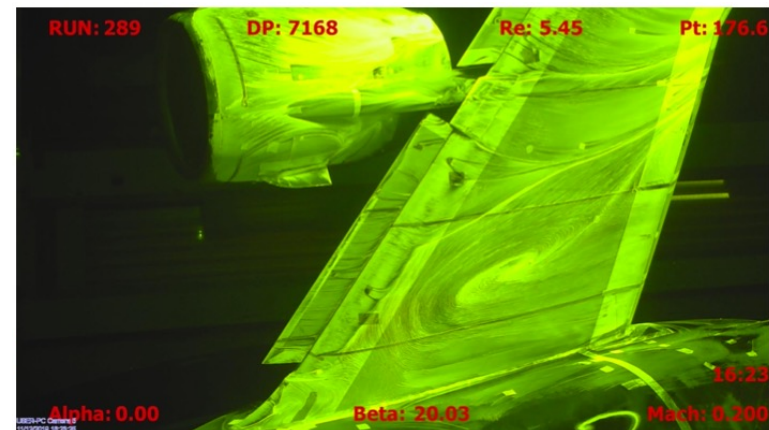


2nd Problem: Excess Spurious Inboard Separation for In-Tunnel Simulations:



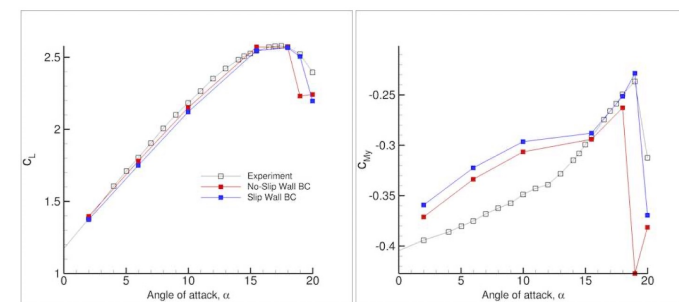
(i) RANS (Top) $\alpha = 19.98^\circ$

(j) RANS (Front) $\alpha = 19.98^\circ$



(b) Oil Flow

- If large coherent separated flow is expected, SA based RANS is an inaccurate tool for predictions – this has been well known in the community for > 10 years.
- This makes RANS inappropriate for at any angle-of-attack including a low angles where RANS overpredicts pitching moment coefficient due to incorrect flap separation.



(a) Lift, SA

(c) Pitching Moment, SA

Scale Resolving Alternatives to RANS



- **Delayed Detached Eddy Simulations (DDES) - HRLES**
 - Sensitivity to timestep size, grid quality and numerics
 - Comparison with in-tunnel experimental data
- **Wall Modeled Large Eddy Simulations (WMLES)**
 - Grid generation bottleneck - Cartesian vs curvilinear
 - Is there a systematic grid convergence for pressure loading?
 - Do Cartesian and Curvilinear agree amongst themselves and with experiment?
- **Cost Comparison**
- **New capability (under development): unstructured (Voronoi) WMLES**

DDES: Should the Mesh Differ from RANS?



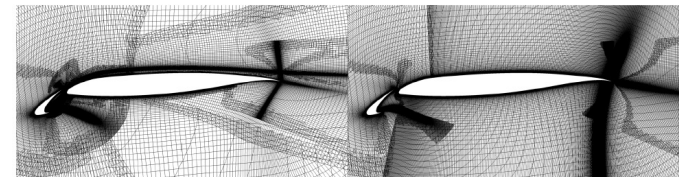
Typical community practice: RANS grids are utilized for HRLES scale-resolving simulations is a common mistake, no universal best practices exist?

best practice grid is Grid H-D and non-dimensional $\Delta t = 1.95e-3$

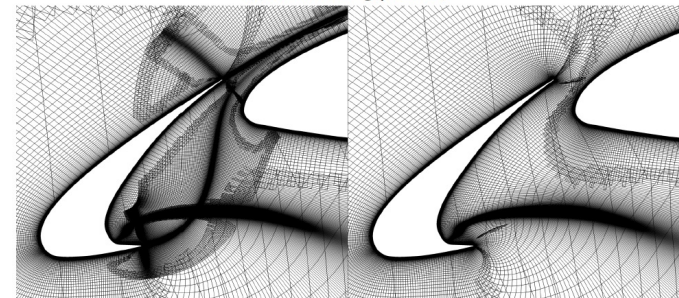
Name	Solve Points	Target y^+	Max Stretching Ratio	Comments
Grid R-C	224M	1.0	1.10	[12, 44]
Grid H-A	365M	1.0	1.10	inboard + outboard refinement
Grid H-B	325M	1.0	1.10	modified slat wake grid + outboard refinement
Grid H-C	421M	1.0	1.10	outboard refinement
Grid H-D	571M	1.0	1.10	inboard + midboard + nacelle refinement

RANS Grid R-C

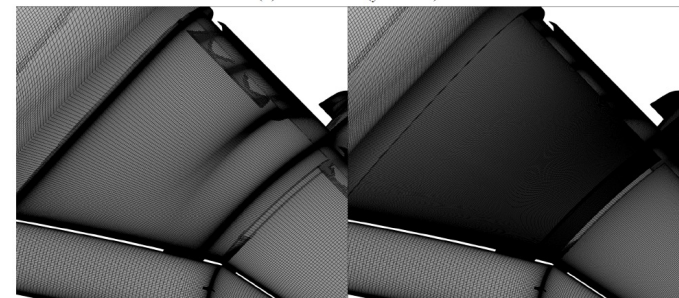
HRLES Grid H-D



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

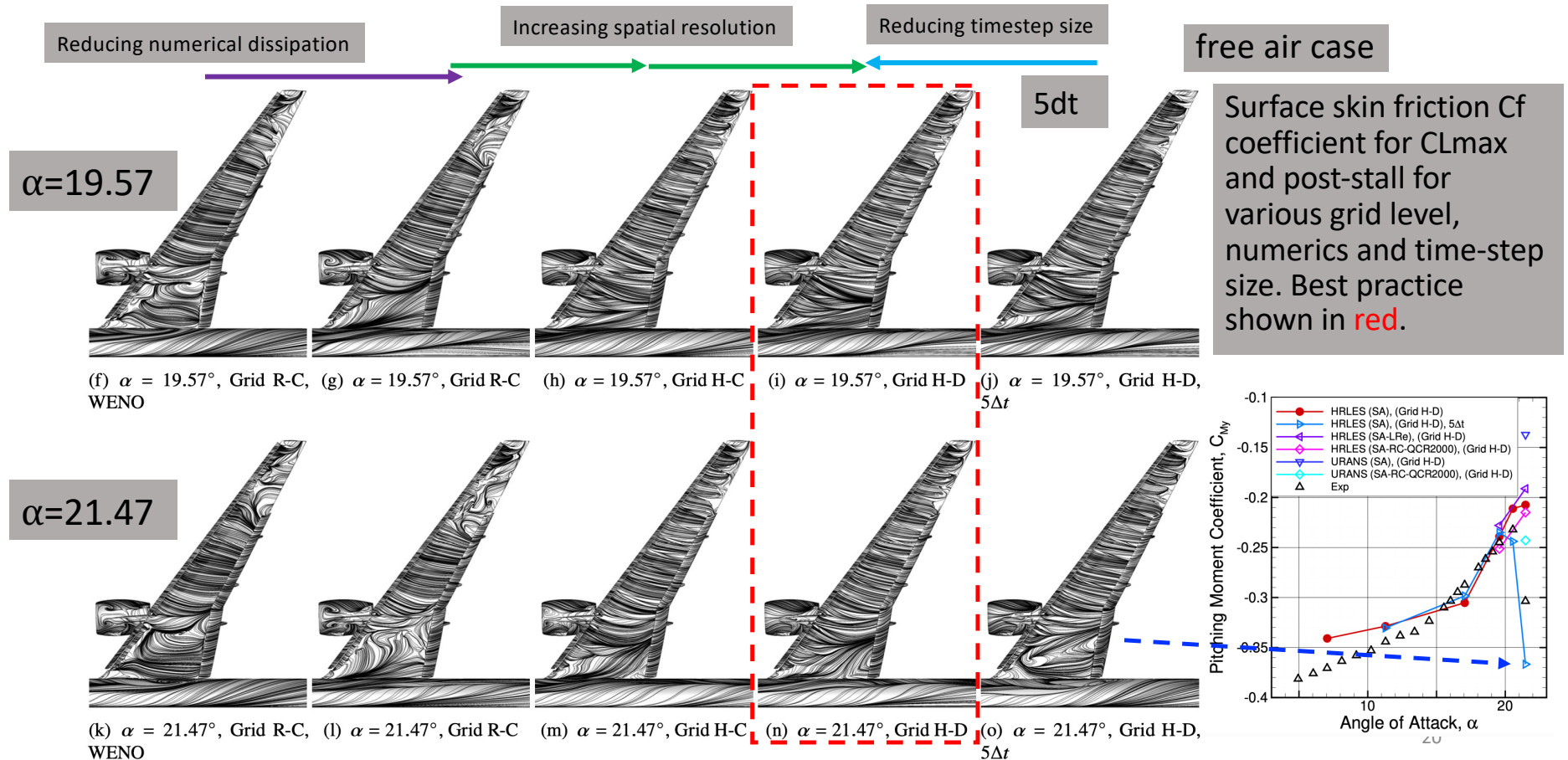


(b) Slat element ($y = 15$ m.)



(c) Inboard wing upper surface

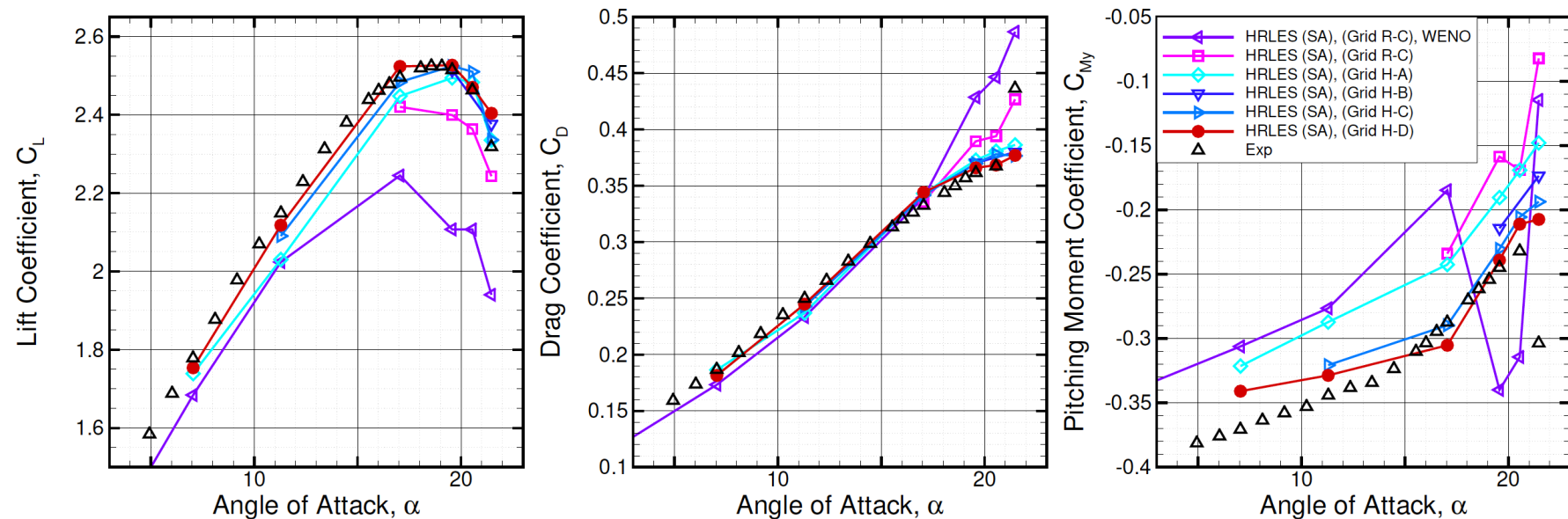
DDES: A Menagerie of Sensitivities



DDES: Effect of Grid Resolution

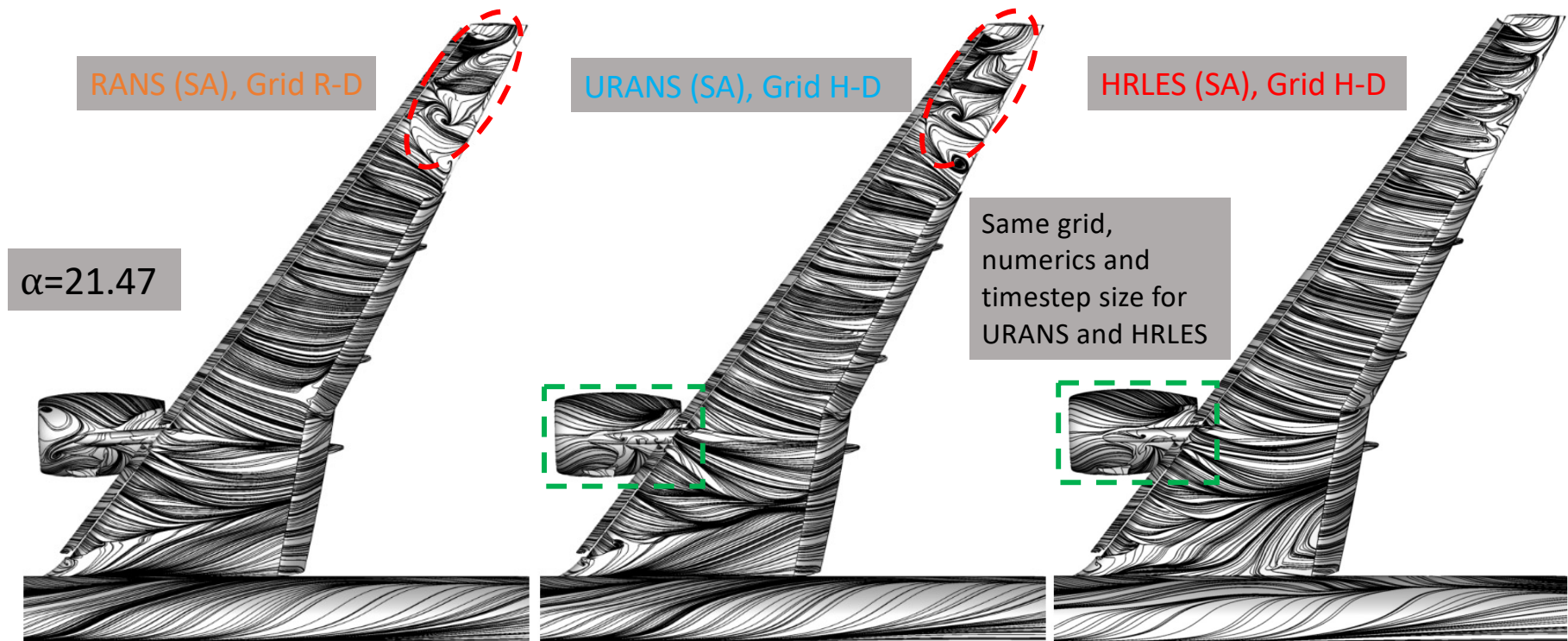


Aerodynamic loads for various grid levels and numerics computed with HRLES compared with corrected experimental results. Best practice HRLES is shown in red.



Note: pitch break not guaranteed in free air case

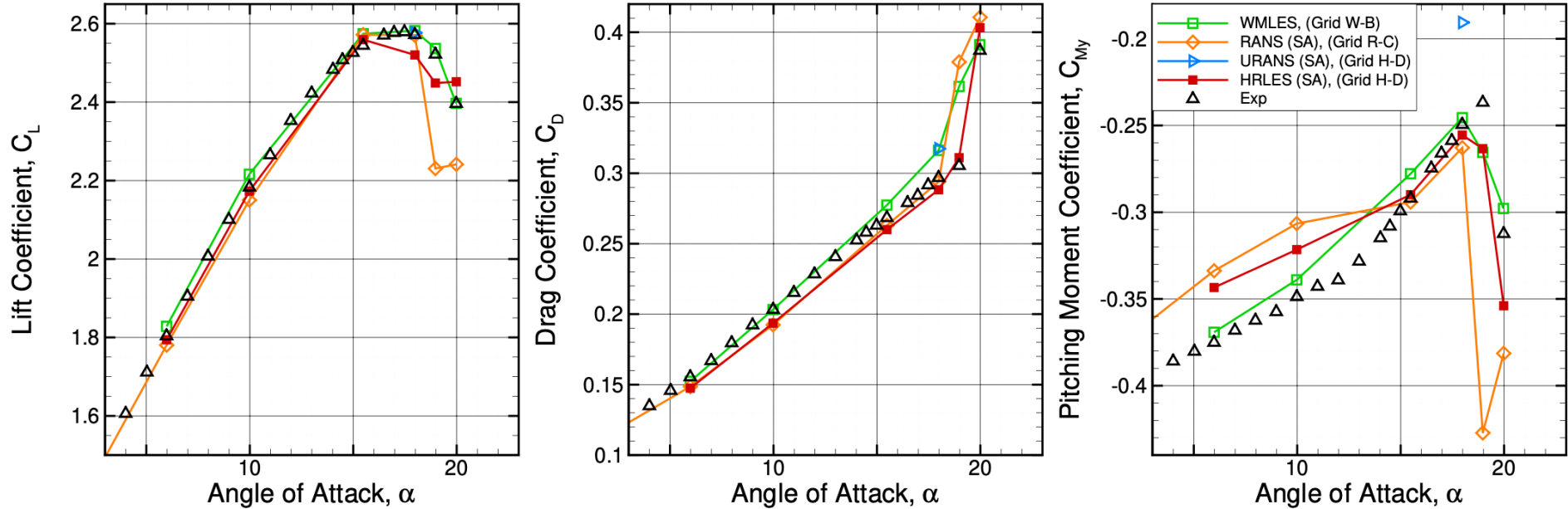
DDES Improvement closure model or discretization?



DDES: Simulating the In-Tunnel Configuration



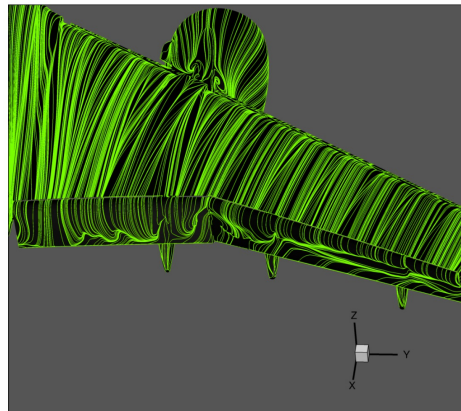
Aerodynamic loads comparison between LAVA **RANS**/**URANS**, **HRLES** and **WMLES** with uncorrected experimental results.



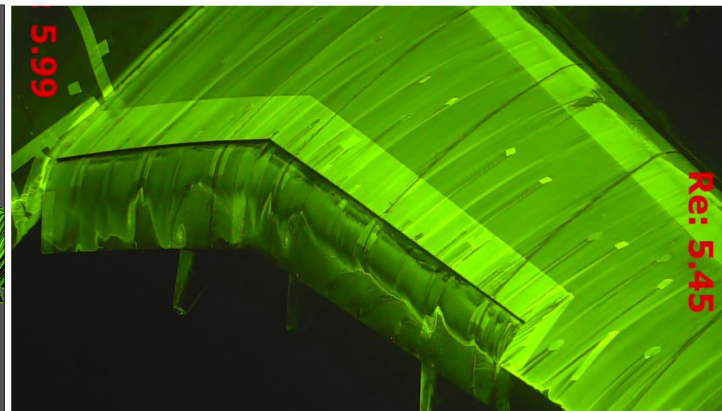
DDES: Streamlines vs Oil-Flow Comparison



$\alpha=5.98$



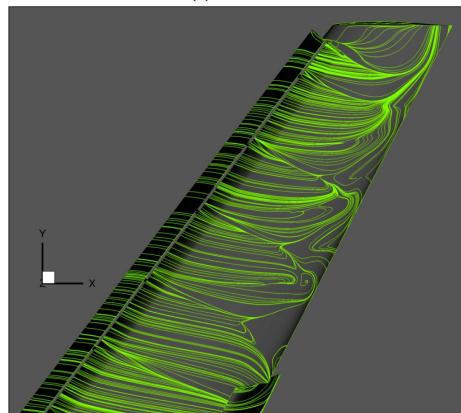
(a) HRLES



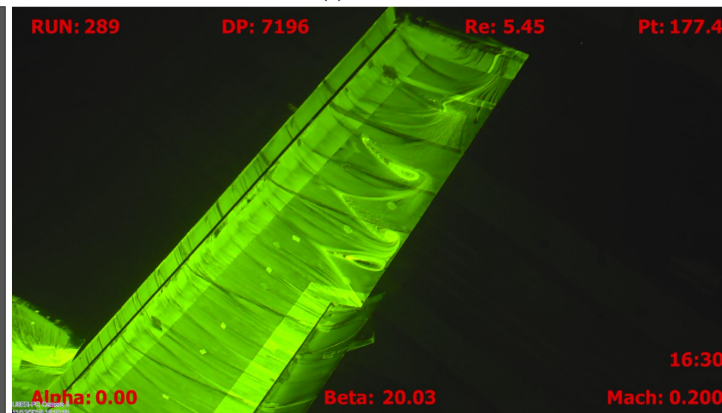
(b) Oil Flow

Comparison of inboard and outboard flaps

$\alpha=19.98$



(a) HRLES



(b) Oil Flow

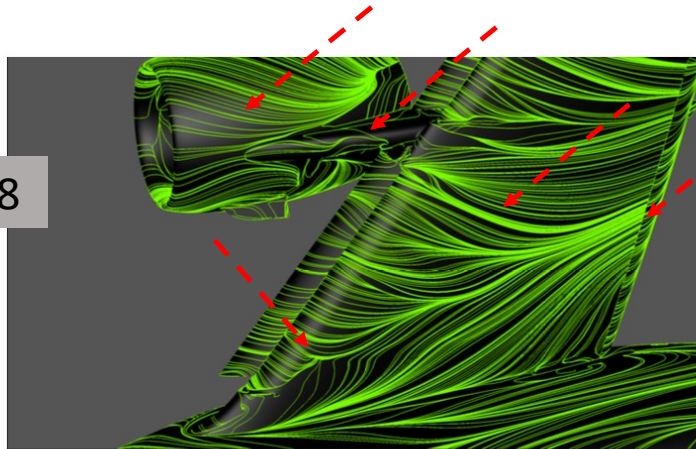
Comparison of outboard region of the wing

QinetiQ tunnel experiments
<https://hiliftpw.larc.nasa.gov>

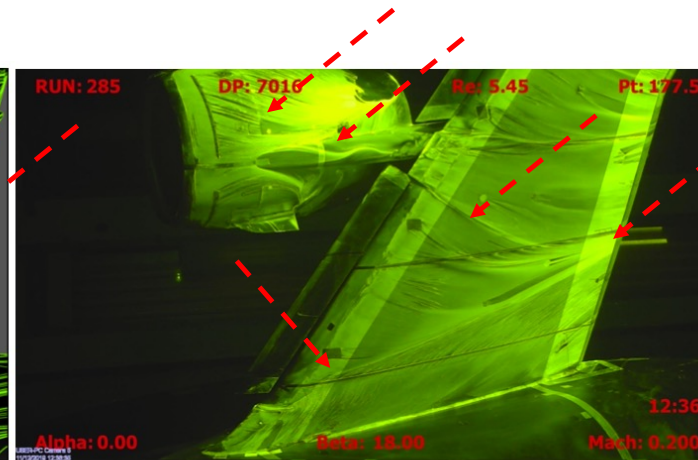
DDES: Streamlines vs Oil-Flow Comparison



$\alpha=17.98$

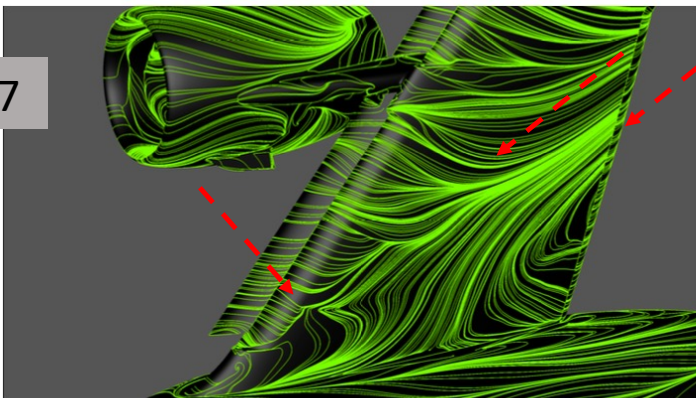


(a) HRLES

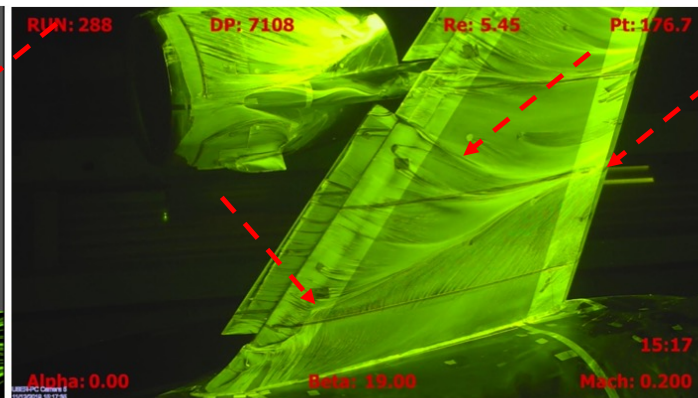


(b) Oil Flow

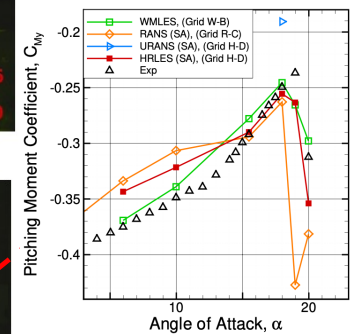
$\alpha=18.97$



(a) HRLES



(b) Oil Flow

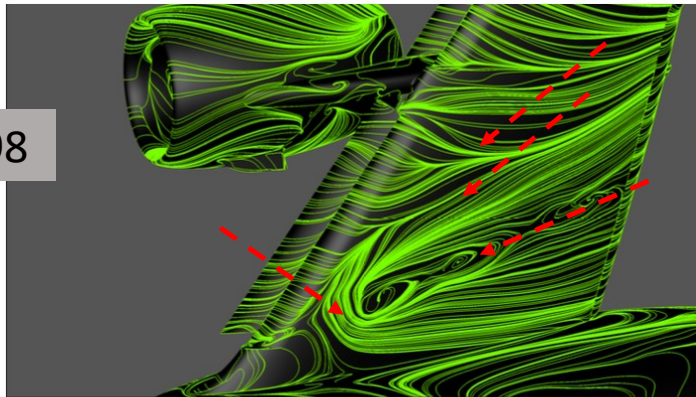


QinetiQ tunnel experiments
<https://hiliftpw.larc.nasa.gov>

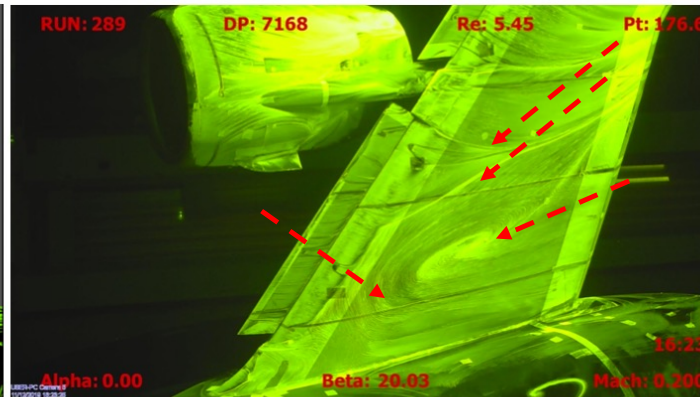
DDES: Streamlines vs Oil-Flow Comparison



$\alpha=19.98$

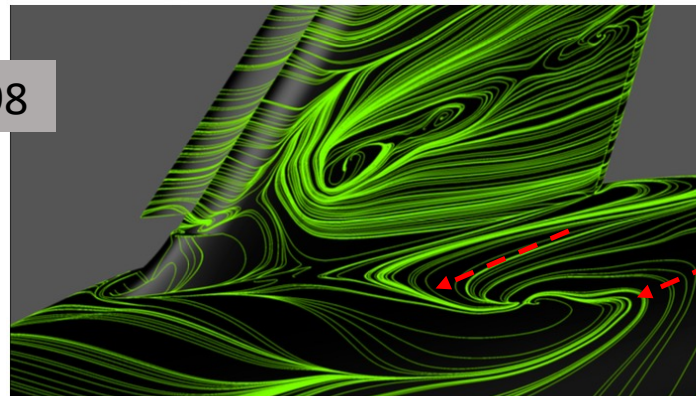


(a) HRLES

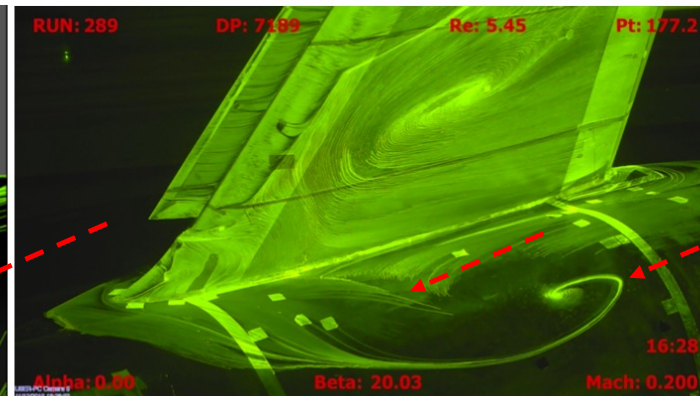


(b) Oil Flow

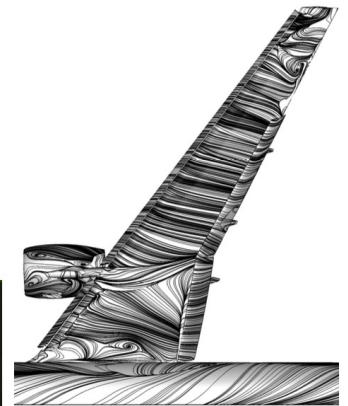
$\alpha=19.98$



(a) HRLES



(b) Oil Flow



(d) RANS (SA), $\alpha = 19.98^\circ$

QinetiQ tunnel experiments
<https://hifltpw.larc.nasa.gov>

Delayed Detached Eddy Simulations (DDES) HL-CRM Summary



LAVA – DDES does show striking agreement to experiment if the following criteria are met:

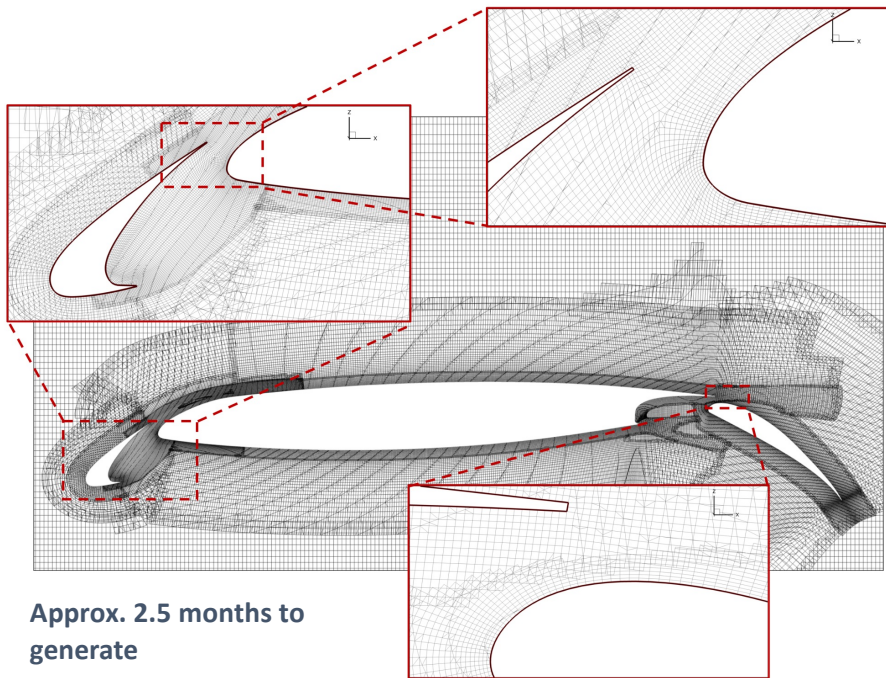
- **Sufficient spanwise/streamwise spacing:** Both wing-root and outboard main-element refined substantially over the finest RANS grid that was studied
- **LES-appropriate grids utilized for shear-layers:** Slat wake/main-element wakes require low-aspect ratio grids for resolvable content
- **Low time-step size:** Dissipation due to BDF2 needs to be limited by respecting temporal time-scales corresponding to resolvable length scales $\left(\tau \propto k_{\Delta}^{-\frac{2}{3}}\right)$
- **Low-dissipation discretization:** Convective flux operators need to be non-dissipative
- Sensitivity to underlying RANS closure reduced when **more domain was under LES mode**
- Typical strategy: use a cell aspect ratio mask to override LES closure into RANS when poor grid cells are present.
- DDES solution quality improves as best-practices become more “LES-friendly”

Why not perform LES everywhere and model what is not-resolvable (or subgrid)?

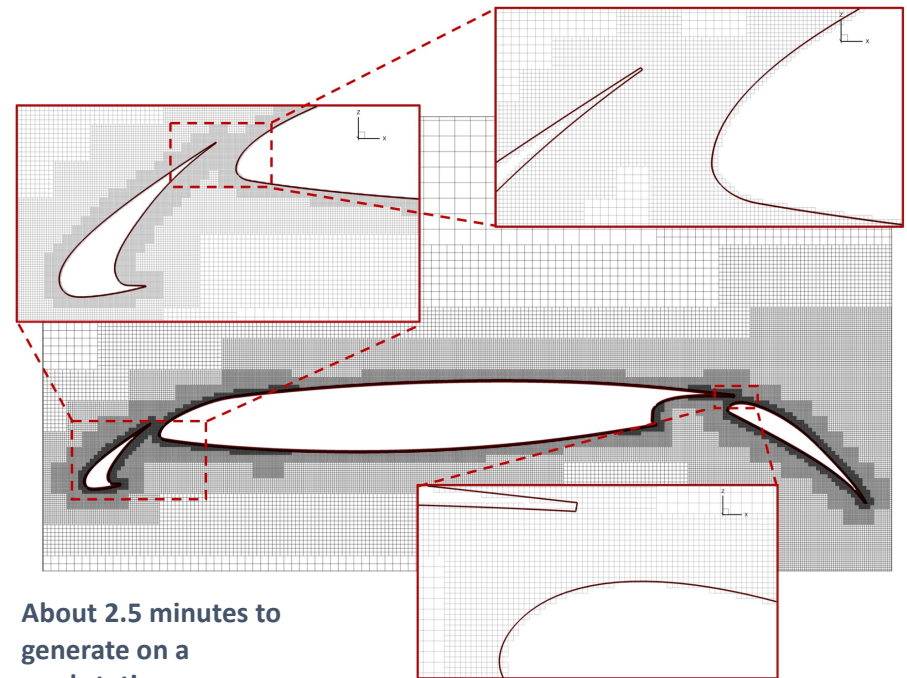


Wall Modeled Large Eddy Simulations (WMLES)

What is the correct grid paradigm?



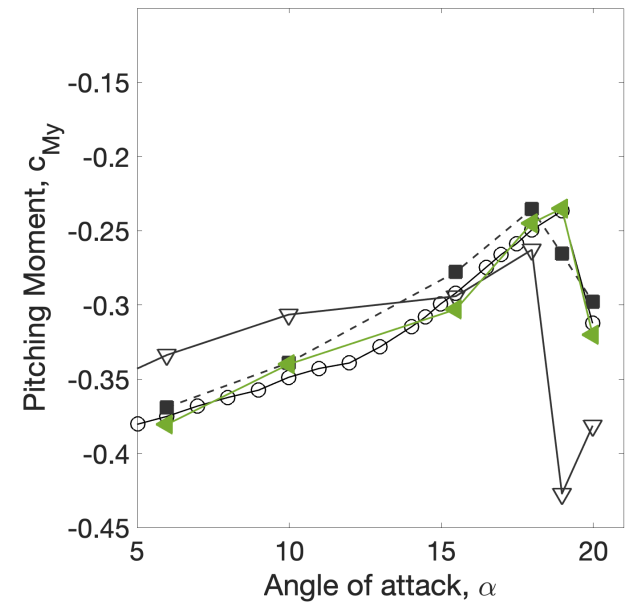
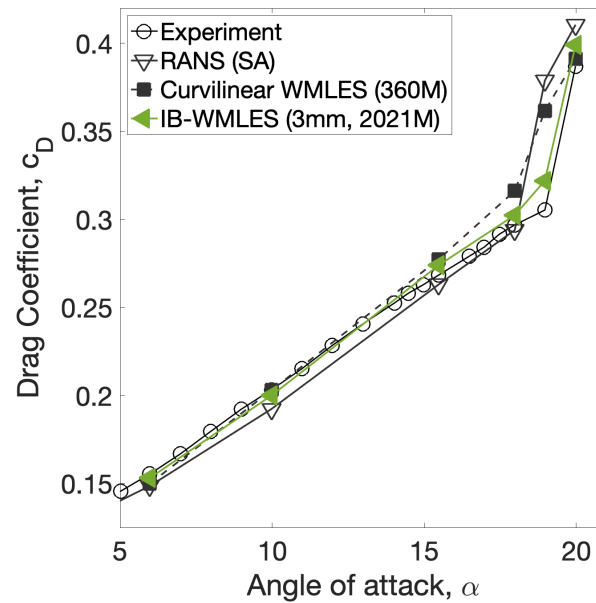
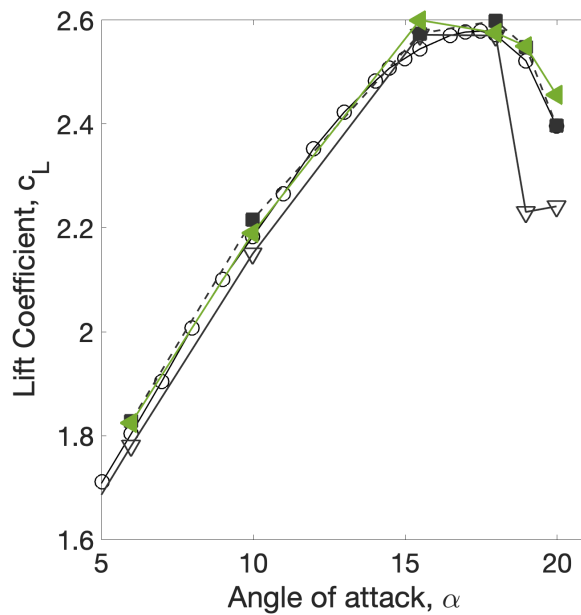
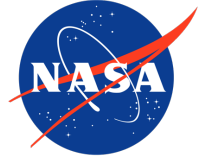
(a) Curvilinear Overset Topology



(b) Cartesian Octree Topology

New immersed boundary WMLES method
developed (manuscript in preparation)

WMLES: In-Tunnel Simulations



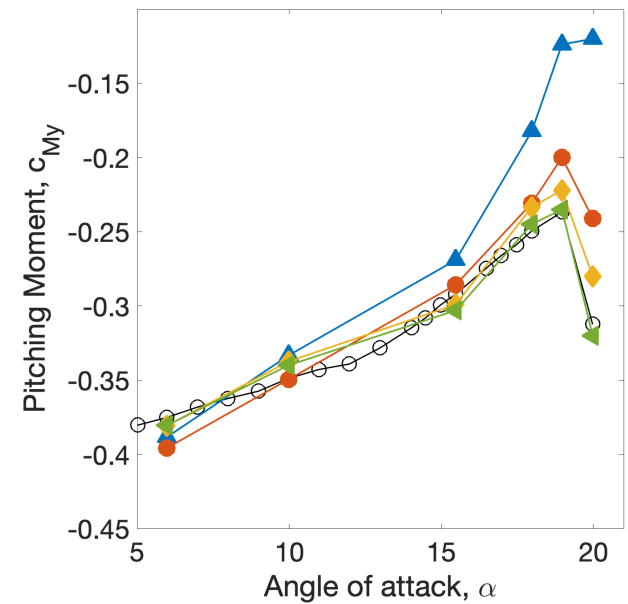
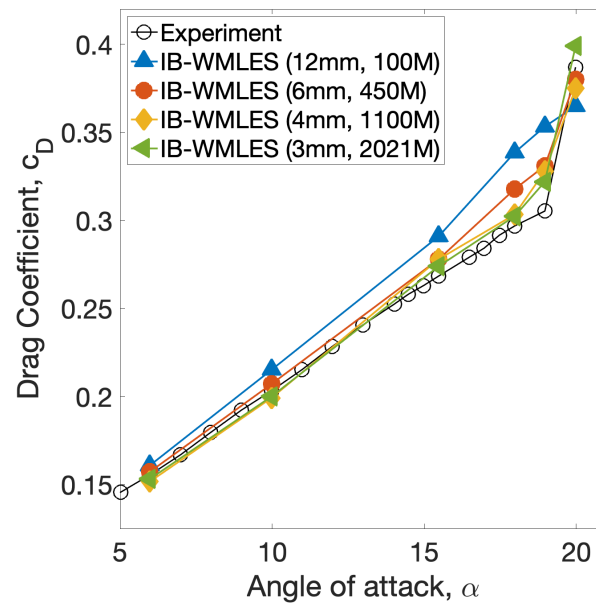
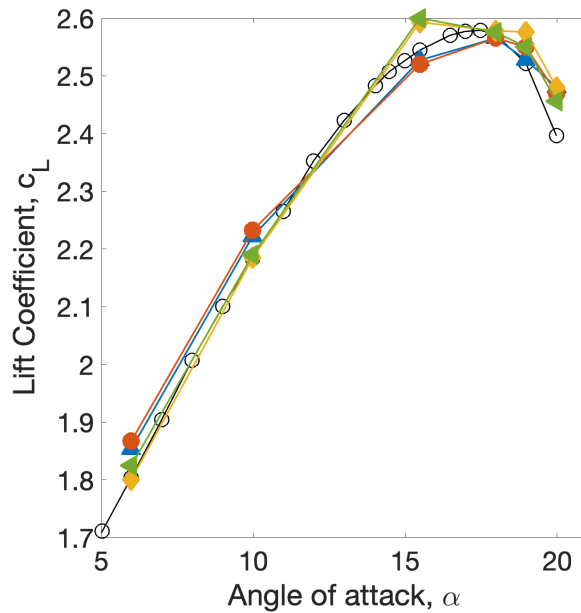
Refer to paper for information on:

1. Initialization procedure (tunnel back-pressure)
2. Tunnel floor BL comparisons with rake data

After interpolation to primary/final grid:

1. Transience washout: 10-20 CTU
2. Statistical averaging: 10-30 CTU ($\alpha < 18^\circ$) and 80 CTU ($\alpha > 18^\circ$)

WMLES: Grid Convergence



Refer to paper for information on:

1. Initialization procedure (tunnel back-pressure)
2. Tunnel floor BL comparisons with rake data

After interpolation to primary/final grid:

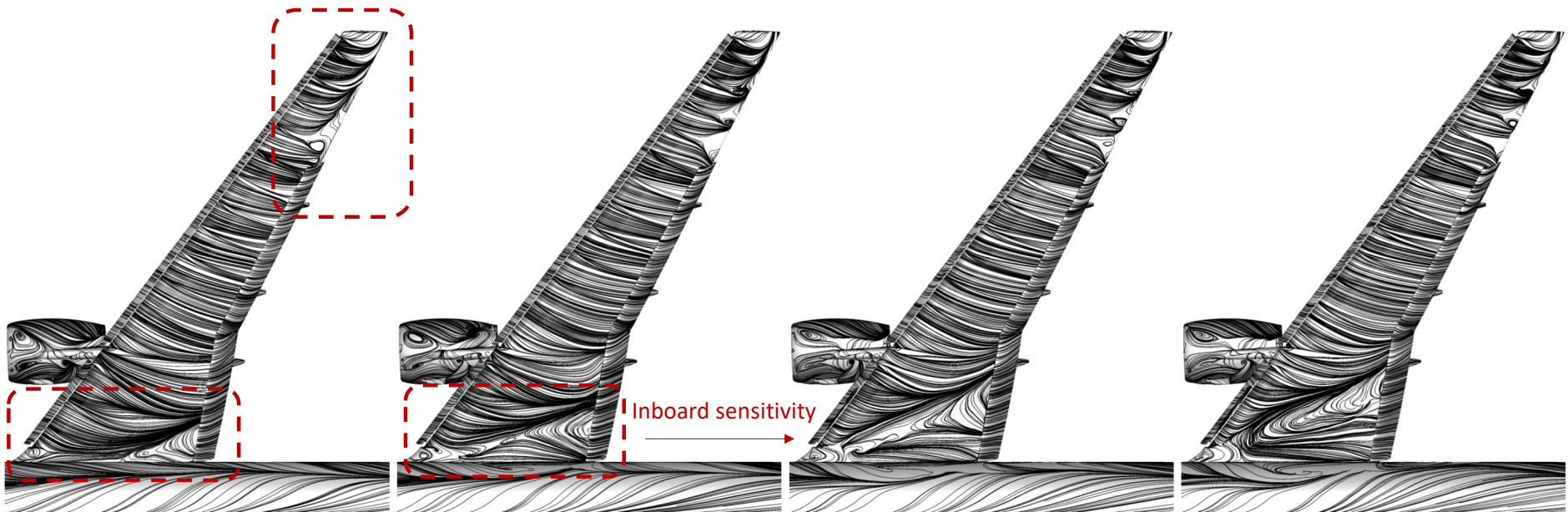
1. Transience washout: 10-20 CTU
2. Statistical averaging: 10-30 CTU ($\alpha < 18^\circ$) and 80 CTU ($\alpha > 18^\circ$)

WMLES: Effect of Grid Resolution at CLmax



$$\alpha = 19.98^\circ$$

Time-averaged surface streamlines



(a) 12mm Grid (100M)

(b) 6mm Grid (450M)

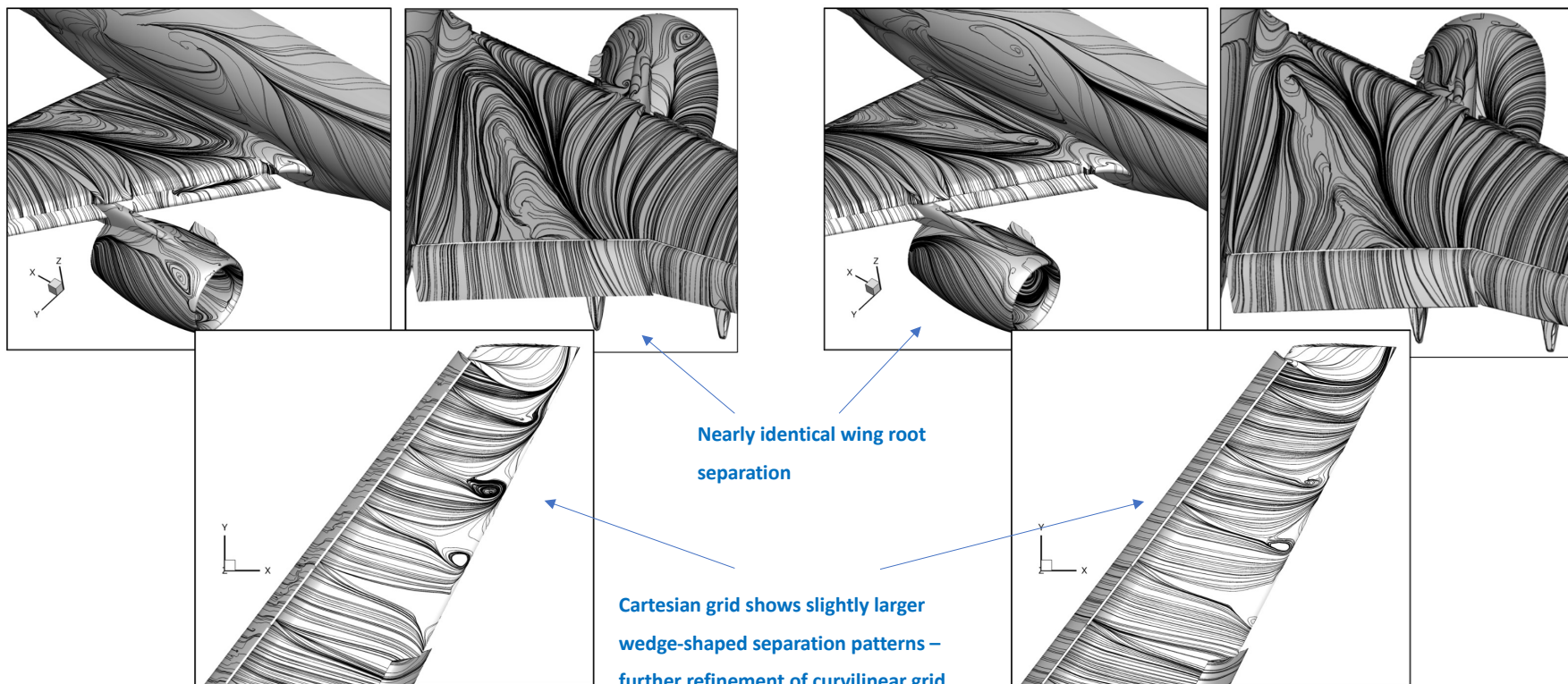
(c) 4mm Grid (1100M)

(d) 3mm Grid (2021M)

WMLES: Post-CLmax Stalled State



$\alpha = 19.98^\circ$



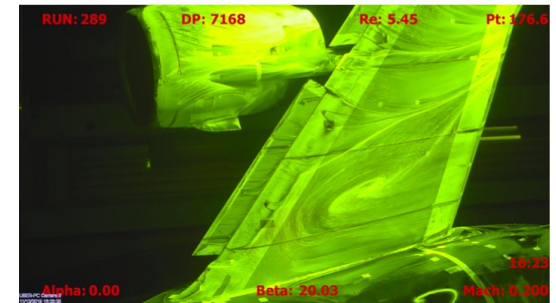
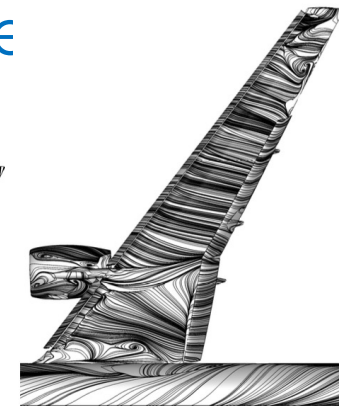
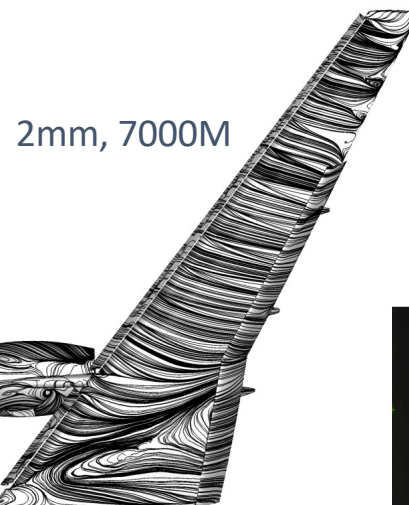
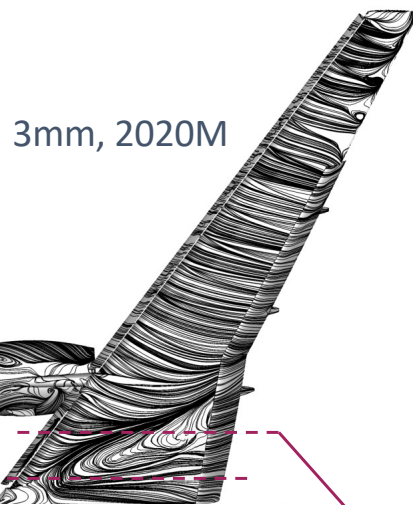
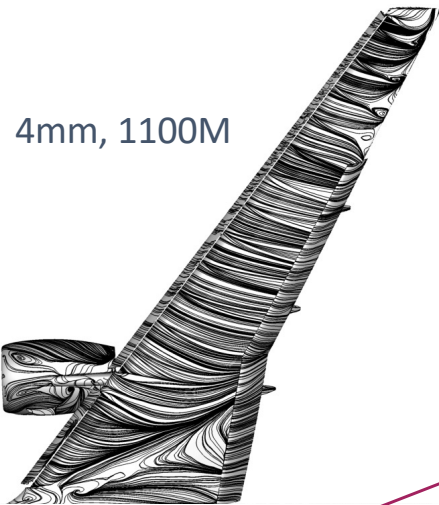
(a) Cartesian WMLES (3mm Grid)

(b) Curvilinear WMLES

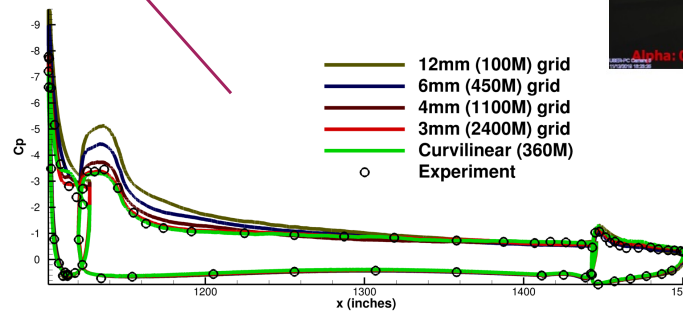
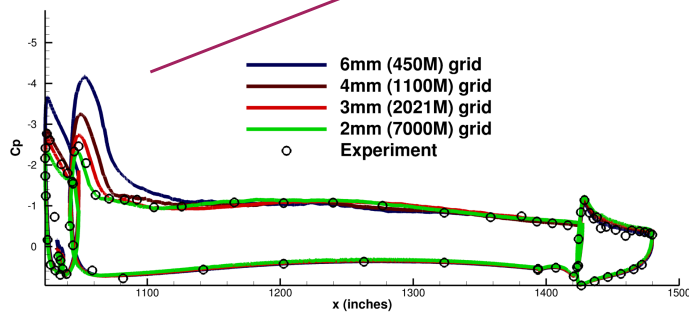
WMLES: "Scientific" Best Practice

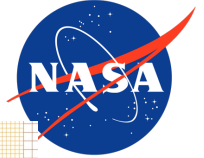


- Do we need to refine further for $\alpha = 19.98^\circ$?



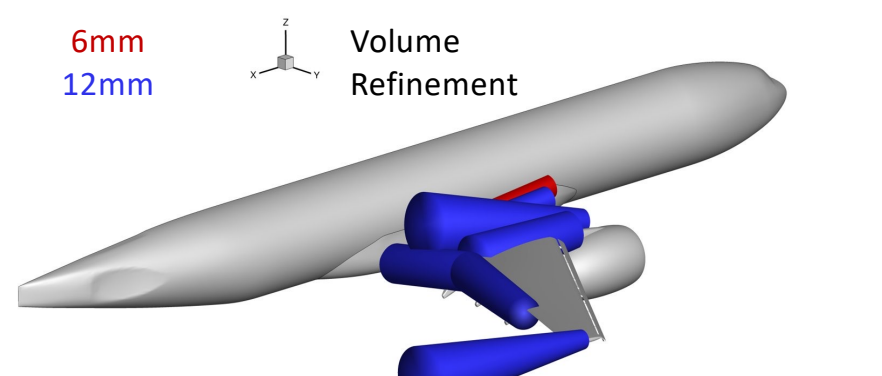
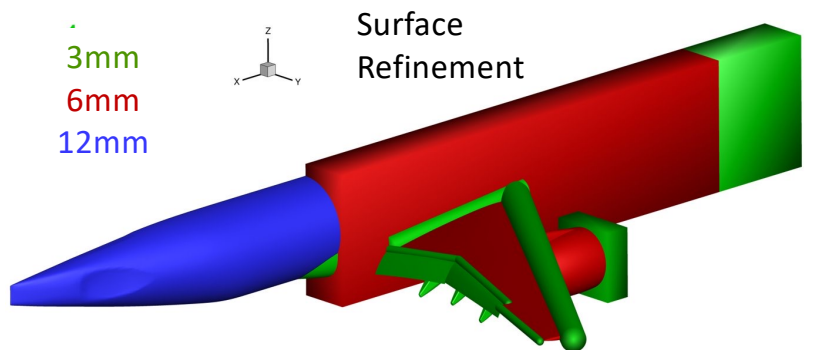
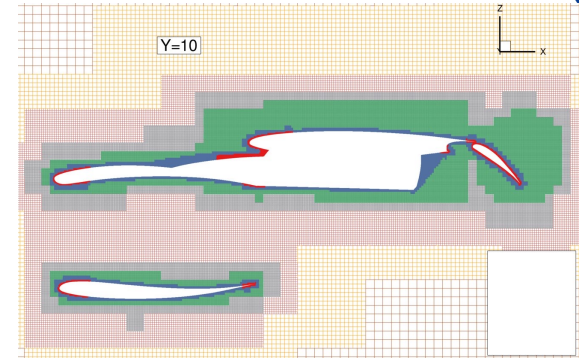
(b) Oil Flow





WMLES: Do We Really Need 7 Billion Grid Points?

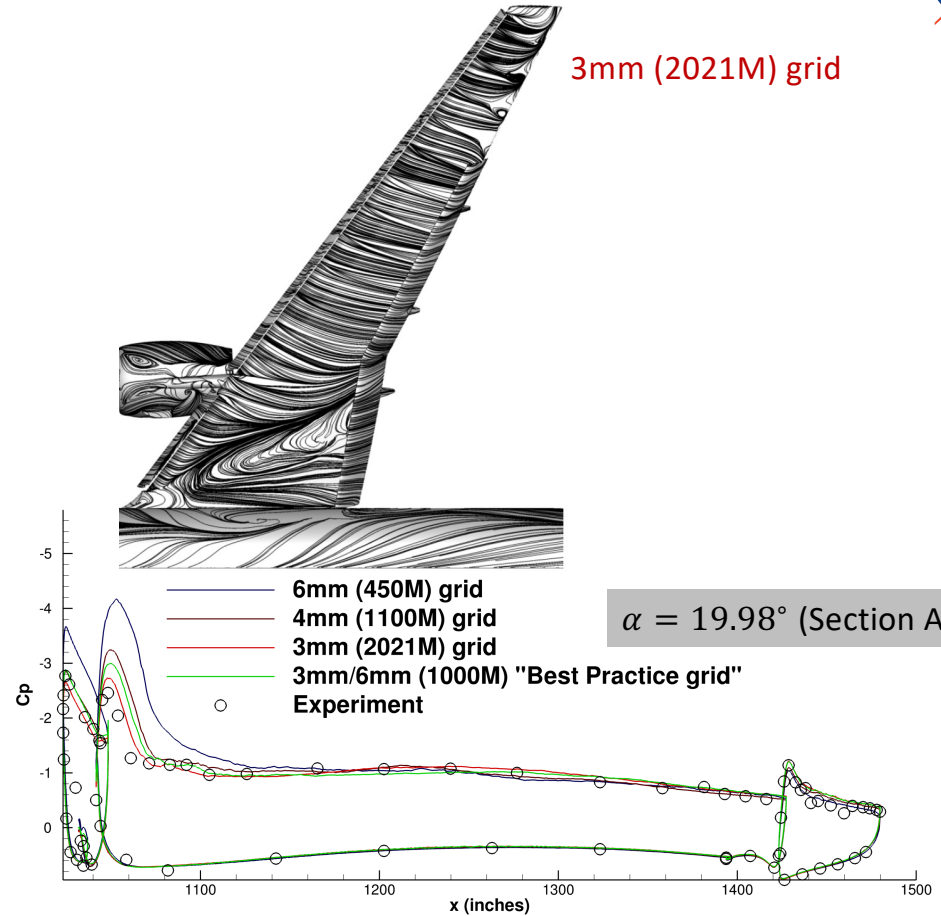
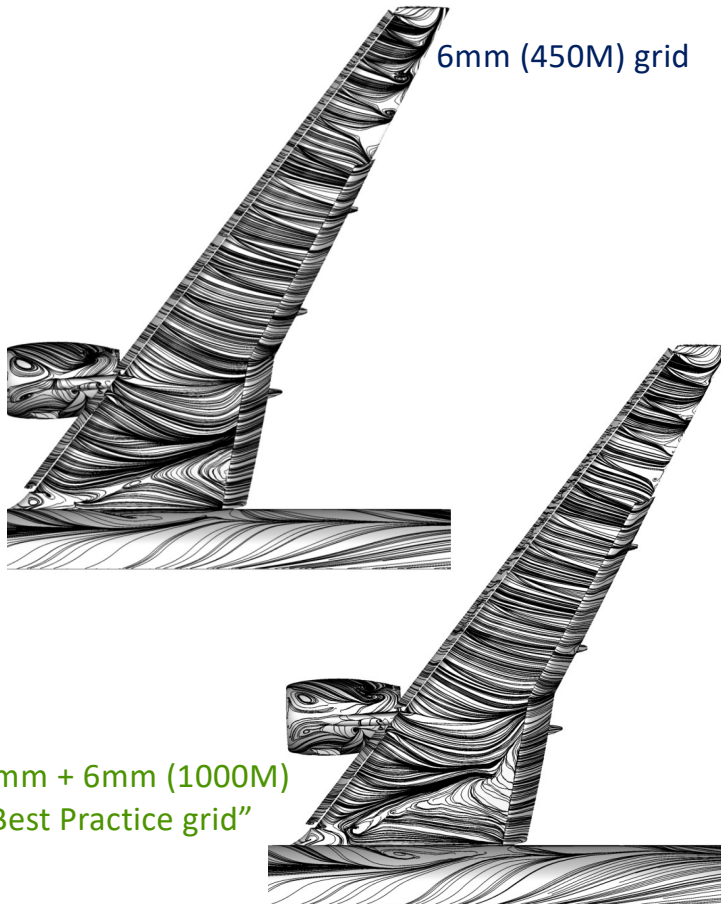
- Engineering “Best-practice” grid can be designed using **targeted refinement** sensitivities shown before



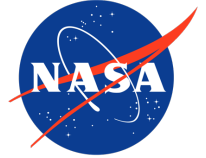
6mm grid (450M) → 3mm + 6mm grid (1000M)*

* Refinement blocks shown above are slightly different from the final refinement strategy that was used

WMLES: "Engineering" Best Practice



HL-CRM Cost and Timing Comparisons



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-BP
Solve Points	223M	550M	360M	571M	1000M
Timestep size	-	-	$3.5 \times 10^{-6}s$	$2.0 \times 10^{-4}s$	$3.45 \times 10^{-6}s$
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)	100 Skylakes (40 cores/node)
Core-time per compute point per timestep	-	-	$2.03\mu s$	$139.5\mu s$	$0.75\mu s$
Timesteps per CTU	-	-	29,338	514	29,561
Core-time per CTU	-	-	5970 hours	11360 hours	6100 hours
Simulation time needed for $\alpha = 19.57^\circ$	-	-	50 CTU	50 CTU	50 CTU
Core-time needed for $\alpha = 19.57^\circ$	21,000 hours	44,800 hours	298,500 hours	560,000 hours	308,000 hours
NAS SBUs needed for $\alpha = 19.57^\circ$	835	1,600	9,470	22,120	12,240
Relative Cost over typical RANS	1.0	1.91	11.3	26.4	14.6
Grid Generation (Human Effort)	2-4 months	2-4 months	2-4 months	2-4 months	2-4 hours

← Isotropy requires more grid points

← Much more efficient algorithm

← Both Curvilinear and Cartesian WMLES have similar accuracy/cost advantages over RANS

← Order of magnitude more expensive than RANS

← Negligible human effort for cartesian octree grids (scalable process)

Wall Modeled Large Eddy Simulation (WMLES) HL-CRM Summary

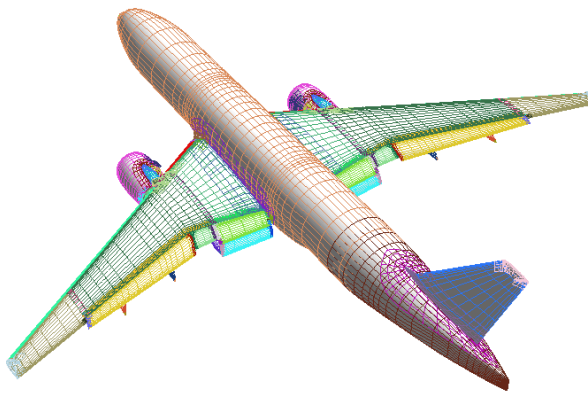


- **Grid convergence:** Grid convergence was assessed based on both “scientific metrics” as well as engineering “metrics”; in-tunnel simulations show excellent convergence towards the experiment
- **Grid topology:** Both curvilinear overset and cartesian octree (with immersed boundary) were demonstrated to produce consistent solutions for in-tunnel configuration; free-air configuration has larger uncertainties (see last point below)
- **Grid quality:** High-quality (low-aspect ratio) grids are essential in LES to allow explicit time-stepping and achieve cost competitiveness with RANS; simulations shown here capture dynamically active time-scale for over 6 orders of magnitude!
- **Advantage Cartesian Octree:** While both curvilinear and cartesian grids were successful with similar computational costs, cartesian octree grids reduce human mesh generation effort from months to minutes.
- **Insight on flow-physics:** First principles methods such as LES which offer the best accuracy-per-unit-cost predictions, can serve to study flow-phenomena responsible for sensitivities such as the tunnel-environment (see Ghate et al., AIAA 2022-3434 for further details).
- **Promising potential credibility:** Planned blind comparison with upcoming NASA Langley experiments (next step).

LAVA CFD Grid Paradigms

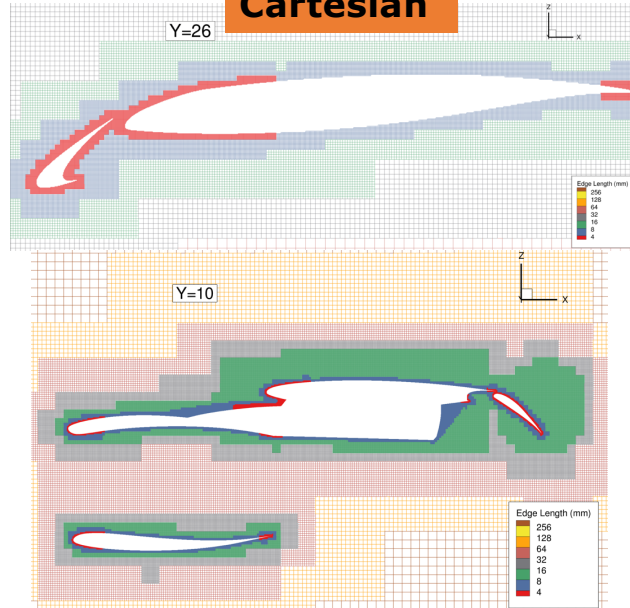


Structured Curvilinear



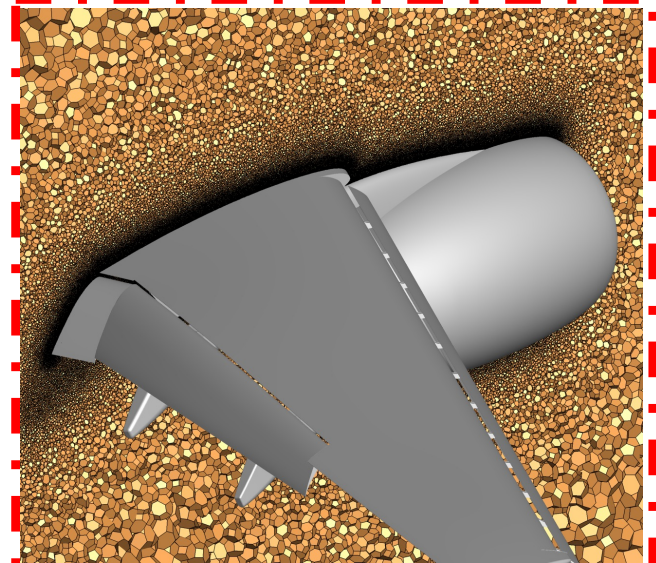
- High quality body fitted grids
- Low computational cost
- Reliable higher order methods
- Grid generation largely manual and time consuming

Cartesian



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

Unstructured

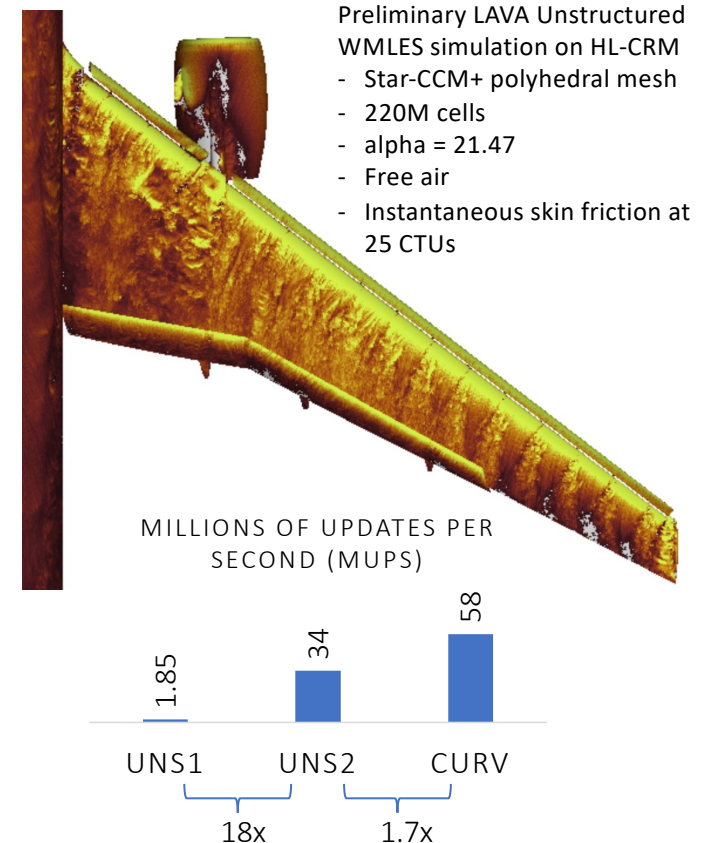


- Partially automated grid generation
- Body fitted grids
- Grid quality can be challenging
- High computational cost
- Higher order methods yet to fully mature

Unstructured Solver for WMLES



- LAVA Unstructured solver has been refactored to achieve high computational efficiency and scalability on CPUs
 - Achieved ~18X speed-up over the legacy LAVA unstructured
- Low dissipation fluxes and models needed for WMLES has been implemented and validated using fundamental test problems
- GPU porting of LAVA Unstructured is in progress
- Preliminary simulations of the HL-CRM were conducted using Star-CCM+ generated arbitrary polyhedral meshes
 - Demonstrated excellent robustness and scalability
- However, we are reaching the limit of commercial meshing tools for large, scale-resolving meshes (e.g., HL-CRM)
 - Not scalable to billions of elements
 - Non-ideal unstructured cell quality results in excessive dissipation
 - No ability to strictly control minimum cell size in order to use an explicit time-stepping scheme with a reasonable step size



Voronoi Mesher for WMLES

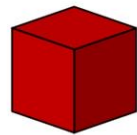


- Voronoi meshing allows for highly automated and scalable body-fitted mesh creation
 - Inherent Voronoi properties results in a high-quality mesh, ideally suited to LES applications
- Development effort has been ongoing to implement LAVA Voronoi mesher with properties:
 - Completely automated (user inputs: surface geometry, simple text file for sizing regions)
 - Coarse/fine interface refinement ratios and blending smoothness can be easily controlled
 - Body-aligned layers
 - Near-body cells are clipped using the geometry with automatic de-featuring of sub-cell details
 - i.e. no manual work needed to simplify geometries
 - High performance, scalable implementation with MPI/OpenMP parallelism (in progress)

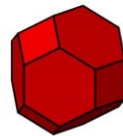
"Growing" of Voronoi cells from seeds



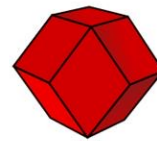
Various cell types can be generated by seeding accordingly



Cube
(Cartesian)

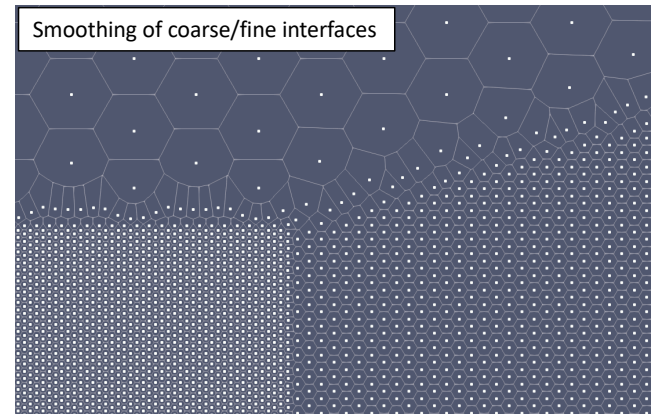


Truncated octahedron
(body-centered cubic)



Rhombic dodecahedron
(face-centered cubic)

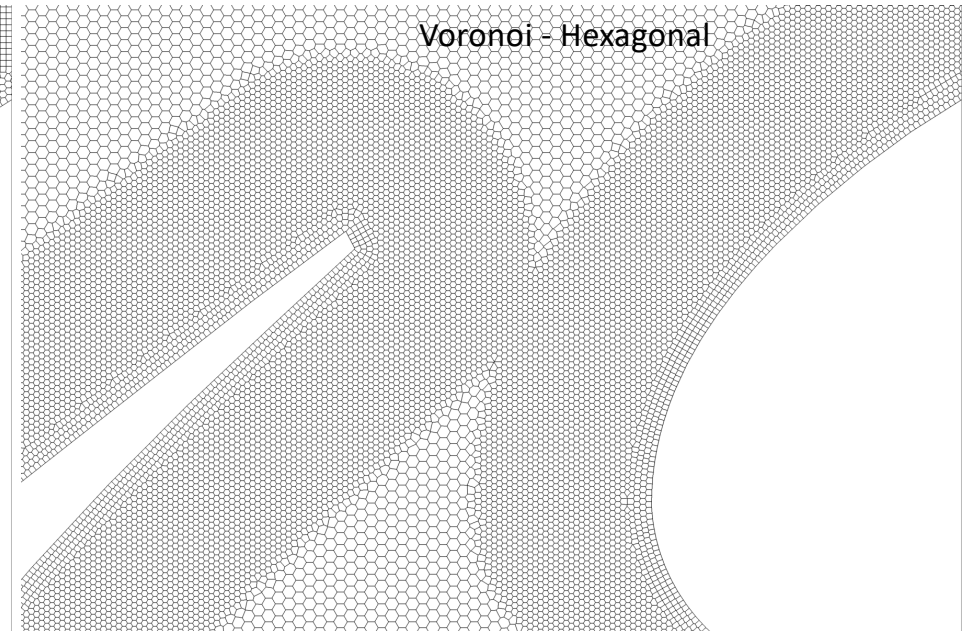
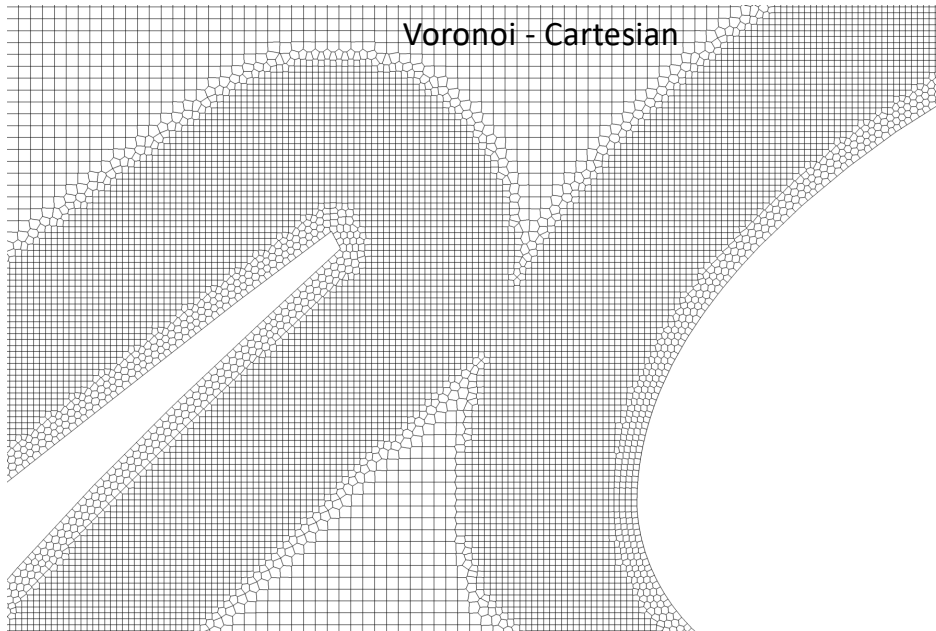
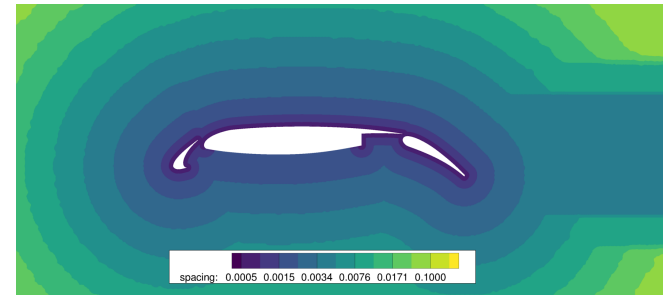
Smoothing of coarse/fine interfaces



Voronoi Mesh – 30P30N



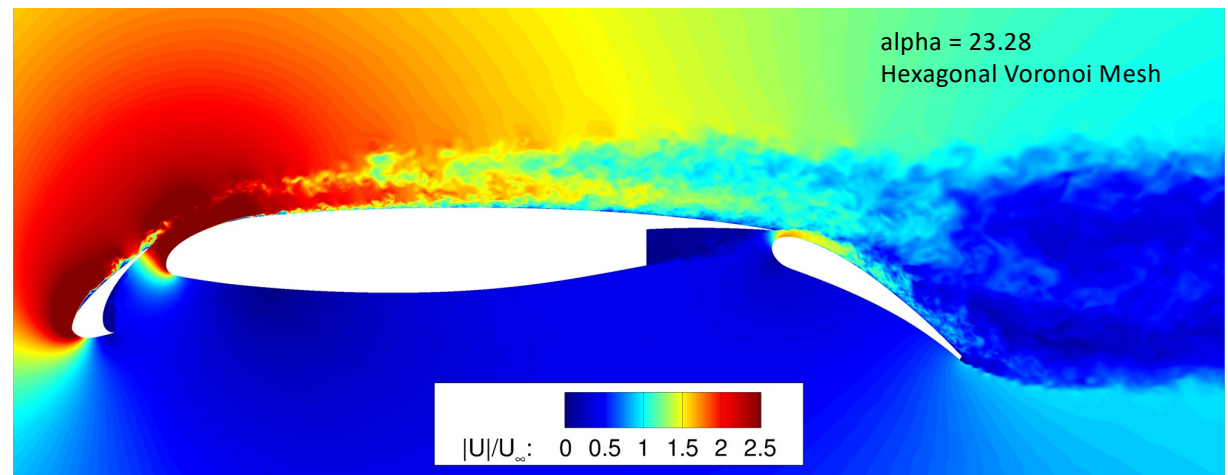
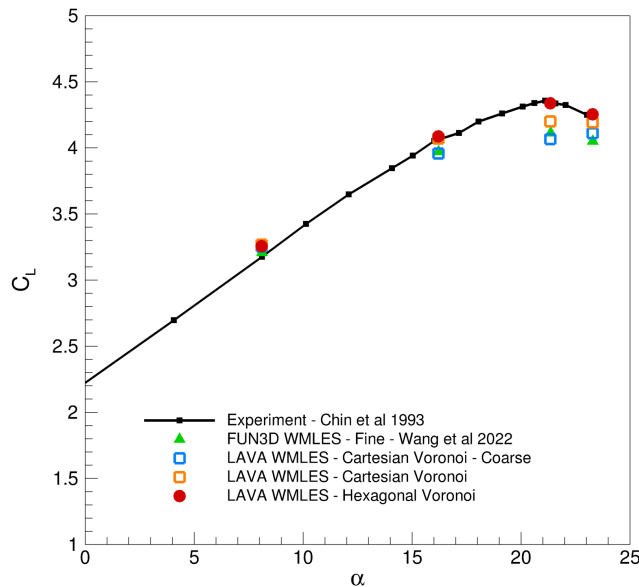
- Multi-element airfoil meshed using telescoping wall-distance based refinement zones
 - 1.5x coarsening factor for each consecutive band
 - Added wake refinement box
- 4 body-aligned wall layers
- Created both Cartesian and hexagonal type meshes



Unstructured WMLES Results – 30P30N



- $Ma = 0.2$, $Re = 9e6$,
- 3D, 10% chord simulated span-wise with periodic boundary conditions
- Wall-modeled LES with subgrid scale model and central blended convective flux formulation

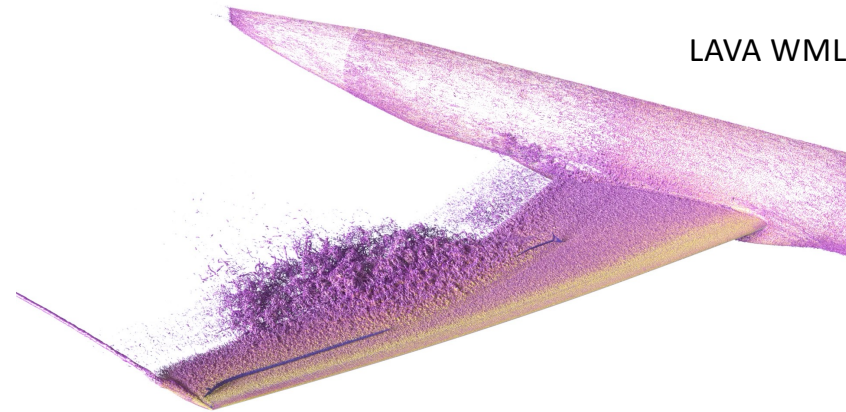


Mesh	# Cells (millions)	Span extent (% chord)
LAVA Voronoi - Hexagonal	51	10
LAVA Voronoi - Cartesian	42	10
FUN3D – Mixed Element - Fine	10	4

“Evaluation of Voronoi Meshes for Large Eddy Simulations of High Lift Aerodynamics”, Sozer et. al. AIAA SciTech 2023

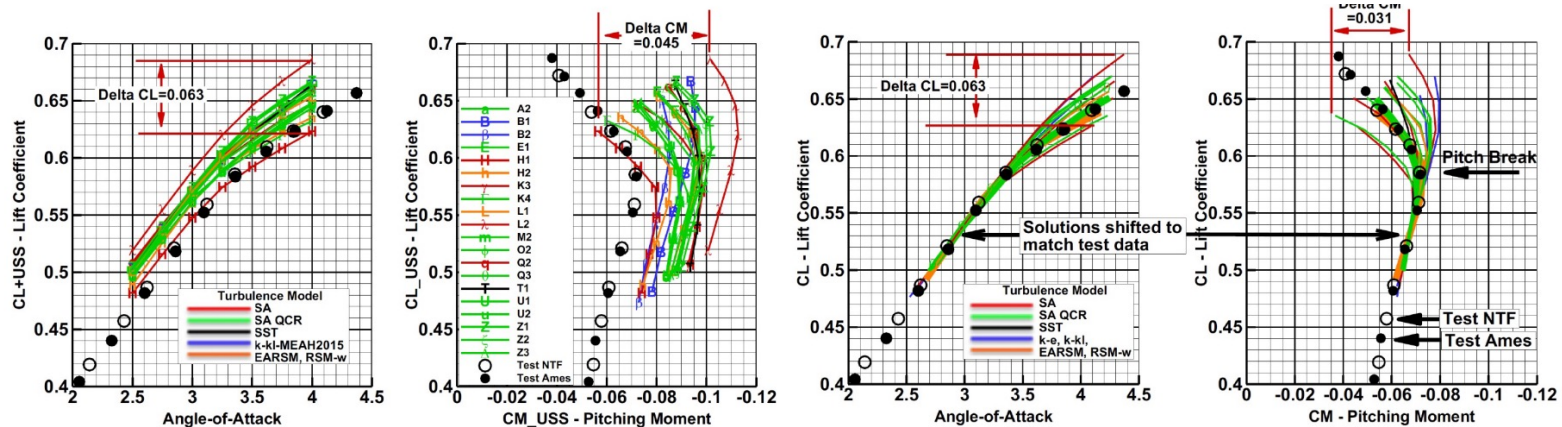
Transonic Buffet: Shock Induced Flow Separation

- Perturbations to Angle of Attack and Mach number about the cruise state can result in onset of a flow instability: shock-induced buffet.
- Large scale flow-separation can induce large-scale unsteadiness: classical RANS models have been shown to be inaccurate in such flow regimes
- Problem has been the focus of 7 previous AIAA “Drag Prediction Workshops”



LAVA WMLES

T = 0.000s



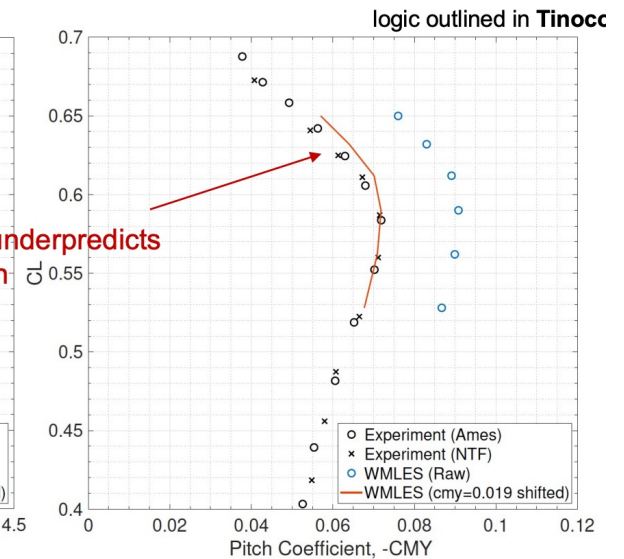
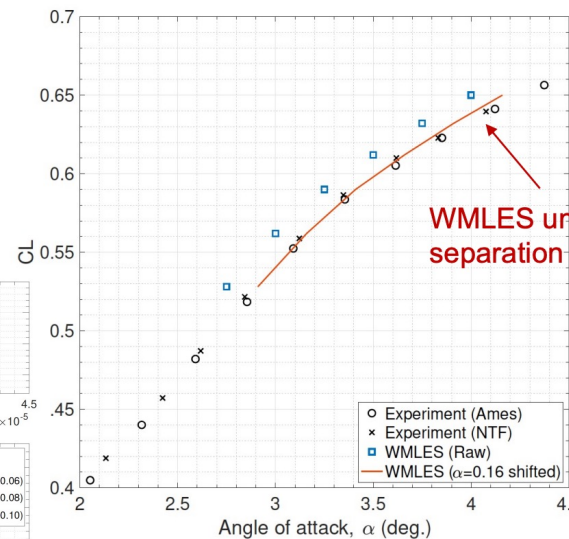
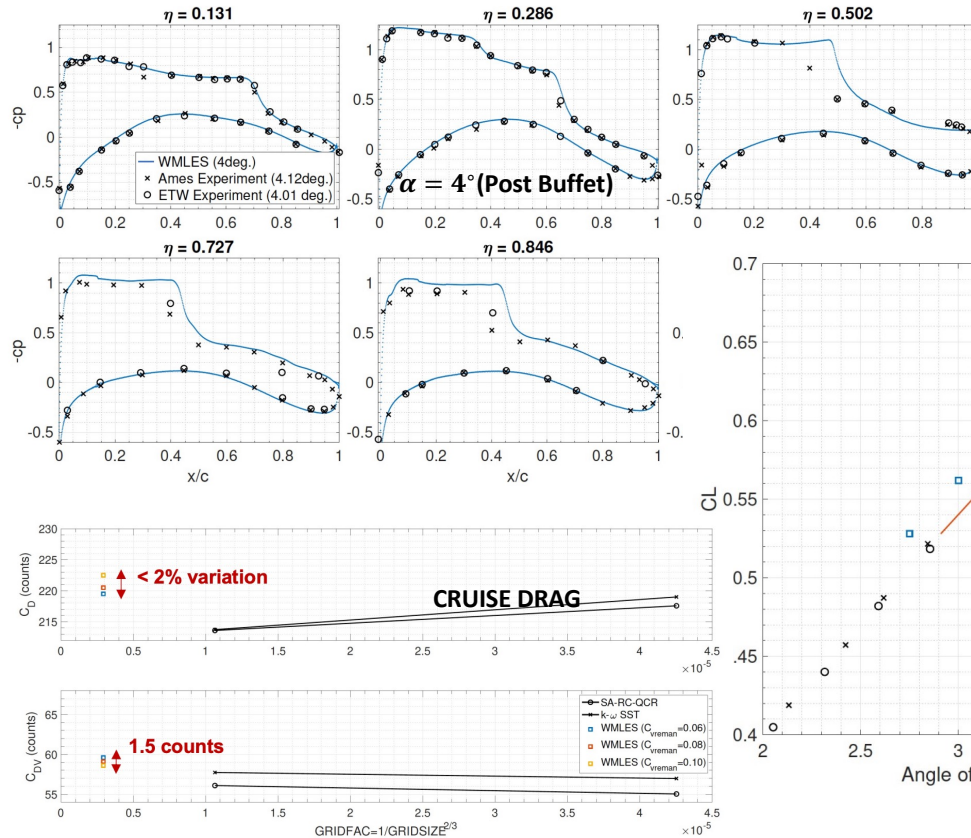
(a) Raw data

(b) Shifted data



Transonic Buffet: Shock Induced Flow Separation

First WMLES to show accurate predictions of cruise conditions and post-buffet separated flow



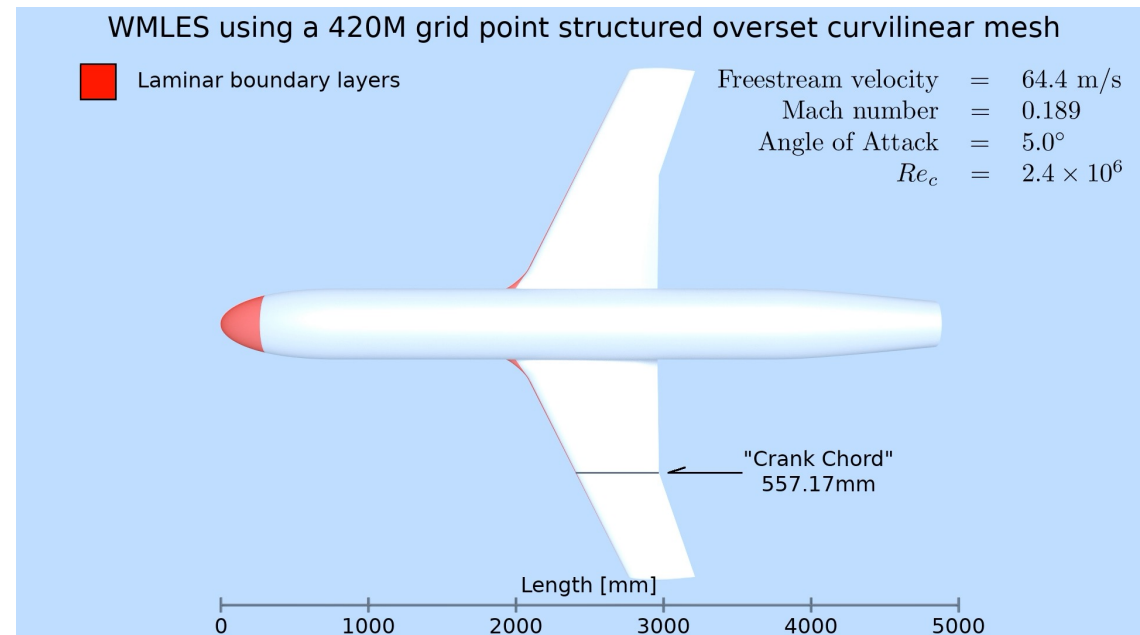
“Transonic lift and drag predictions using Wall-Modelled Large Eddy Simulations” by Ghate et. al. AIAA SciTech 2021 Forum <https://doi.org/10.2514/6.2021-1439> and AMS Seminar <https://www.nas.nasa.gov/pubs/ams/2021/04-01-21.html>

NASA Juncture Flow Model



- Benchmark experiment performed at NASA Langley 14x22ft tunnel to study CFD predictiveness when **corner-flow separation** occurs:

- Linear eddy-viscosity closures have a fundamental flaw for flows in corners – they do not permit occurrence of secondary flow
- Corrections such as Quadratic Constitutive Relation (QCR) seem to have mixed results; also require additional tuning parameters and calibration
- Scale resolving simulation methods such as WMLES appear to be attractive given the complexity of the underlying physics

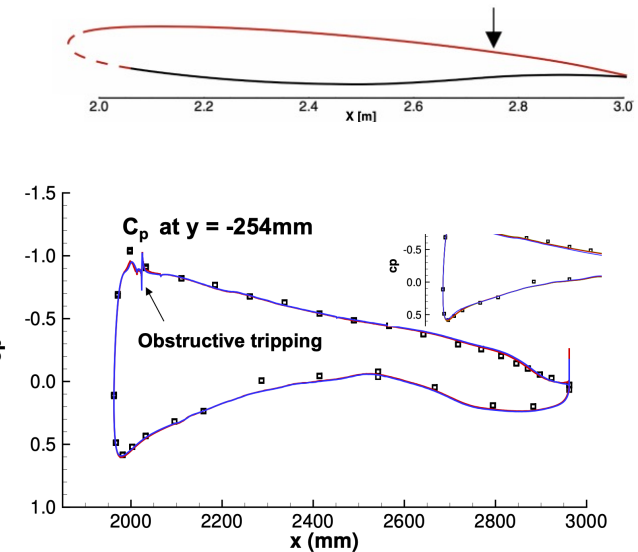
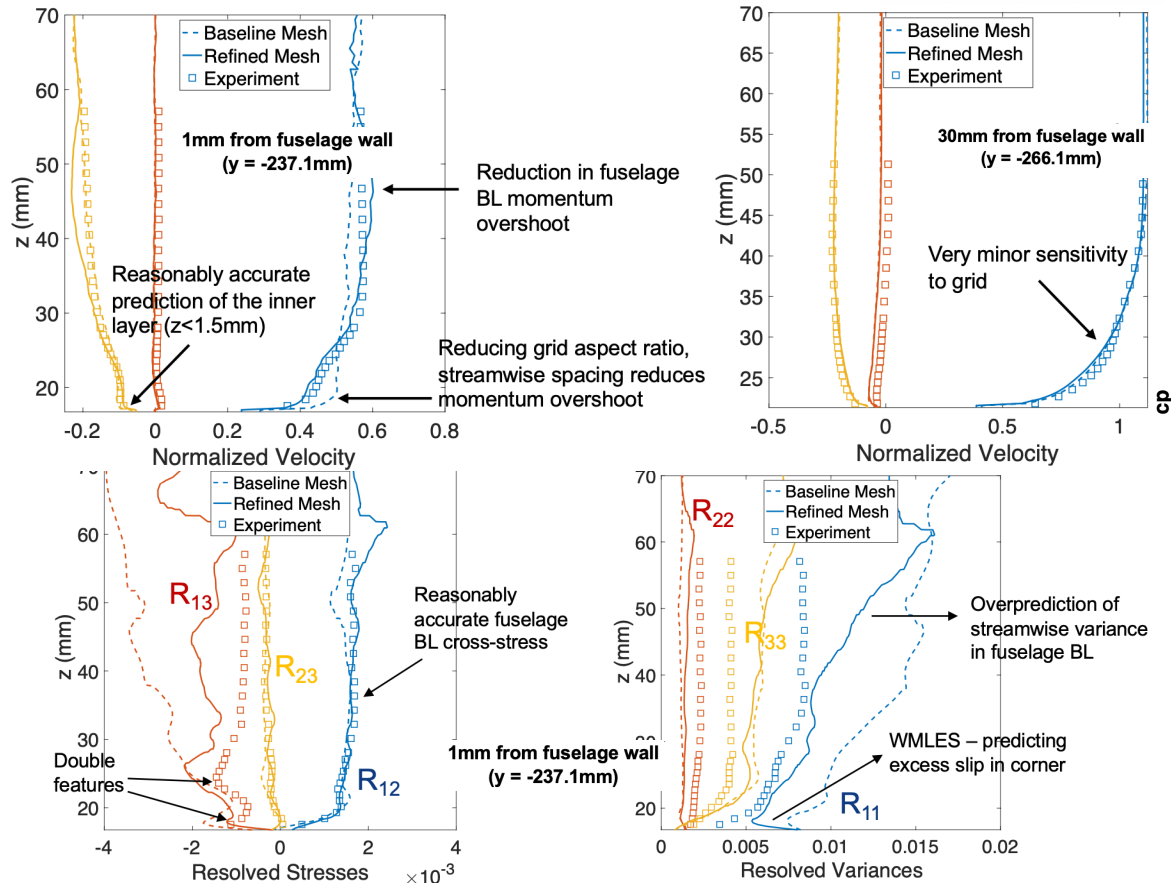


- Juncture flow experiment allows for a **very rich set of comparisons** between experiment and simulations: several profiles of velocity and Reynolds stresses available for comparison along with time-averaged pressure loadings.

“Scale Resolving Simulations of the NASA Juncture Flow Model using the LAVA Solver” by Ghate et. al. AIAA Aviation 2020 Forum .

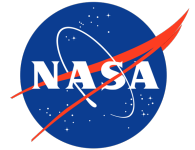
<https://doi.org/10.2514/6.2020-2735> and AMS Seminar <https://www.nas.nasa.gov/pubs/ams/2020/09-10-20.html>

NASA Juncture Flow Model



WMLES shows a clear trend towards convergence to the experimental results with grid-refinement

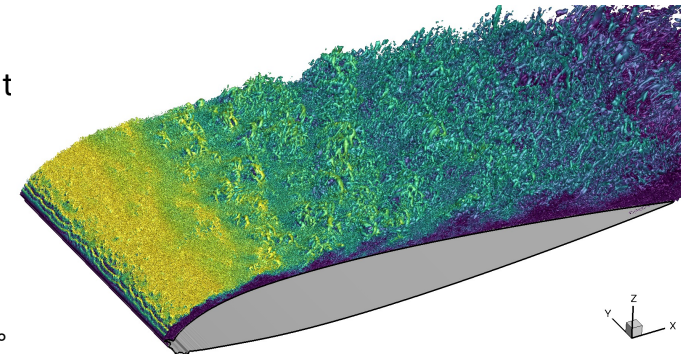
Scale Resolving Simulations to Predict Iced Aircraft Aerodynamics



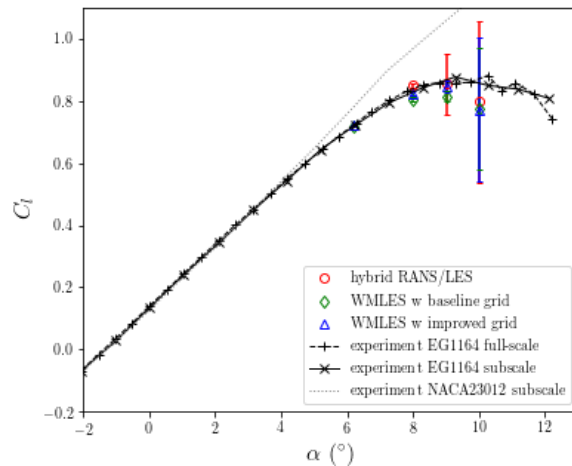
- Penalty immersed boundary approach with hybrid RANS/LES (HRLES) and wall-modeled large-eddy simulation (WMLES) methods on the aerodynamics prediction using overset curvilinear mesh is investigated
- The subscale benchmark case of a NACA23012 airfoil* with horn-ice accretion at Reynolds number **1.8 million** and Mach number **0.18** chosen
- The numerical results from hybrid RANS/LES and WMLES with the penalty immersed boundary method compare well with the experimental results

"Numerical Study on the Aerodynamics of an Iced Airfoil with Scale-Resolving Simulations" Wong et al. AIAA SciTech 2023 Forum

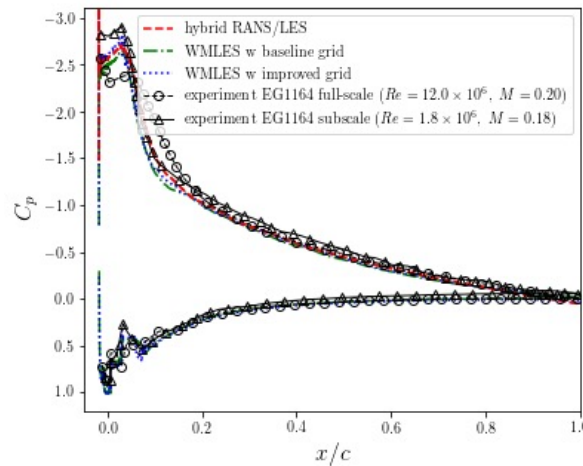
Q-criterion isosurface from HRLES at $\alpha = 8.0^\circ$



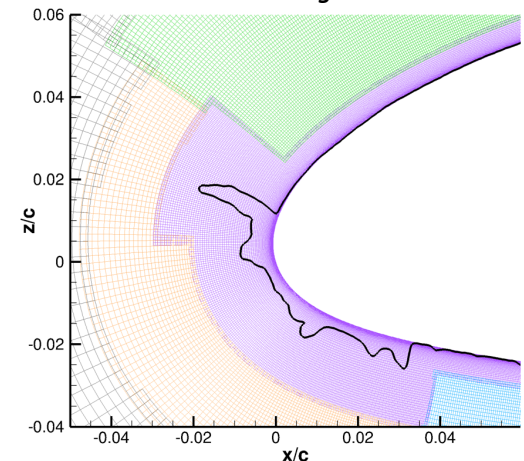
Lift curve



Pressure coefficient at $\alpha = 8.0^\circ$



2D tracing of the ice accretion on the HRLES grid



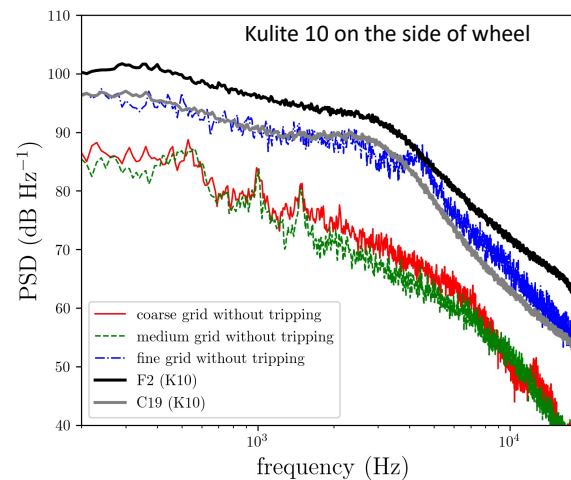
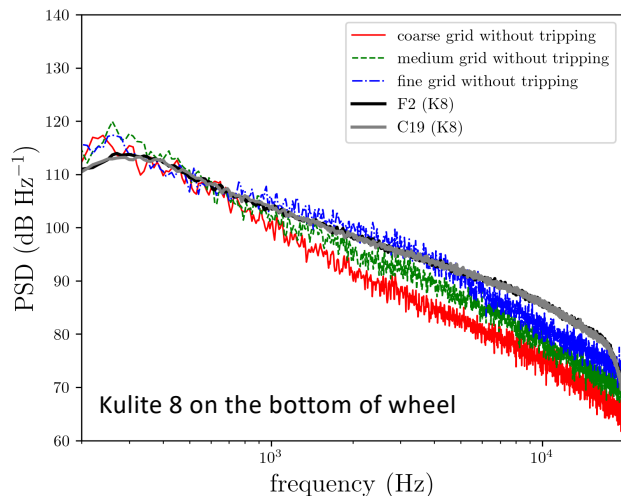
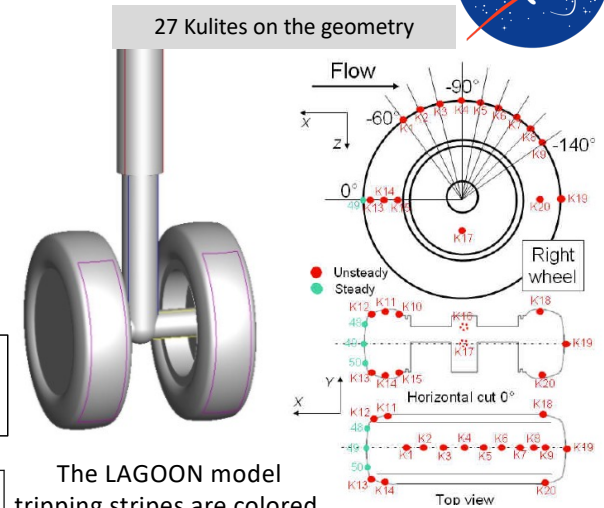
**EG1164 case: full scale 72-inch-chord NACA 23012 with horn ice [Broeren, Andy P., et al. 2010]*

WMLES to Predict Landing Gear Acoustics

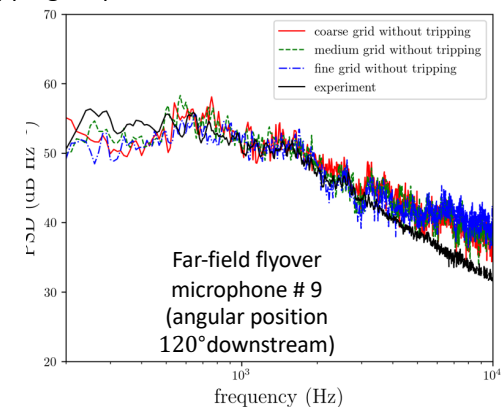


- BANCIII benchmark LAGOON landing gear problem [Manoha & Caruelle 2015]
- 2-wheel landing gear (LG) which is a 1:2.5 nose LG for an Airbus A320 aircraft
- Reynolds number: 1.55 million; Mach number: 0.23
- The irregular shape of the landing gear with the struts and axle is challenging for body-fitted meshing, especially for a fully-dressed landing gear
- Laminar to transition tripping stripes imposed on wheels, axle and struts to model the actual flow past a real nose landing gear
- Detailed experimental results from F2 and C19 wind tunnels

"Predictions of LAGOON Nose Landing Gear Flow and Noise using Wall-Modeled Large Eddy Simulations" Wong et al.
28th AIAA/CEAS Aeroacoustics 2022 Conference. DOI: <https://doi.org/10.2514/6.2022-2850>
AMS Seminar - <https://www.nas.nasa.gov/pubs/ams/2022/08-30-22.html>

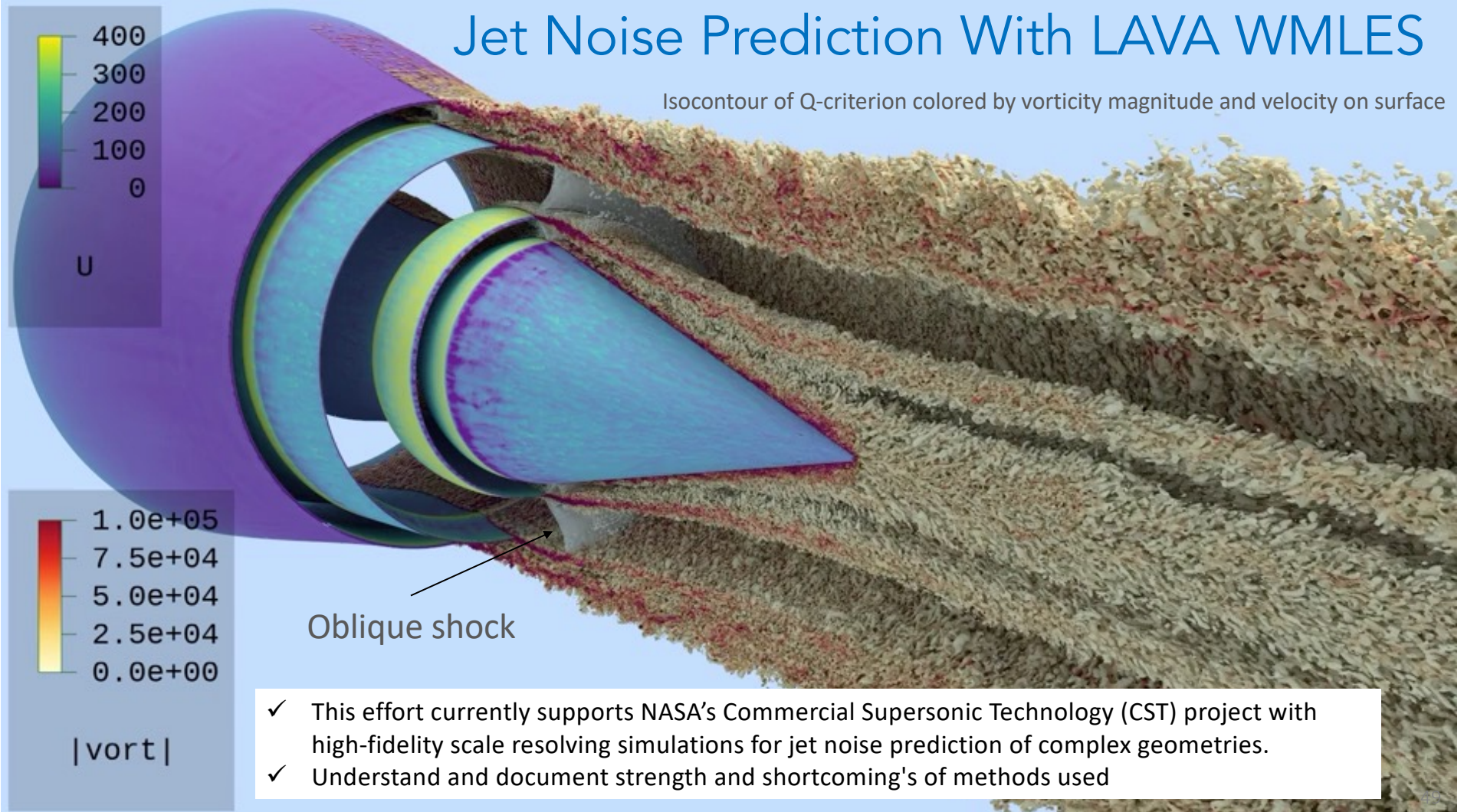


The LAGOON model
tripping stripes are colored



Jet Noise Prediction With LAVA WMLES

Isocontour of Q-criterion colored by vorticity magnitude and velocity on surface

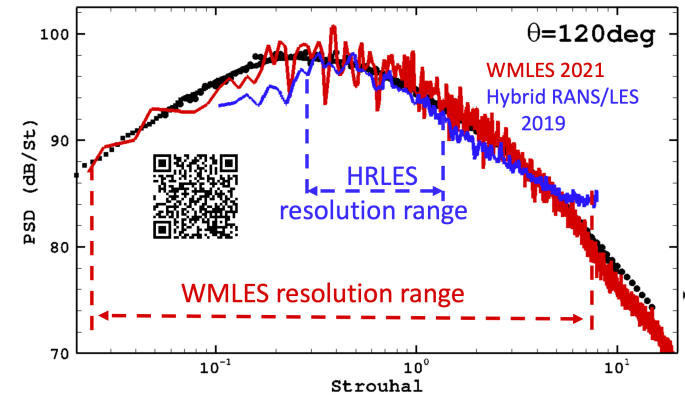


Jet Noise Prediction with WMLES



- **WMLES successfully applied to the prediction of jet noise within NASA CST**
 - Significant improvements in turnaround times (63x) compared to hybrid RANS/LES have been demonstrated
 - Improvements have enabled simulations previously not feasible
- **A first of it's kind database was generated utilizing WMLES within LAVA for NASA CST's Prediction Uncertainty Reduction (PUR) technical challenge.**
 - A total of 20 different flow configurations have been simulated using high-fidelity scale-resolving LES
 - Each simulation takes around 24hr and generates 100 TB of data
 - Excellent agreement with experiments within 1dB (comparable to experimental rig-to-rig uncertainty)

Improved resolution range for far-field noise at 100D from nozzle exit



Stich et. al. AIAA2022-3002 & AIAA2022-0684

Path towards a robust, reliable and fast WMLES solver for jet noise database generation

November 2019

Hybrid RANS/LES

6.5 days [100 Broadwell]



63 x speedup

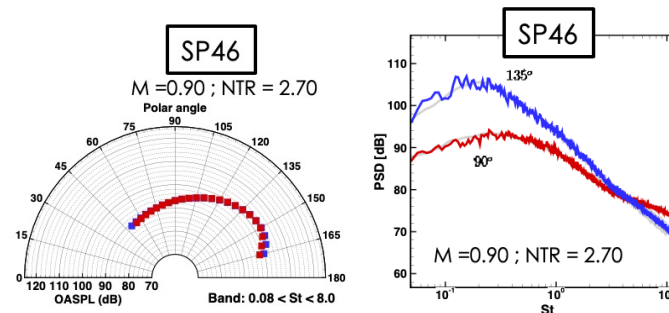
Today

WMLES + Optimized Code & Best Practices & Scaling

150 minutes [100 Rome]

Set Point SP	Ma [-]	M _j [-]	M _∞ [-]	NPR [-]	NTR [-]	Exp. Data PIV MIC
3	0.50	0.51	0.0	1.197	0.96	✓ ✓
7	0.90	0.98	0.0	1.852	0.84	✓ ✓
23	0.50	0.38	0.0	1.102	1.76	✓ ✓
27	0.90	0.68	0.0	1.368	1.76	✓ ✓
29	1.33	1.00	0.0	1.898	1.76	✓ ✓
38	1.33	0.88	0.0	1.664	2.27	✗ ✓
46	0.90	0.56	0.0	1.219	2.70	✓ ✓
49	1.48	0.90	0.0	1.697	2.70	✓ ✓
101240	1.14	0.85	0.0	1.608	1.78	✗ ✓
100084	1.32	1.09	0.3	2.110	1.48	✗ ✓
100024	1.01	0.85	0.3	1.616	1.40	✗ ✓
100274	1.20	0.99	0.3	1.875	1.47	✗ ✓
101244	1.13	0.85	0.3	1.603	1.78	✗ ✓

PUR Database Set Points



Overall Sound Pressure Level (OASPL) and Power Spectral Density (PSD) for SP46 at 100D from nozzle exit

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Iso-surfaces of Q-criterion
 $\alpha = 19.98^\circ$, Cartesian WMLES
3mm, 2010M point mesh
Video Credit: Timothy Sandstrom



Thank you for your attention!