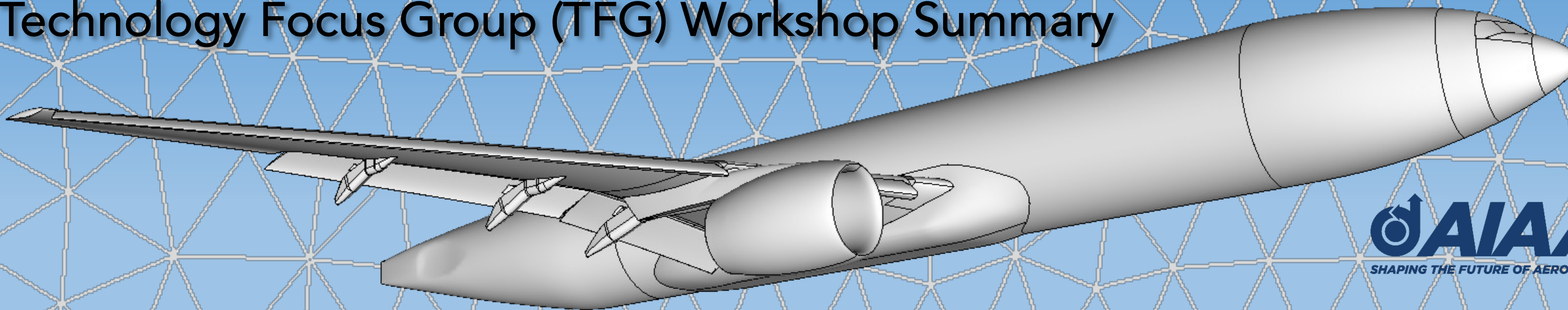
HLPW-4/GMGW-3: Wall-Modeled LES and Lattice-Boltzmann Technology Focus Group (TFG) Workshop Summary



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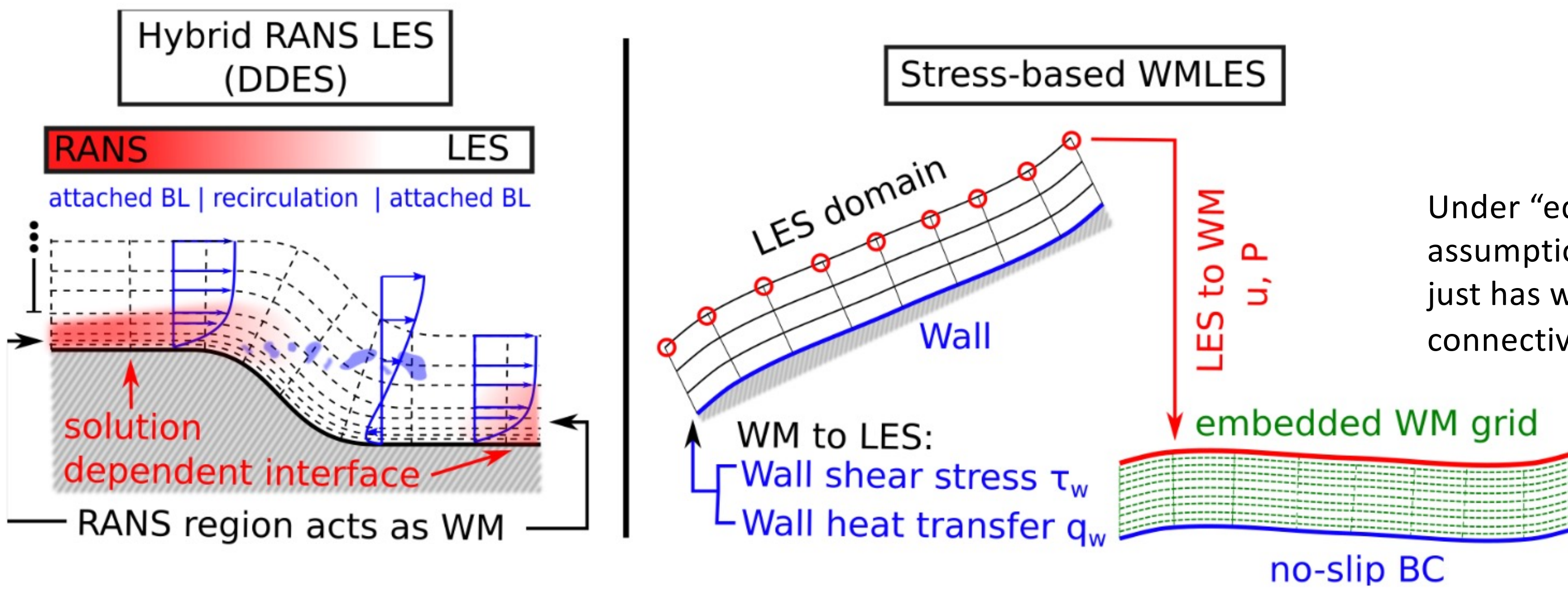
- ✓ *Partially supported by NASA ARMD T^3*
- ✓ *Special thanks to*
  - *WMLES-LB TFG Teams*
  - *Chris Rumsey (NASA LaRC)*
  - *Nigel Taylor (MBDA UK)*

AIAA Aviation Forum, Chicago, IL, June 27-30, 2022

Terminology

- **Equilibrium 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.**



Under “equilibrium” assumption this grid just has wall-normal connectivity

Terminology

- **LES**: Large Eddy Simulations; grid scale is used as the filter length scale since no participant is using explicit filtering
- **Subgrid scale (SGS) modeling**: Closure model used to capture effect of unresolved scales on the large resolved scales. All participants are using either a) eddy viscosity closures (purely dissipative SGS), or b) no SGS model with numerical dissipation serving as an SGS model (implicit LES).
- **Wall-model/Wall-function**: Model used to approximate the wall-stress using the solution at a certain distance from the wall. The wall-stress is either directly applied as a stress BC or interpreted via numerical discretization. Most participants are using an algebraic model that requires a Newton solve, while one participant is using an ODE-based model which requires a tridiagonal solve.
- **Exchange location**: The distance from the wall where the solution is interpolated as an input to the wall model. All participants are using a distance between 0.5Delta – 2Delta. None of the participants use any time filtering of the LES solutions prior to its use in the wall-model.
- **Numerical transition**: WMLES that relies on development of boundary layer instabilities to capture laminar to turbulent transition with a turbulent boundary layer assumed everywhere. This transition treatment can be grid-size, numerical discretization and SGS closure dependent with some sensitivity to grid refinement expected. For low Reynolds numbers, it is often preferable to “numerically trip” the flow using either an obstacle or via suction/blowing.

Team Details

TFG ID (Name)	W (WMLES-LB)
Number of Active Participants	9 teams (~18)
Number of Observers	20+

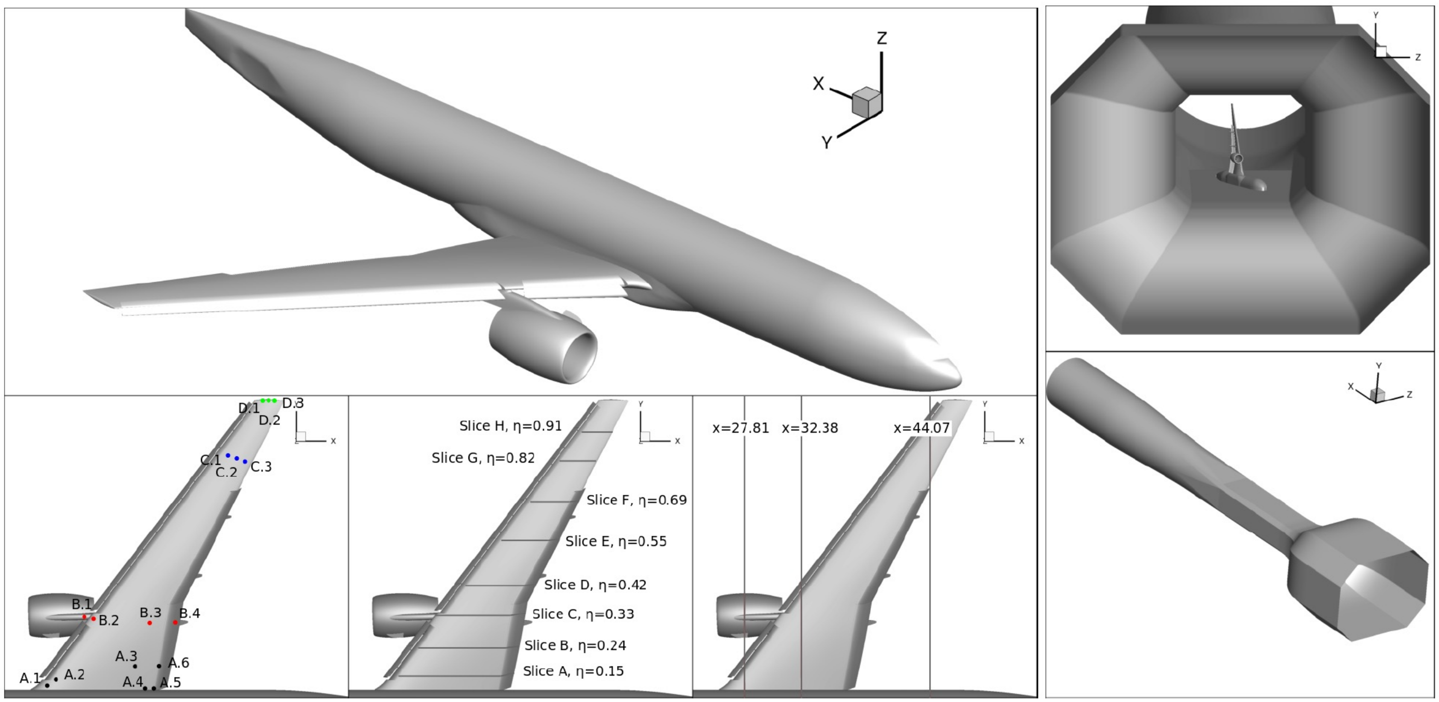
- Two participants used “committee grids”
- No major changes in geometry definition
- Case 1a/b – Flap Deflection Study
- Case 2a - C_{lmax} Study Free Air
- Case 2b - C_{lmax} Study In Tunnel

			Cases						Grid Used
Group ID	Members (Org)	Tools	1a/b	2a	2b	Time Integration	Spatial discretization	Grid Topology	Committee (C) Self (S)
W-020	NASA ARC	LAVA		x	x	RK3	$4^{th}/2^{nd}$ order finite difference	Structured overset	S
W-021	Stanford & Cascade Tech	charLES		x	x	RK3	2^{nd} order finite volume	Voronoi unstructured	S
W-030	KTH	Real Flight Simulator 2021.01		x		Implicit	finite element	Unstructured adaptive mesh	C
W-031	Boeing	BCFD Version 8r2		x		Implicit BDF2	blended 2^{nd} order finite volume	Unstructured	S
W-032	Dassault Systèmes	PowerFLOW 6-2021	x	x	x	Explicit LBM		Cartesian	S
W-034	Barcelona Supercomputing Center (BSC) & MIT	Alya		x		RK3 conv implicit CN viscous	2^{nd} order finite element	Unstructured	S
W-047	University of Kansas	hpMusic		x		Implicit BDF2	p2 flux reconstruction	Unstructured	C
W-049	Tohoku University	FFVHC-ACE		x		RK3	KEEP	Cartesian	S
W-050	NASA LaRC	FUN3D		x		Implicit BDF2	2^{nd} order finite volume	Unstructured	S

CRM-HL: Free Air and Wind Tunnel Installed

Case 2a - 9 submissions

Case 2b - 3 submissions



(a) Free Air (Case 2a)

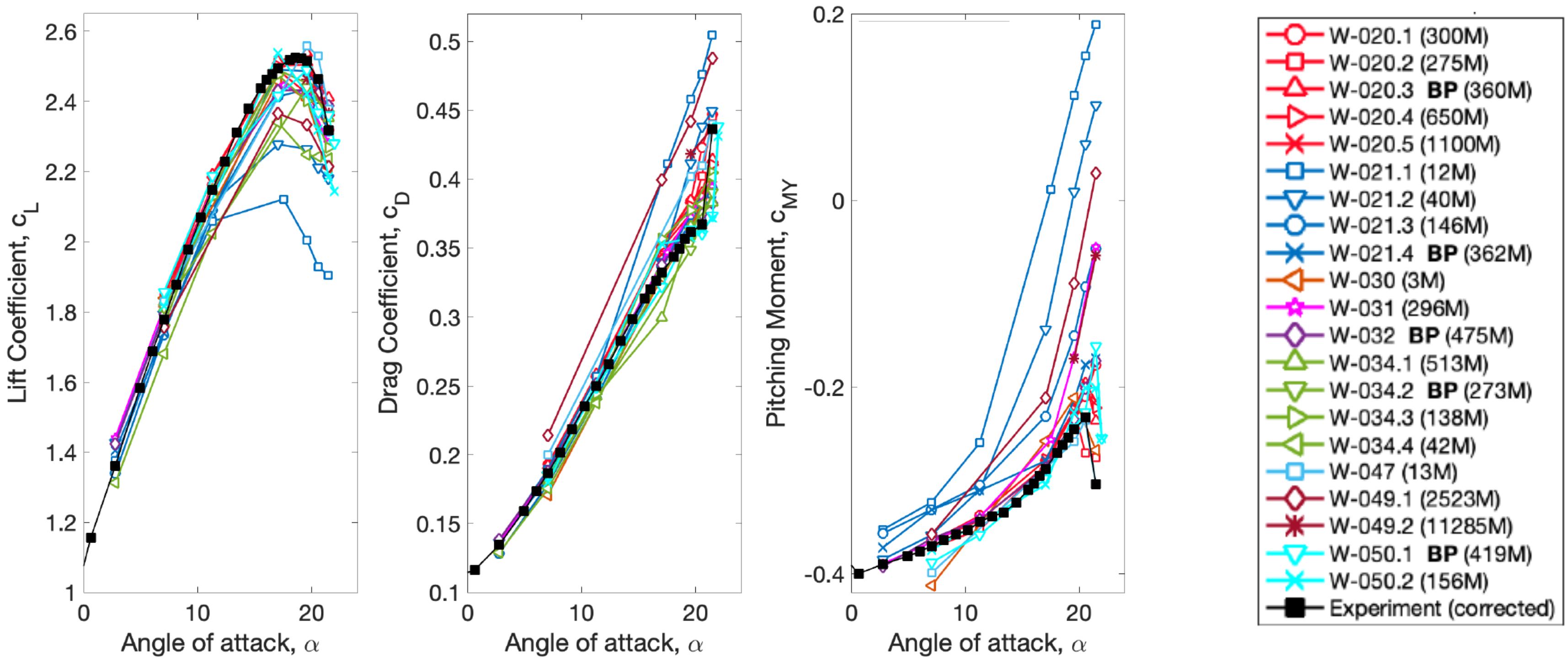
(b) Wind Tunnel (Case 2b)

WMLES-LB TFG Key Questions

- Sensitivity of integrated forces and moments to the computational grid being utilized
- Best grid strategy for WMLES and LB: Enforcing aspect ratio 1 vs. reducing off-wall spacings
- Importance of leading-edge resolution: inviscid curvature effects vs. thin transitional boundary layers
- Importance of time integration in WMLES: implicit vs explicit
- Post-CLmax stall: Role and importance of tunnel environment compared to the free-air configuration

Integrated Loads

All Submissions – Free Air (case2a)

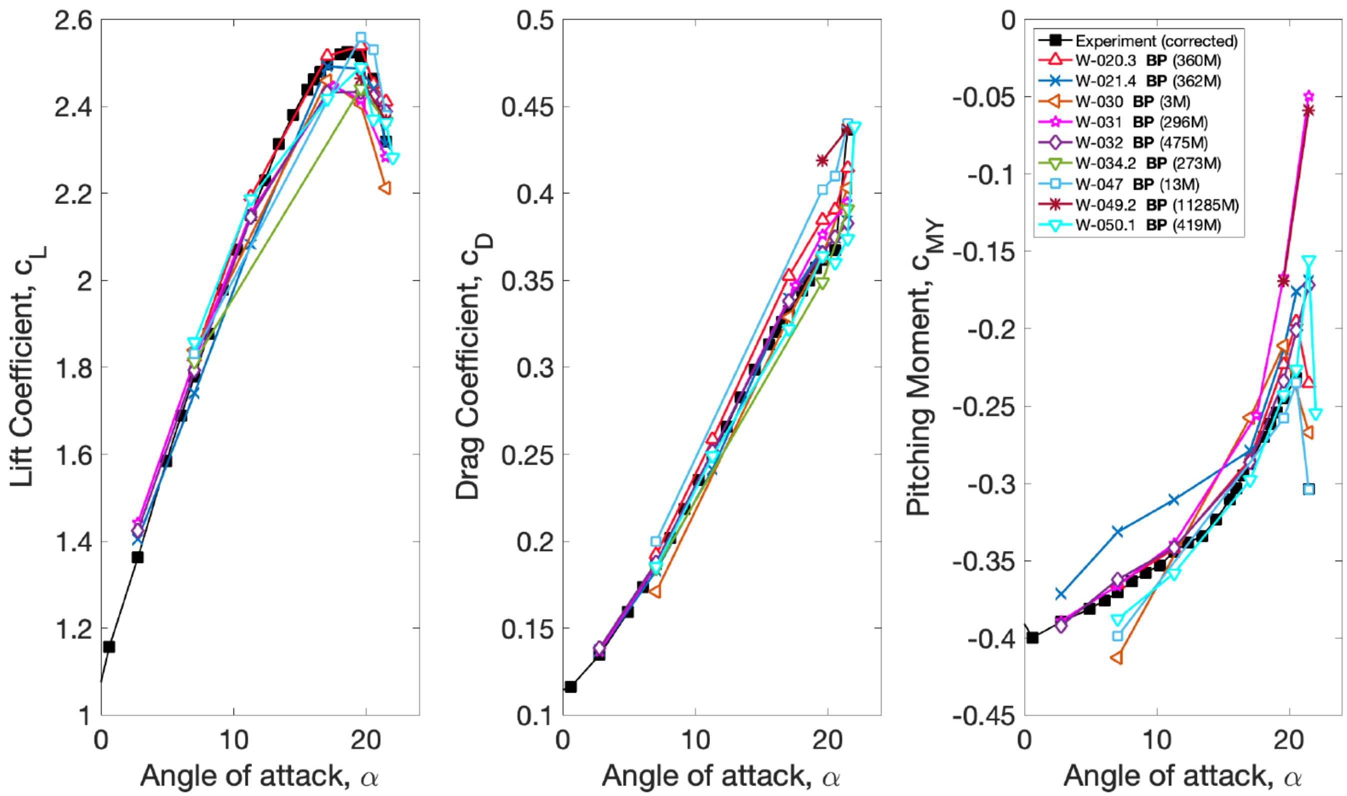


Integrated Loads

Best Practice Only – Free Air (case2a)

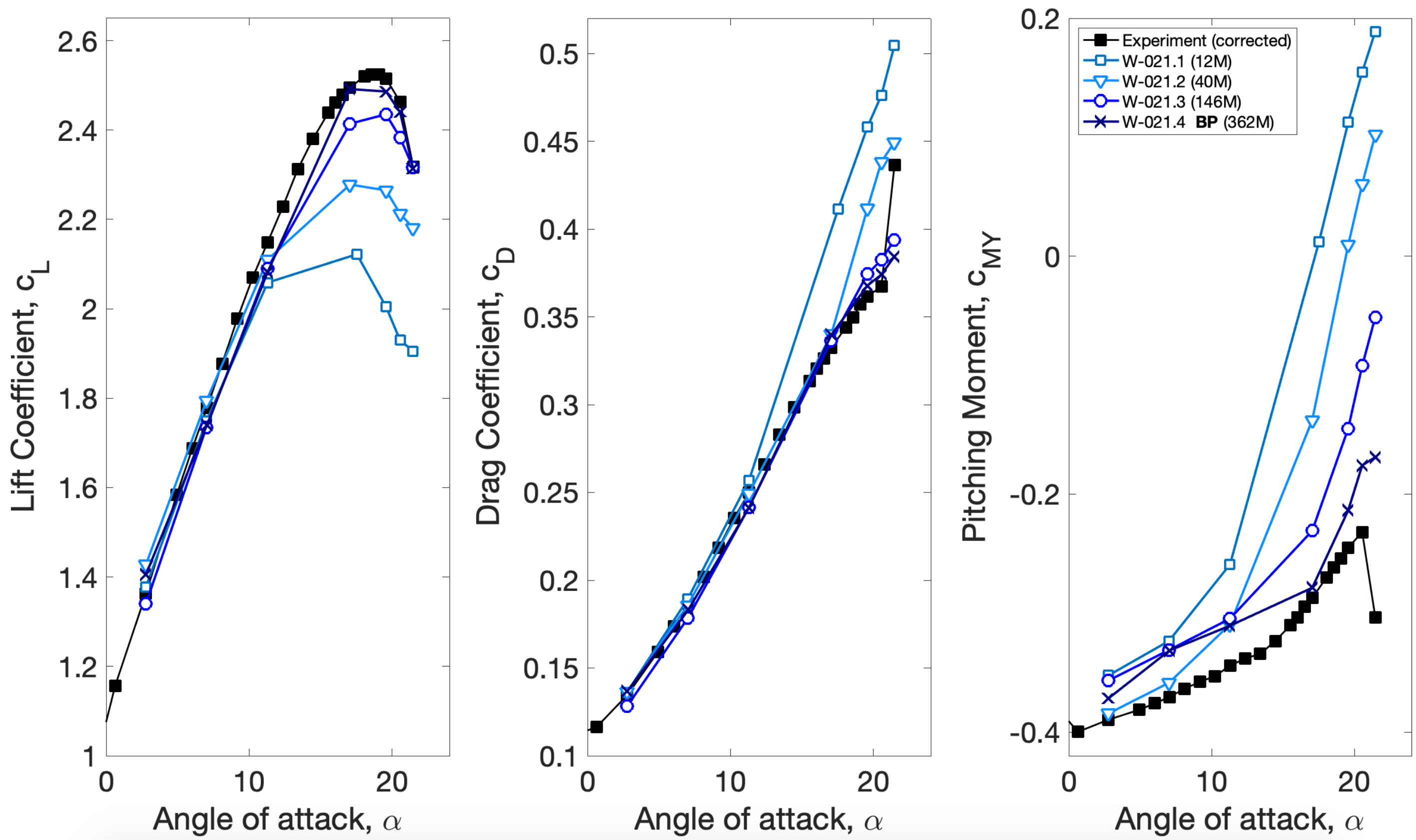
To establish integrated loads credibility, the following needs to investigated:

1. Grid convergence or sensitivity to grid
2. Stationarity of the loads history



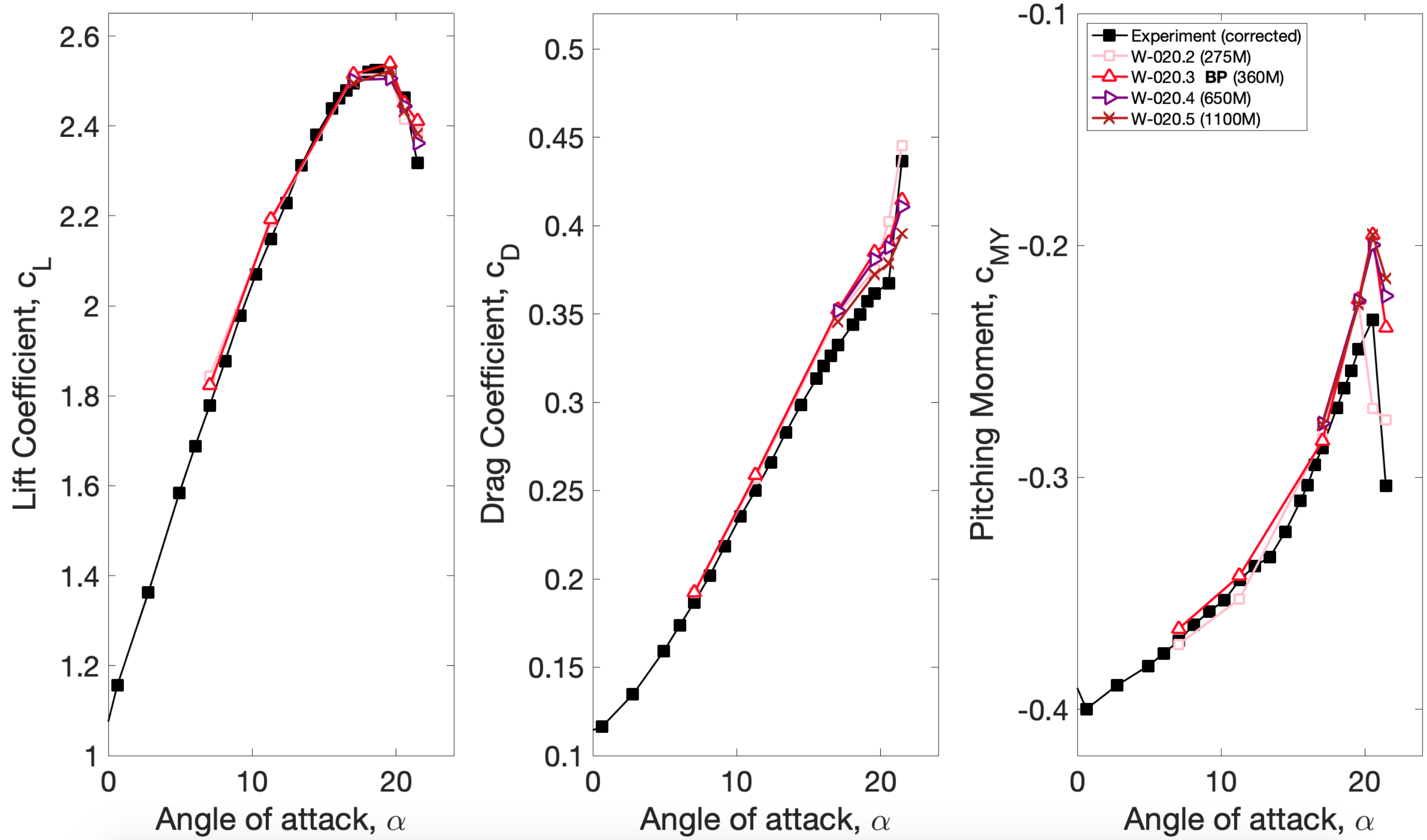
Integrated Loads

Grid Convergence Studies – Free Air (case2a) – W-021

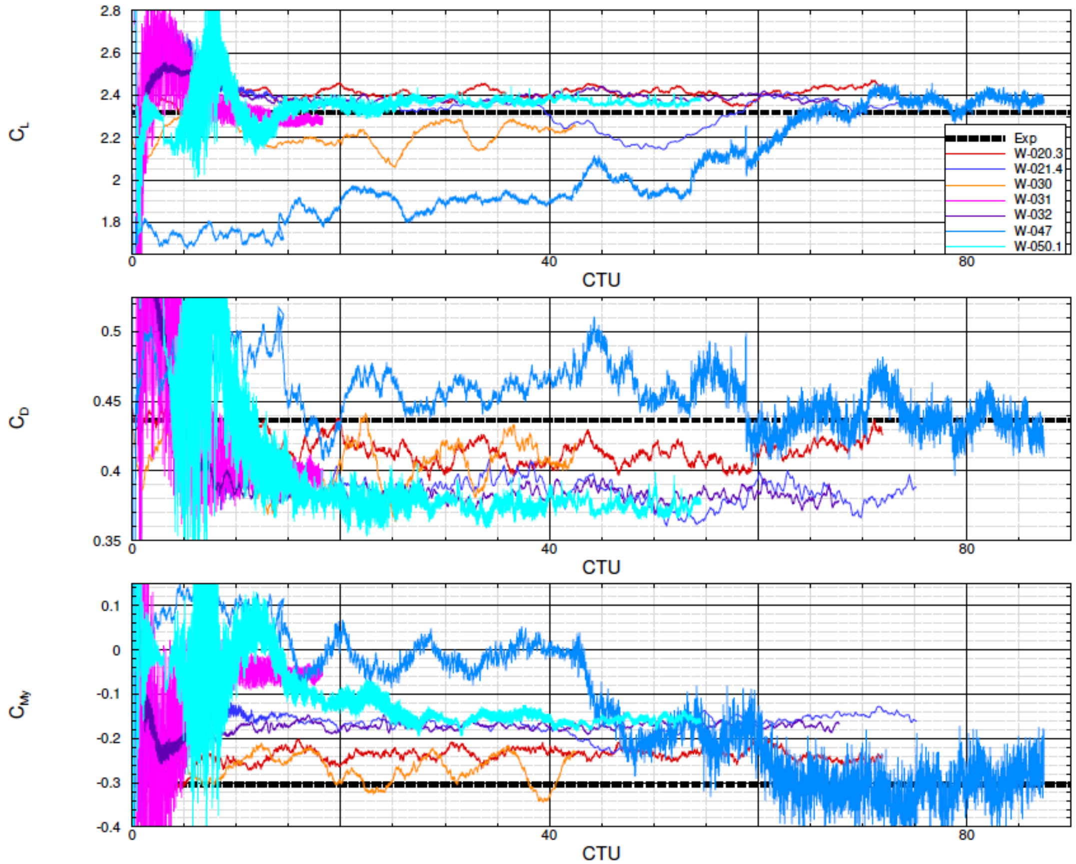


Integrated Loads

Grid Convergence Studies – Free Air (case2a) – W-020



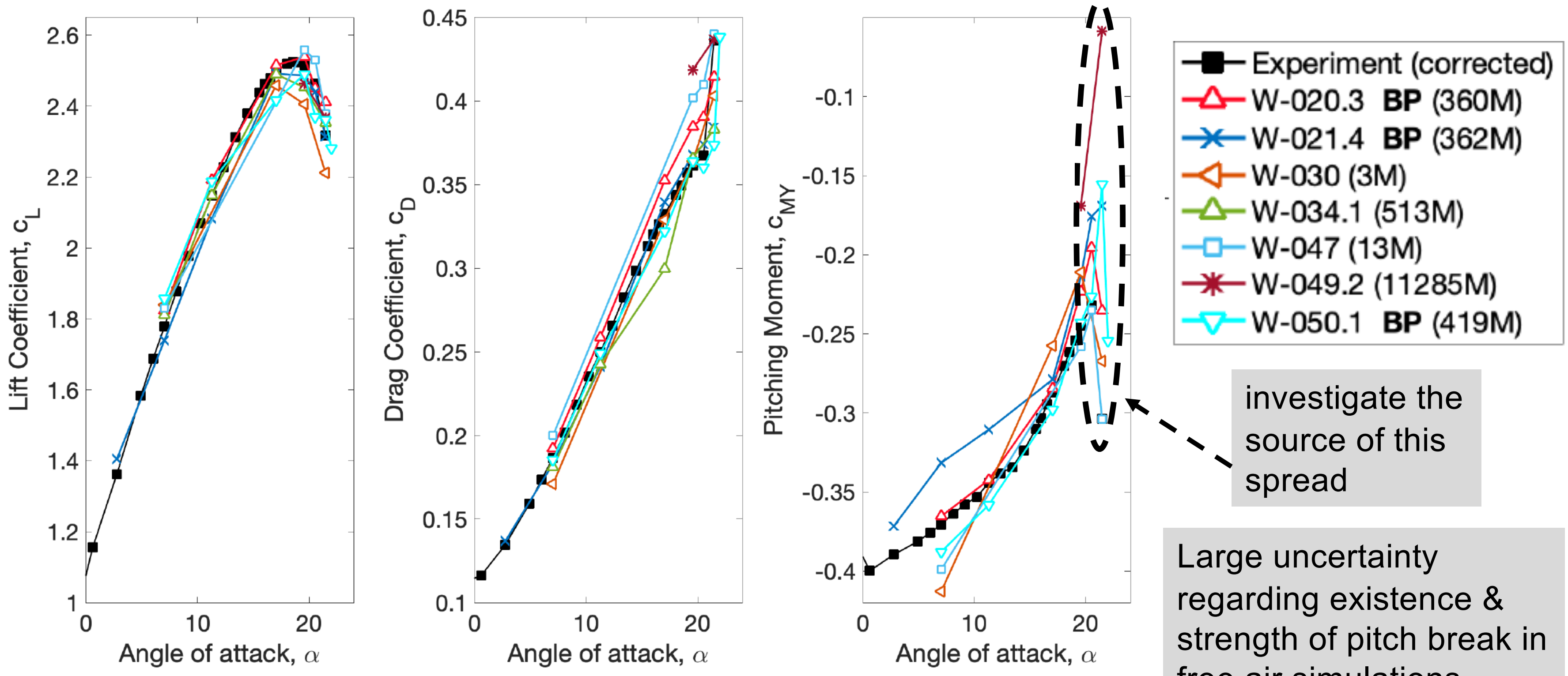
Stationarity of the Load History at 21.47°



- For high angle of attacks, it is evident that >70 CTU's is needed to have confidence in the stationary of the solution.
- No rigorous definition of stationarity was employed. Simpler test cases need to be utilized to develop a robust procedure.

Integrated Loads

Error metric (+/- 2%) at CLmax (17.05º or 19.57º) - Free Air (case2a)



investigate the source of this spread

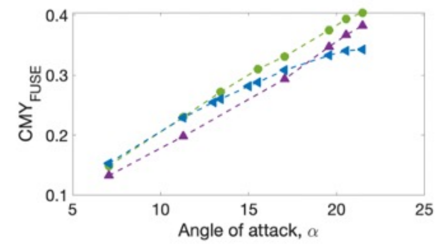
Large uncertainty regarding existence & strength of pitch break in free air simulations

Moment Balance for Pitch Break

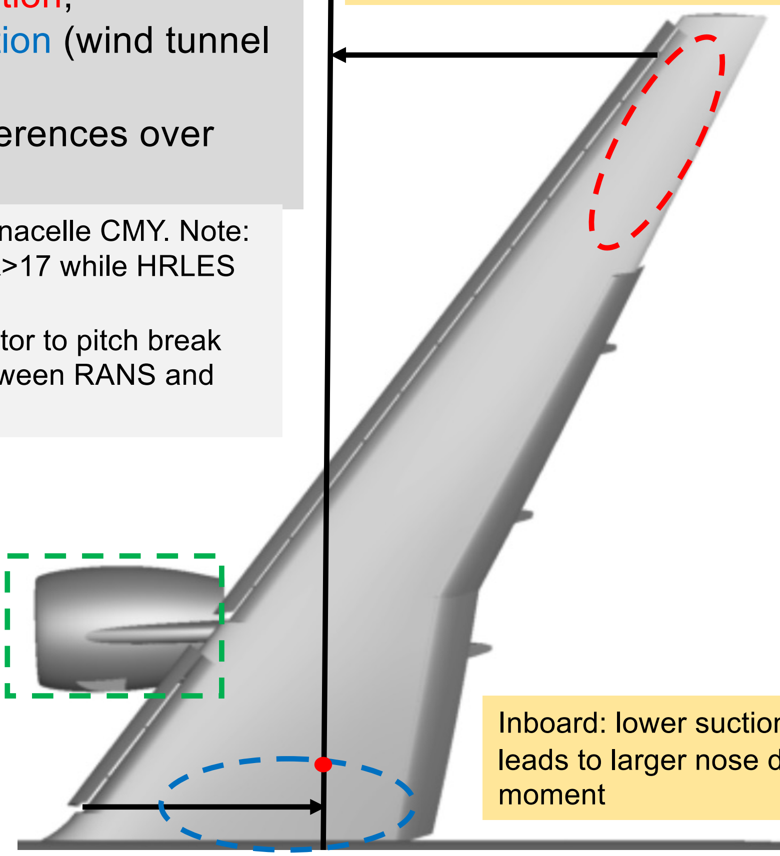
CFD will not predict a pitch break if:

- It predicts excessive outboard separation,
- It does not produce wing-root separation (wind tunnel installation effects could play a role).
- Need to emphasize flow topology differences over integral values

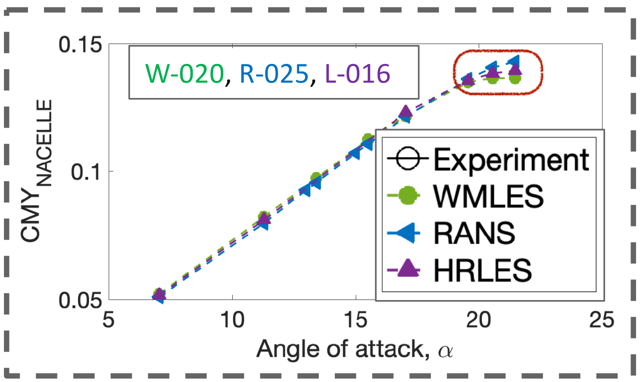
- Nacelle separation does not appear to influence nacelle CMY. Note: WMLES + RANS predict nacelle separation for α>17 while HRLES does not.
- Fuselage does not appear to be a major contributor to pitch break discussions based on the CMY comparisons between RANS and WMLES (see AIAA-2022-1554).

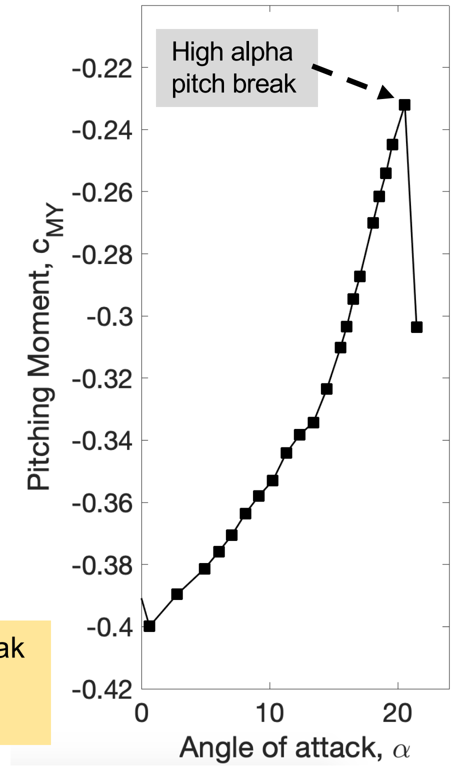


Outboard: higher suction peak leads to larger nose down moment



Inboard: lower suction peak leads to larger nose down moment



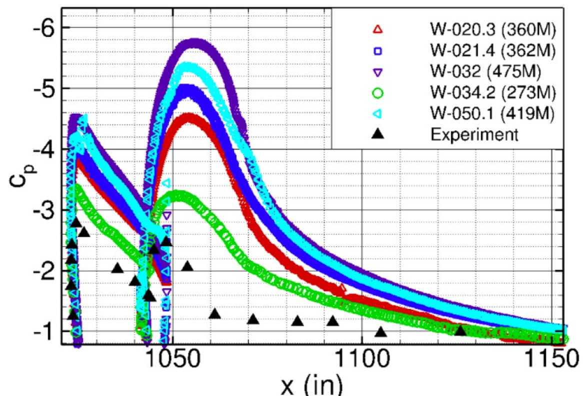


Surface Pressure Coefficient at 21.47°

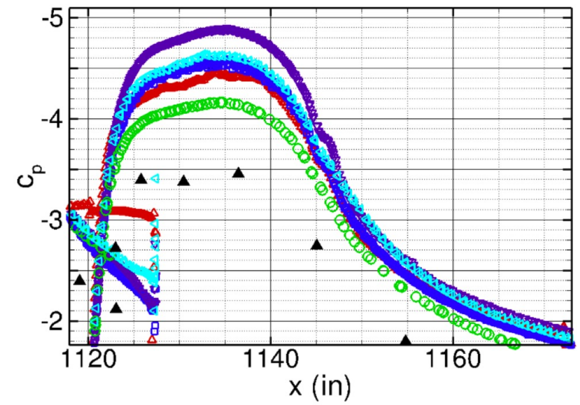
SHAPING THE FUTURE OF AEROSPACE

Free Air (case2a)

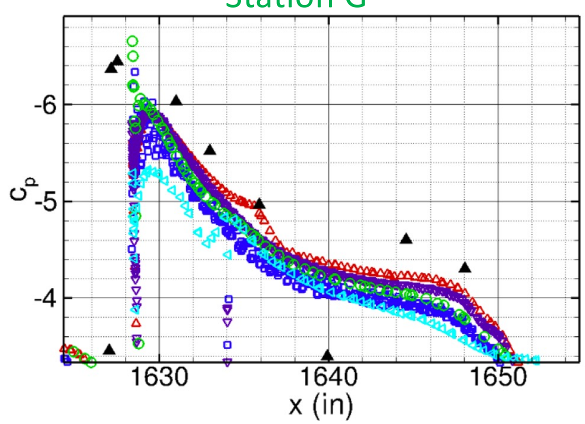
Station A



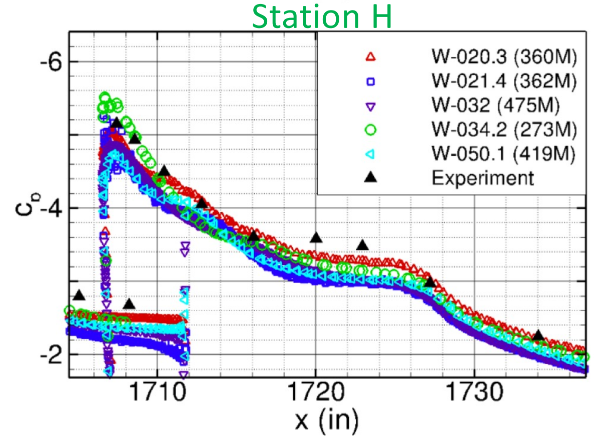
Station B

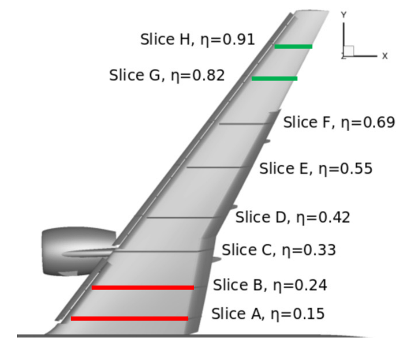


Station G



Station H

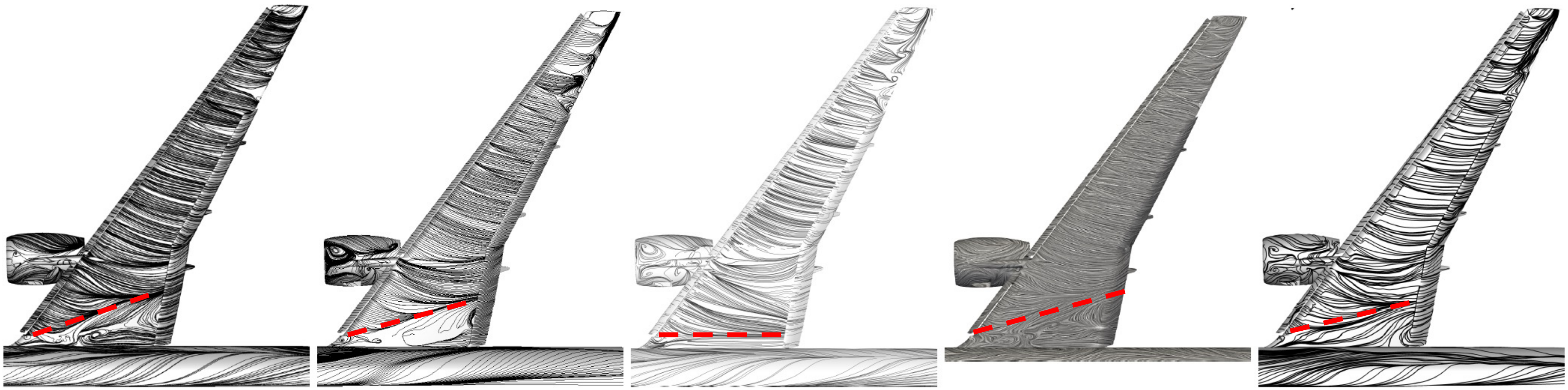




Skin Friction Streamlines at 21.47°

Free Air (case2a)

- Good agreement in the outboard flow topology between the participants – flow remains largely attached with the slat-bracket wakes visible on the main wing.
- (topology A) W-020, W-021, W-034 and W-050 all show some tendency for inboard corner flow separation while the streamlines in (topology B) W-032 remain parallel to the fuselage along the main wing.



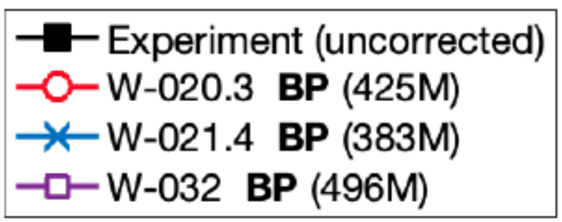
(a) W-020 topology A | (b) W-021 topology A | (c) W-032 topology B | (d) W-034 topology A | (e) W-050 topology A

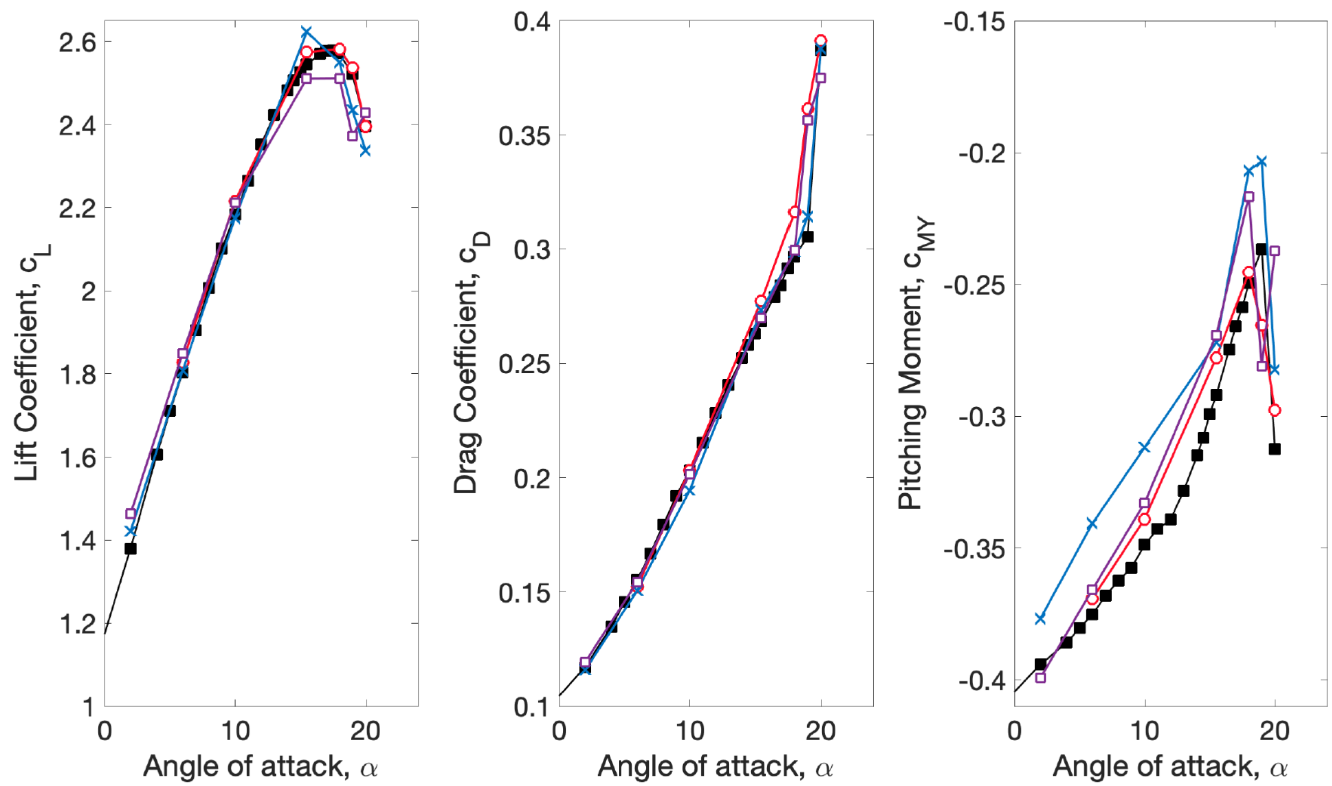
Integrated Loads

Wind Tunnel (case2b)

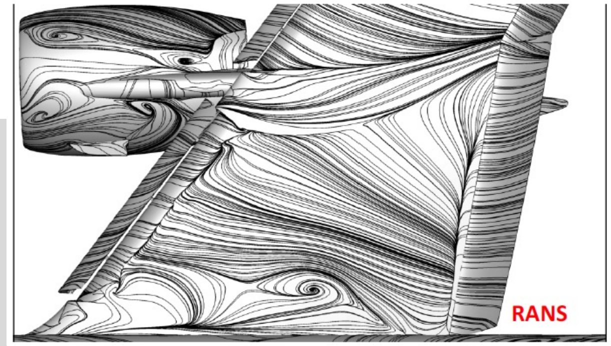
Best Practice (BP) Only

All three submitted results predict CLmax within 2% accuracy and observe a strong pitch break.



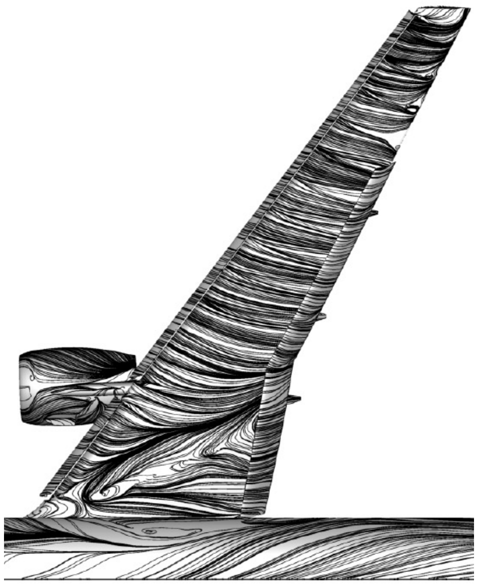


Skin Friction Streamlines at 19.98°

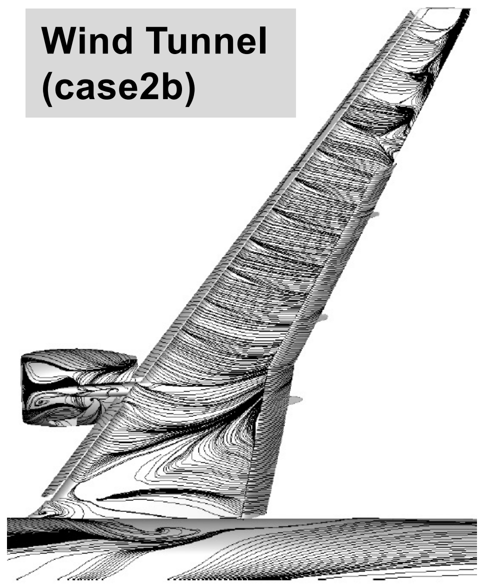


- Large inboard corner-flow separation seen for all three participants which is consistent with the oil-flow photograph from the Qinetiq tunnel experiment.
- The vortices on the fuselage and inboard wing associated with the separation is clearly visible in the skin friction streamlines predicted by WMLES.
- WMLES show significant improvement over RANS simulation (R-025, right).

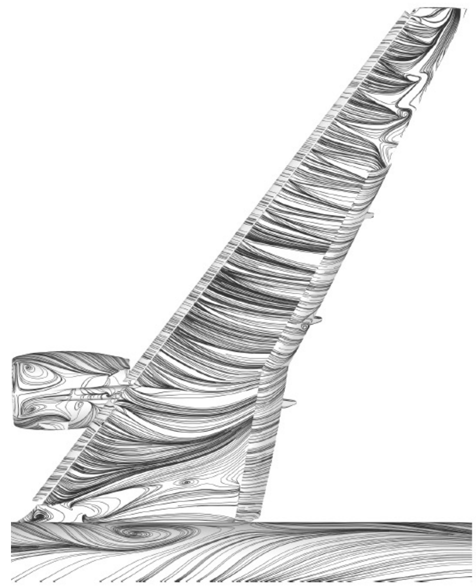
Wind Tunnel (case2b)



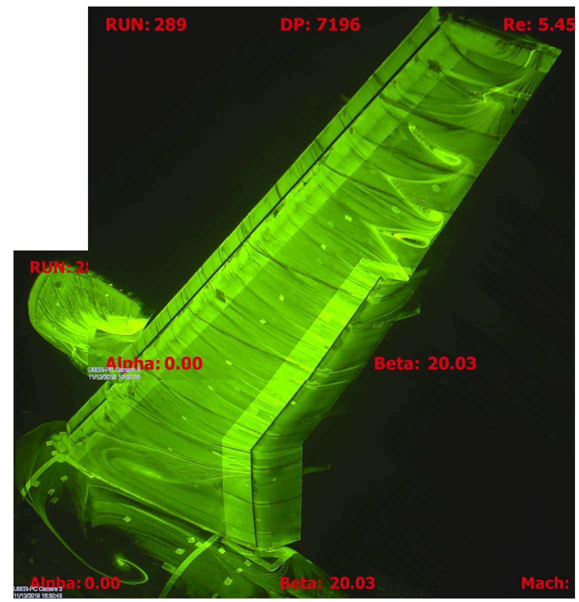
(a) W-020.3



(b) W-021.4



(c) W-032



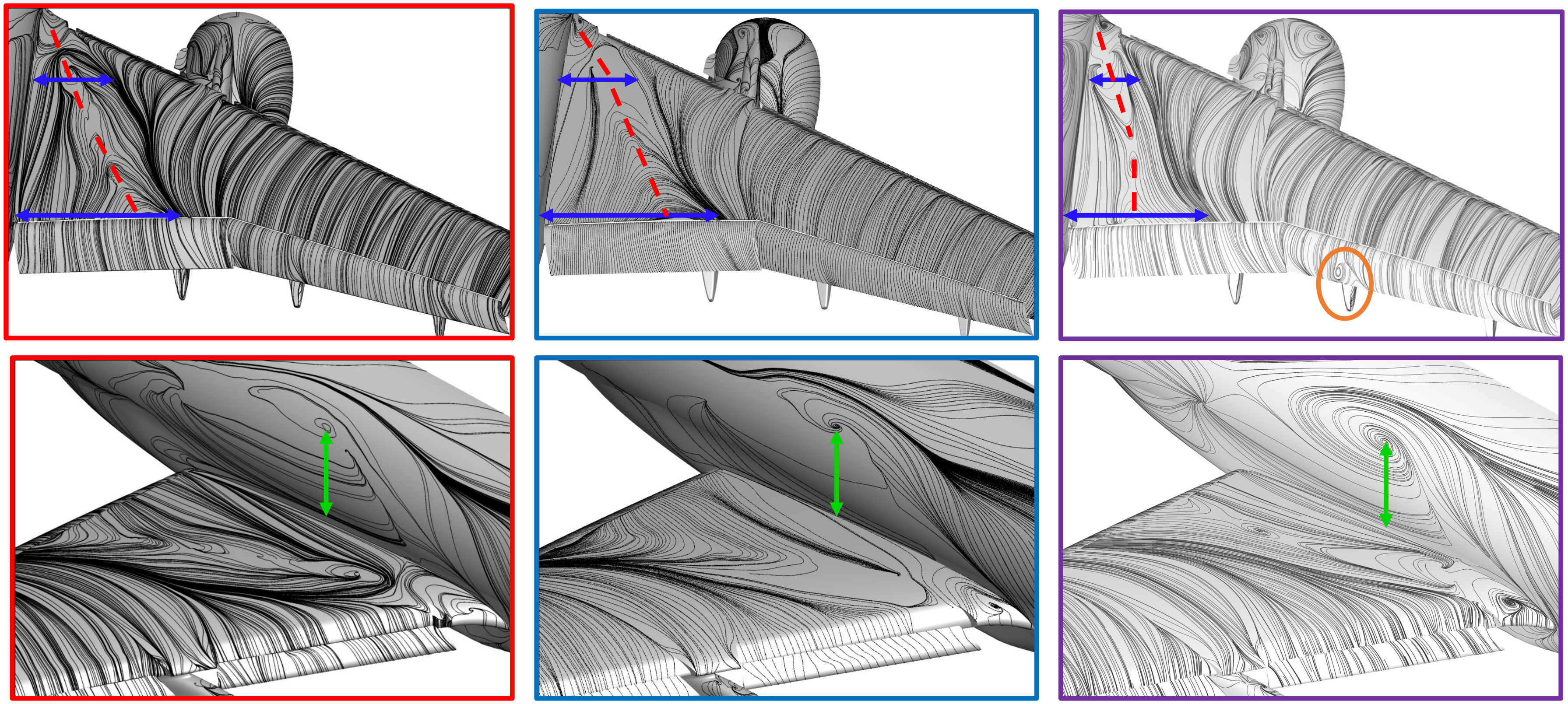
Oil Flow from QinetiQ test

Surface Streamlines at 19.97°

W-020 and W-021 have a virtually identical stalled-state.

Wind Tunnel (case2b)

W-020 W-021 W-032



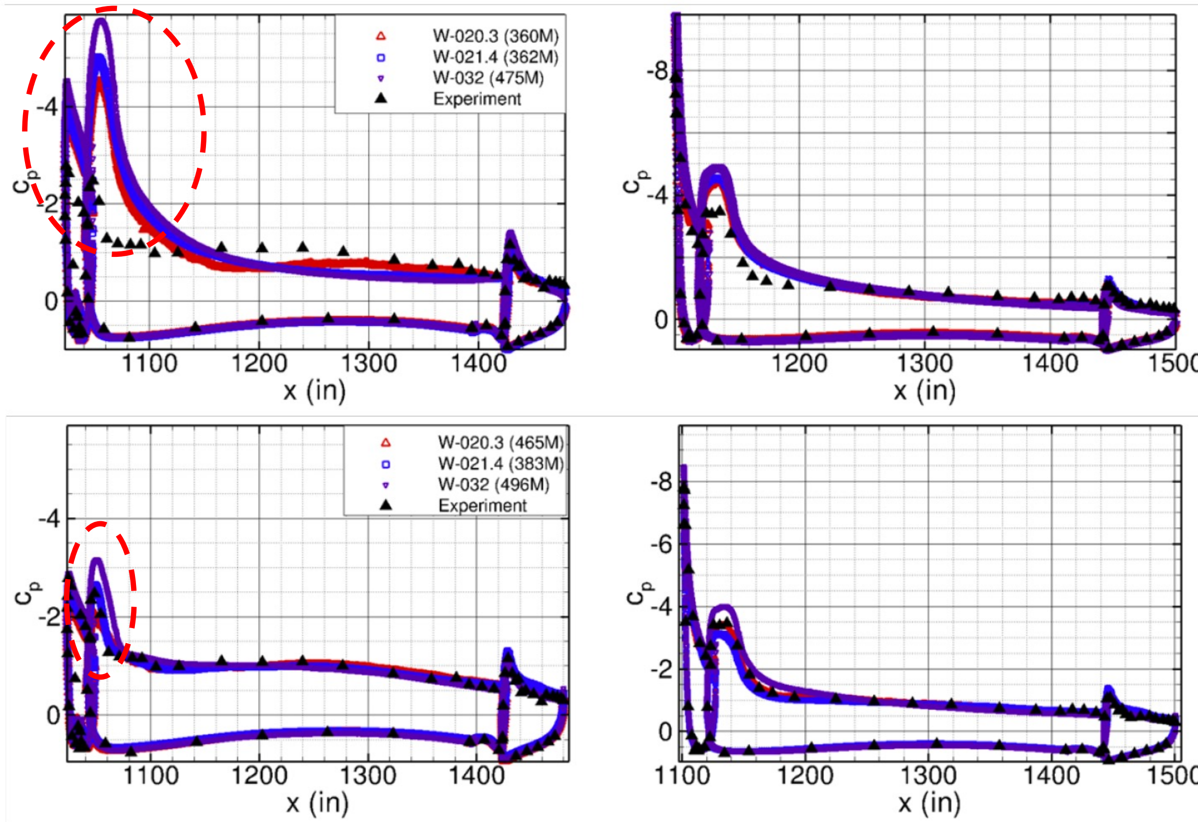
Surface Pressure Coefficient at 21.47° and 19.98°

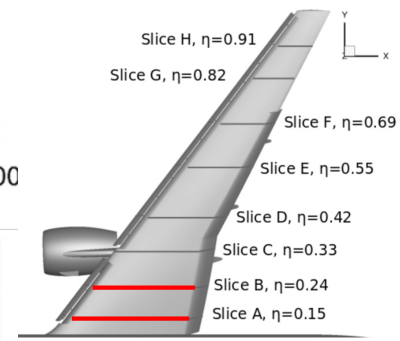
Station A

Station B

Free Air

Wind Tunnel





HLPW4 WMLES-LB TFG Summary

- **Towards establishing best-practices:**
  - At least $250M$ grid cells were needed to capture the outboard slat and main-element loading accurately.
  - A key source of discrepancy between the submissions was the stall onset pattern observed in the free-air simulations. Two distinct flow topologies were observed, it is unclear whether this is due to errors or due to coarse grids.
  - The large scatter in pitching moment coefficient identifies an importance of the grid resolution requirements.
  - CRM-HL poses significant computational challenges and requires a large number of convective time units to establish a stationary solution for high angle-of-attack.

- **Regarding advantages of isotropic grids over anisotropic grids for WMLES:**
  - Unfortunately, no clear answer can be provided in regards to this meshing topology choice.
  - Tests performed by participant W-034 suggest that more accurate outboard pressure can be obtained using fewer grid points with anisotropic compared to the isotropic (Voronoi) grids.
  - However, refinement tests by participant W-020 underscore the need for resolving the off-body vorticity, Isotropic grids are more naturally suited in this regard.

HLPW4 WMLES-LB TFG Summary

- **In-tunnel simulations:**
  - Three different teams employing different numerical discretizations, grid topologies, and SGS closures were able to very accurately predict the CLmax state as well as the wing-root stall mechanism.
  - Groups W-020 and W-021 predicted essentially identical wing-root flow topology at 19.99◦ in excellent agreement with the experimental observations.

- **Regarding computational costs for WMLES:**
  - Most of the best-practice WMLES were approximately 5-10x more computationally expensive than RANS.
  - WMLES are most certainly computationally very competitive with other legacy methods employing RANS closures.
  - Strong potential and suitability of emerging architectures (accelerators such as GPUs) for WMLES.

- **Recommendations to enable more fruitful comparisons between experiments and WMLES:**
  - Velocity profiles at various locations (including on the fuselage) via LDV-type and PIV measurements, would allow for a better understanding of some of the differences observed.
  - Unsteady pressure measurements via instruments such as Kulites would further enable demonstration of broader advantages offered by WMLES over URANS and RANS modeling.
  - More information regarding the tunnel boundary layers is needed.
  - Experimental test comparisons between half-model (wall-mounted) and a full-model (sting-or strut-mounted) would provide a better foundation for the comparisons of future free-air simulations.

Questions

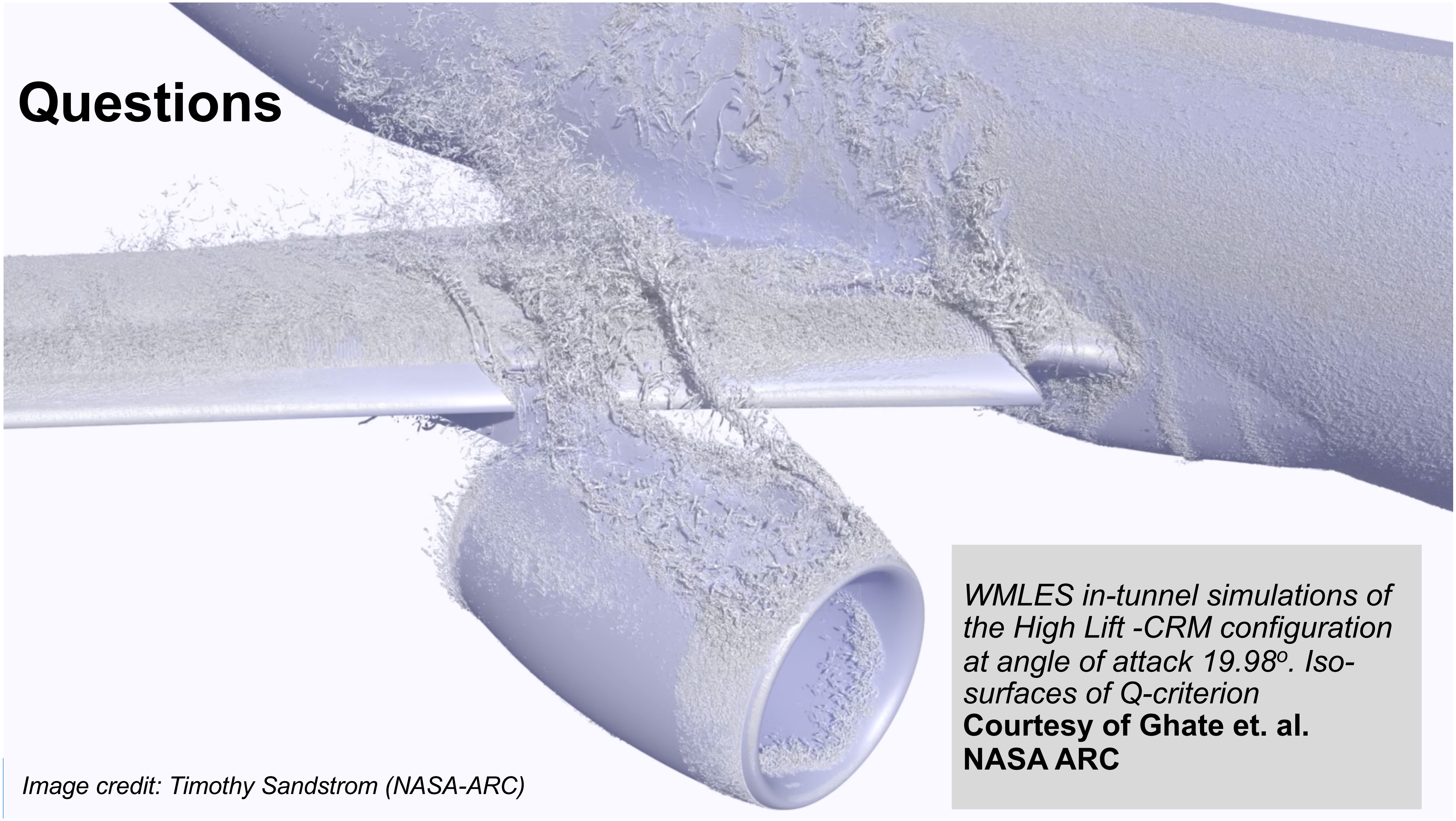


Image credit: Timothy Sandstrom (NASA-ARC)

WMLES in-tunnel simulations of the High Lift -CRM configuration at angle of attack 19.98^{o}. Iso-surfaces of Q-criterion
Courtesy of Ghate et. al.
NASA ARC