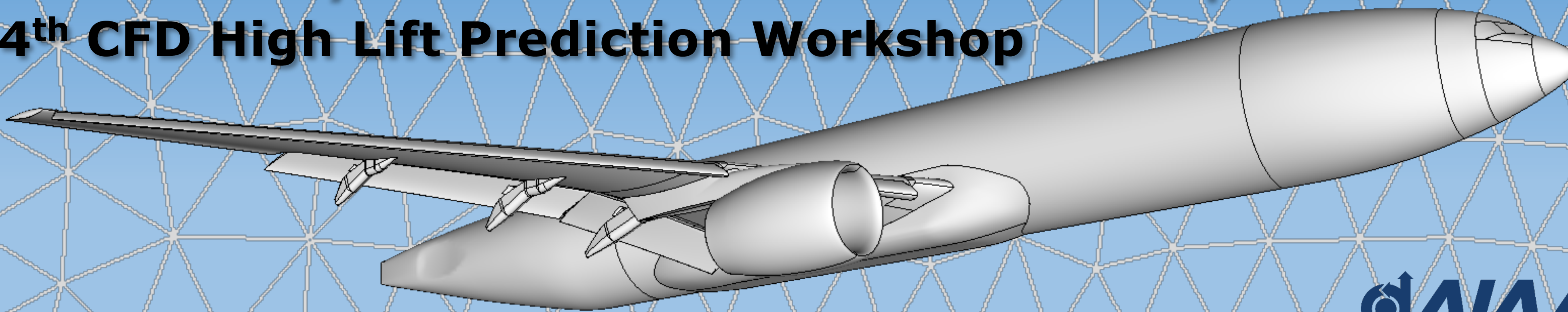
3rd Geometry and Mesh Generation Workshop
4th CFD High Lift Prediction Workshop



Progress Meeting – July 15th, 2021

WMLES/LBM Technology Focus Group

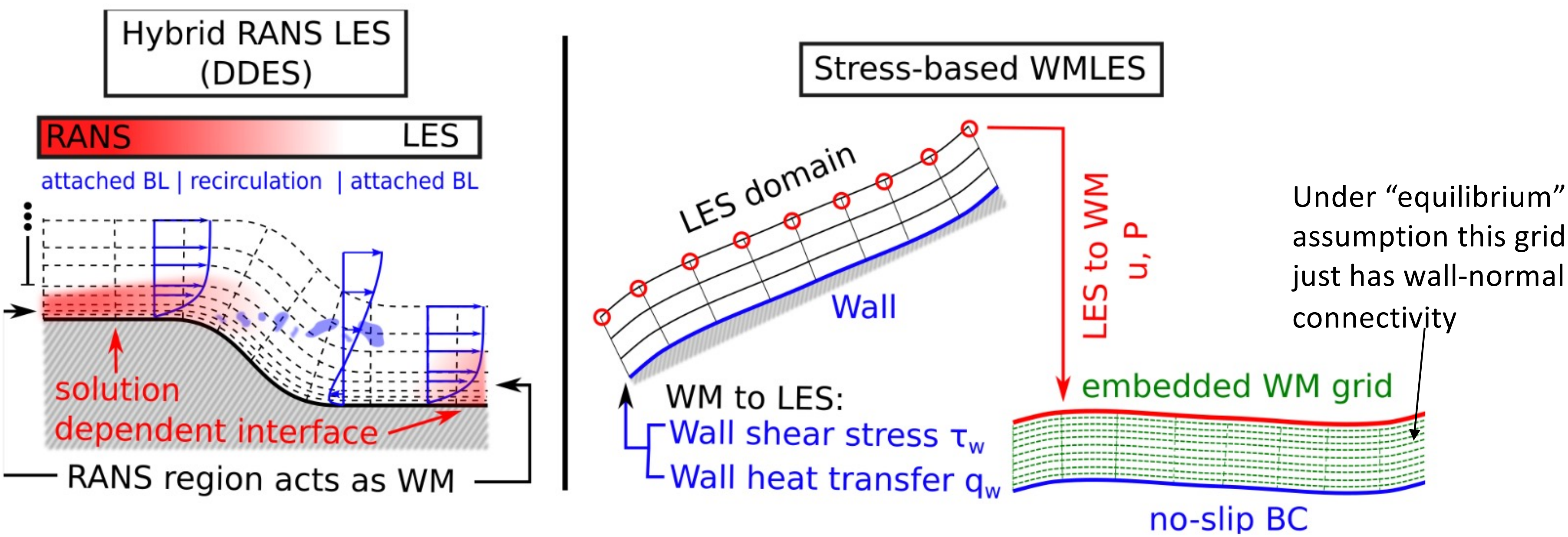
Cetin Kiris (NASA Ames Research Center)
Johan Larsson (University of Maryland)
Jeffrey Slotnick (Boeing)
Nigel Taylor (MBDA)

Special thanks to

- *WMLES/LBM TFG Teams for data submissions*
- *Aditya Ghate, Gerrit Stich, Oliver Browne, and Chris Rumsey for their help for data collection and post-processing*

Terminology - WMLES

- **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.**



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.
- **Upwind sensors:** Numerical sensors used to add targeted dissipation for stability while maintaining a non-dissipative discretization in regions of resolved turbulence. These sensors typically rely on either velocity dilatation, vorticity or entropy.

Demographics

TFG Name	WMLES/LBM
Number of Active Participants (current)	7 teams (~15)
Number of Observers (current)	~ 20

TFG ID/Name
G = Geometry
R = RANS
A = Adaptation
H = High-order
L = Hybrid RANS/LES
W = WMLES/LBM

SHAPING THE FUTURE OF AEROSPACE

Group Submissions Received	Members (Org)	Tools Used (Geom/Grid/Solver/…)	Wall Treatment
W-020	NASA Ames	LAVA – structured overset; Vreman SGS; 4th/2nd order finite difference; algebraic wall model; TVD RK3	Equilibrium WM
W-021	Stanford & Cascade Tech	charLES – Voronoi unstructured; dyn. Smag.; 2nd order finite volume; algebraic wall model; TVD RK3	Equilibrium WM
W-030	KTH	Real Flight Simulator 2021.01 – unstructured adaptive mesh; unsteady Euler/Implicit LES; finite element; inviscid wall; implicit time-stepping	Inviscid Wall
W-031	Boeing	BCFD Version 8r2 – unstructured; Vreman SGS; blended 2nd order finite volume; ODE wall model; implicit time-stepping	Equilibrium WM
W-032	Dassault Systèmes	PowerFLOW 6-2021 – Cartesian non-isothermal LBM; VLES (k-ϵ HRLBM); pressure-aware wall model	Non-equilibrium WM (Tangential Pressure gradients)
W-034	Barcelona Supercomputing Center (BSC) & MIT	Alya – unstructured; Vreman SGS; 2nd order finite element; algebraic wall model; implicit time-stepping	Equilibrium WM
W-047	University of Kansas	hpMusic v2021 – unstructured; implicit LES; p2 flux reconstruction; WMLES/inviscid wall; implicit time-stepping	Equilibrium WM (low AoA) Inviscid Wall (high AoA)

Meshing and Geometry Summary

Geometry:

- No major geometry modifications reported.
- Due to minimum mesh size certain corners have been smoothed (e.g., slat-attachments)

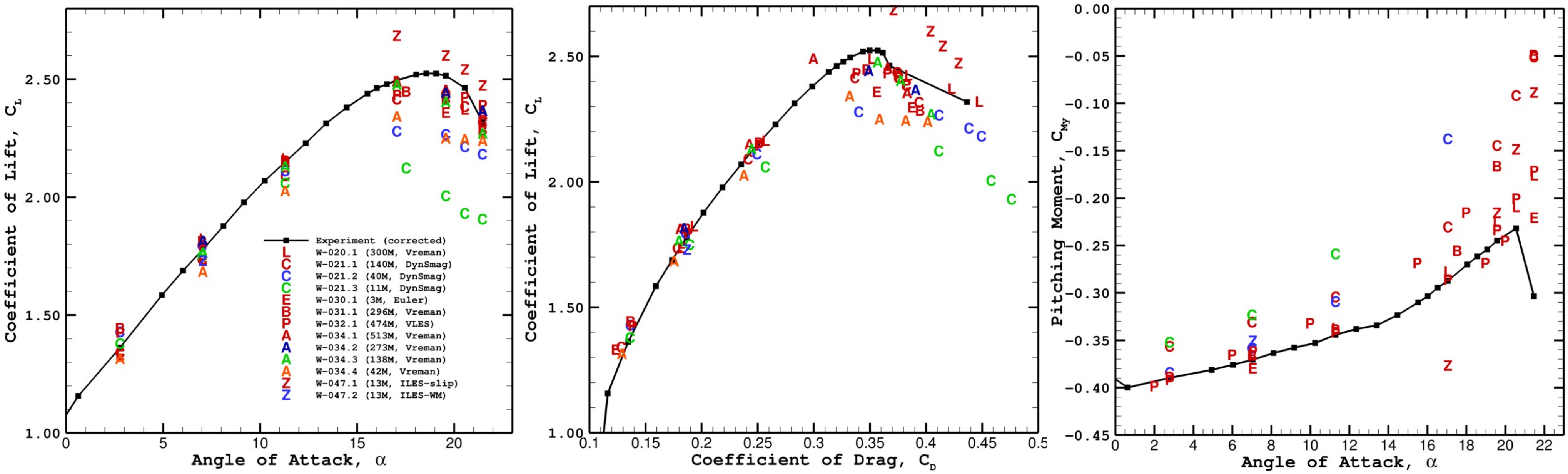
Meshing:

- One participant used committee provided mesh; one adapted starting from a committee provided mesh. Five participants created their own mesh.
- No WMLES guidelines were specified by the TFG regards to mesh spacings
- Small geometric features such as flap/slat gaps and TE couldn't be properly resolved due to time-step restrictions of explicit schemes.
- Structured overset mesh relied on re-meshing of slat-wing gap to change overset to multi-block topology to avoid spurious transition
- Changes in meshing have been applied to achieve more isotropic cells

Submission ID	Members (Org)	Mesh Topology and Degree of Freedom/Mesh Points	Wall-normal grid spacing (assuming full scale geometry with 7m MAC) for finest grid	Aspect Ratio	WM – exchange location
W-020	NASA Ames	300M Structured Curvilinear	2.5mm (up to 10%c); 5mm (after 10%c)	Min 1; Max 4; Nominally 2-3	2nd off-wall point (2 Delta)
W-021	Stanford & Cascade Tech	11M/40M/146M Voronoi Unstructured	6.8mm (up to 25%c); 13.6mm (after 25%c)	1	1st off-wall point (0.5 Delta)
W-030	KTH	0.5M Unstructured	Not available	Min 10; Max 14	Not applicable
W-031	Boeing	300M Unstructured	1.27mm (after 10%c)	Min 10; Max 16	4th off-wall cell (3.5 Delta)
W-032	Dassault Systèmes	474M Structured Cartesian	Approx. 10mm	1	0.5 Delta
W-034	Barcelona Supercomputing Center (BSC) & MIT	513M/138M Voronoi Unstructured, and 273M and 43M Hex Unstructured	7mm (Voronoi); 0.8mm (Hex)	1 for Voronoi; 1-30 for Hex	2nd off-wall point for Voronoi; 3rd off-wall point for Hex
W-047	University of Kansas	13M DOFs/equation, FR/CPR P2 Unstructured	7.2 mm (21.5/3 mm)	Min 1; Max 71	Interface between the 1st and 2nd elements

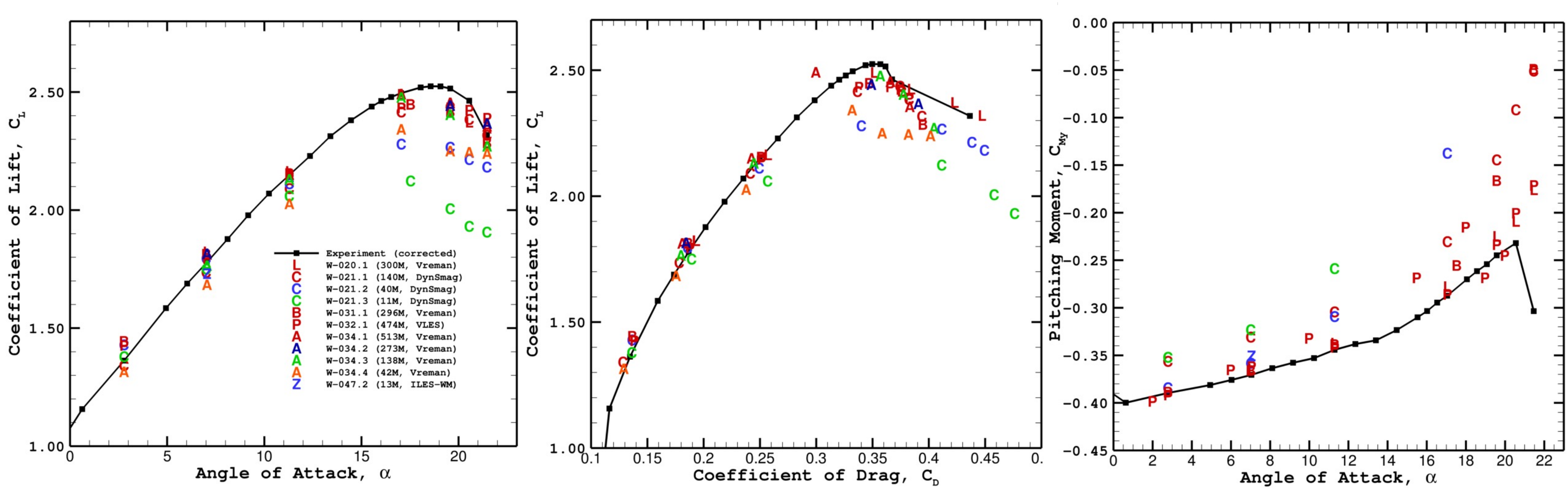
Basic CFD Results

All Submissions – Free Air (Case 2a)



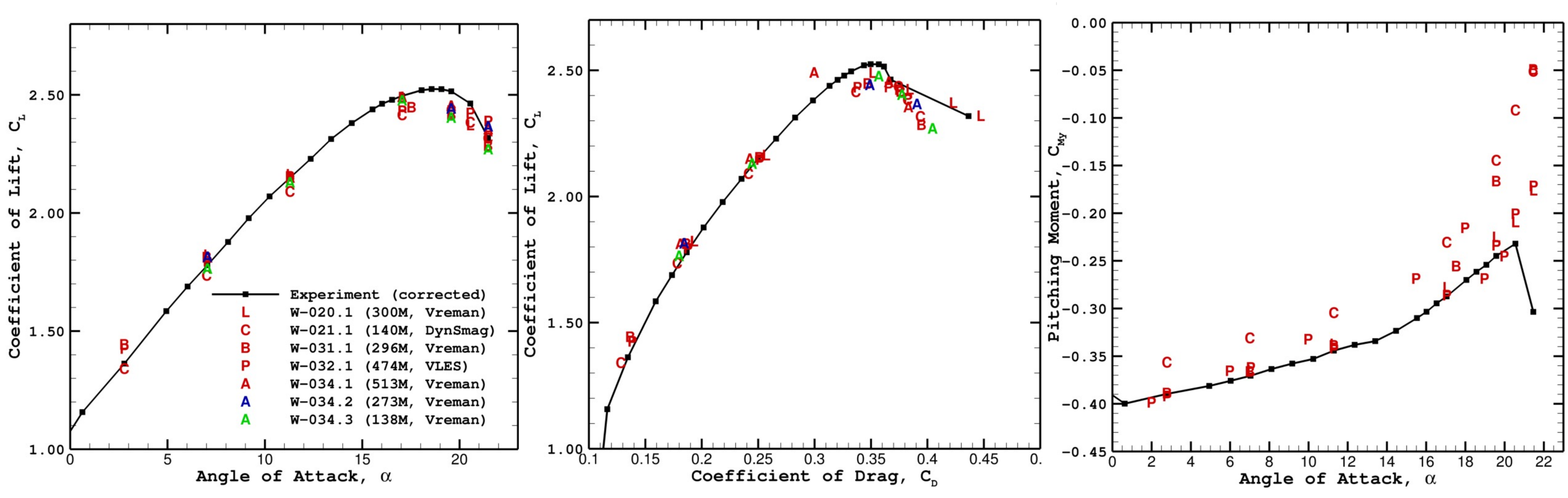
Basic CFD Results

Wall Modeled Only – Free Air (Case 2a)



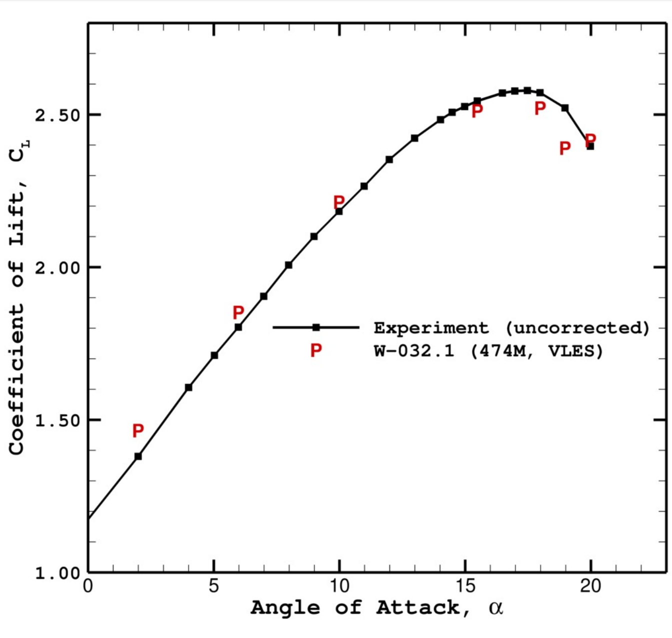
Basic CFD Results

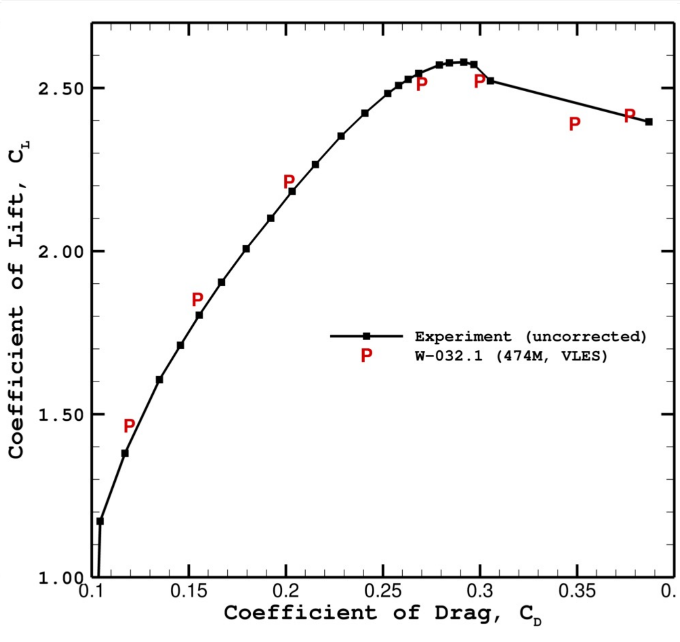
Submissions with DOF > 100M – Free Air (Case 2a)

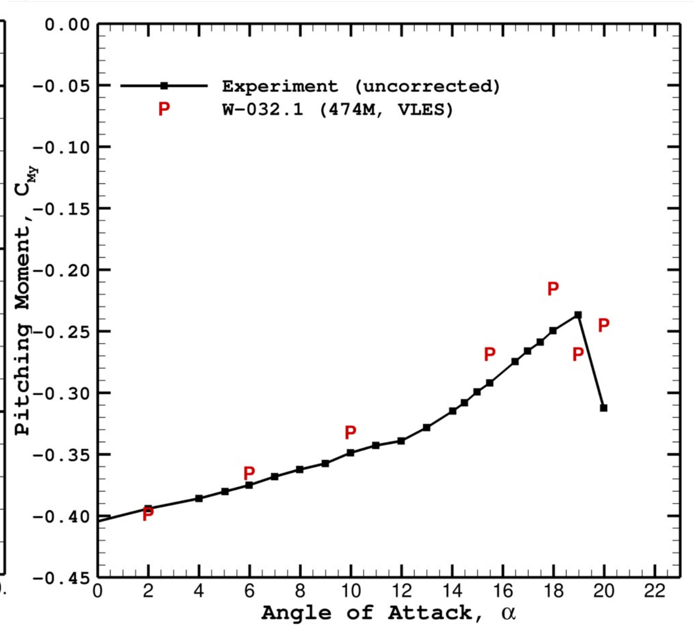


Basic CFD Results

Including Wind Tunnel Geometry (Case 2b)

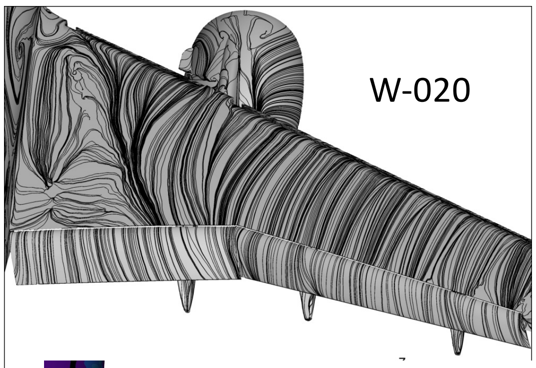




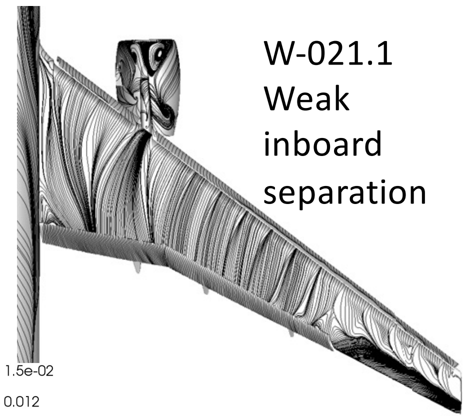


Inboard separation at 21.5deg. (FREE AIR)

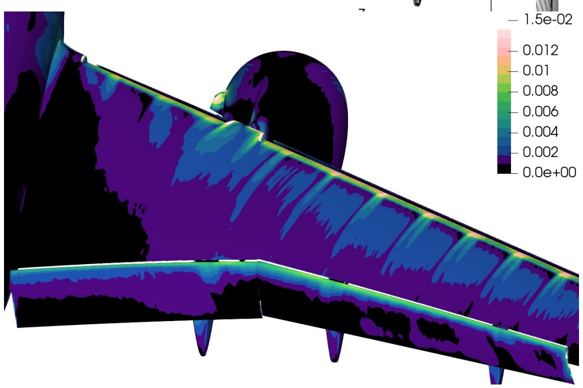
Participants showing inboard separation



W-020



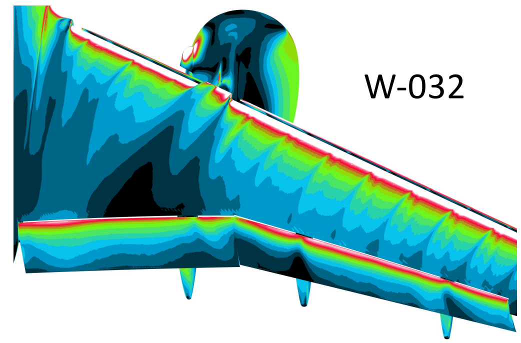
W-021.1
Weak
inboard
separation



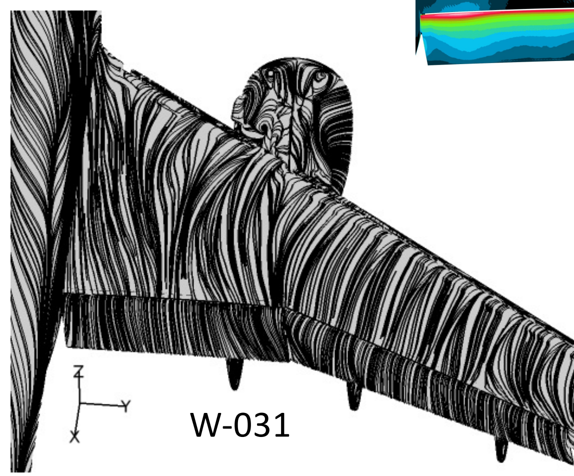
W-034.2

no pitch break because of outboard separation

Participants not showing inboard separation



W-032

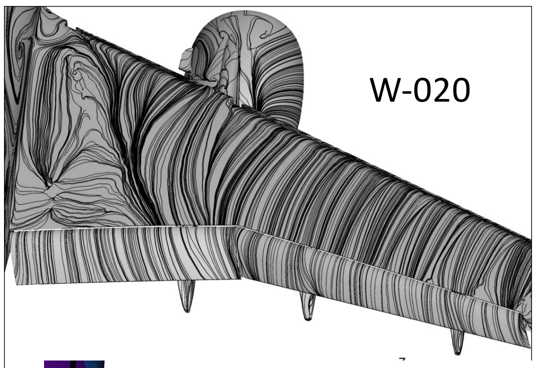


W-031

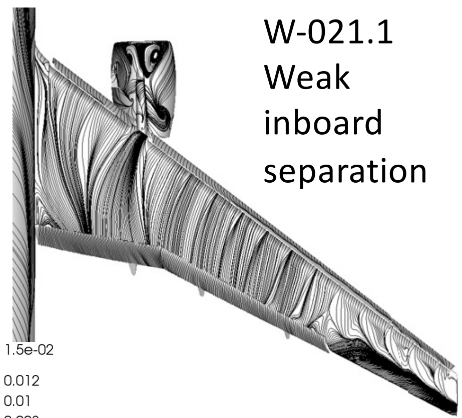
no pitch break because there is no inboard flow separation

Inboard separation

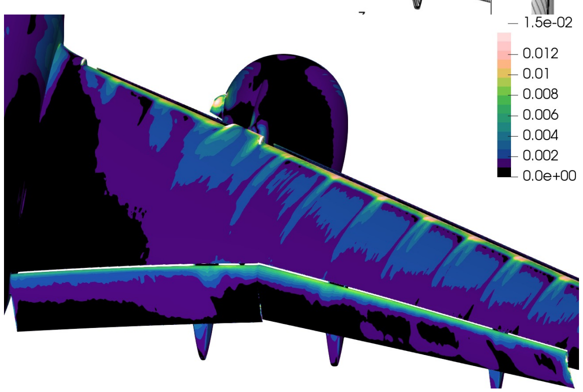
Participants showing inboard separation in FREE AIR at 21.5º



W-020



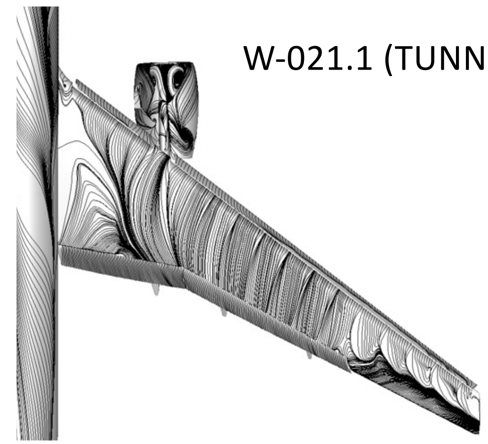
W-021.1
Weak
inboard
separation



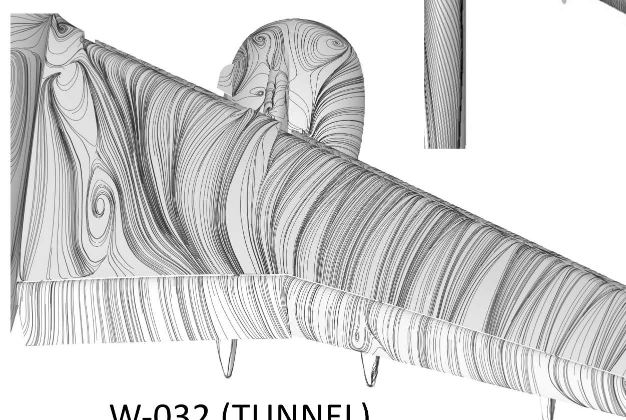
W-034.2

Pitch break **was not captured because outboard separation**

Participants showing separation in TUNNEL at 19.9º



W-021.1 (TUNNEL)



W-032 (TUNNEL)

Pitch break **was captured** upon inboard separation

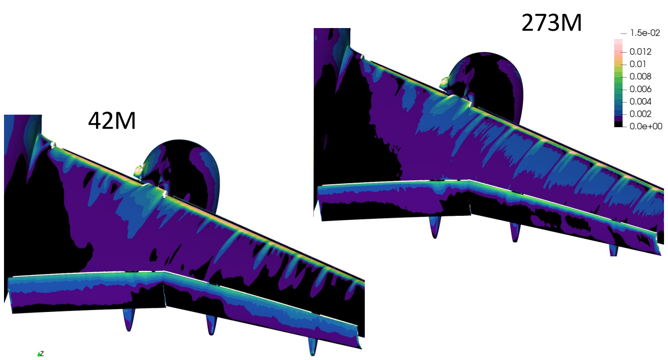
Inboard separation: In Free Air at 21.5deg.?

Large scale separation

W-020: 300M point mesh
Aspect Ratio=2-3; WMLES

W-034.2: 273M point mesh
Aspect Ratio=1-10; WMLES

W-034.4: 42M point mesh
Aspect Ratio=1-30; WMLES



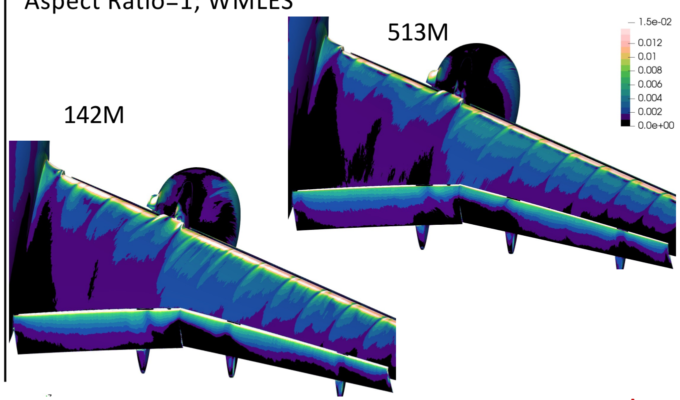
Sensitivity of inboard separation to grid refinement is unclear considering 42M (W-034.4) to 273M (W-034.2)

Some separation

W-021.1: 142M point mesh
Aspect Ratio=1; WMLES

W-034.1: 513M point mesh
Aspect Ratio=1; WMLES

W-034.3: 142M point mesh
Aspect Ratio=1; WMLES



Some increase in separation region with grid refinement from 142M (W-034.3) to 513M (W-34.1)

No separation

W-032: 475M point mesh;
Aspect Ratio=1; Hybrid RANS/LES

W-031: 300M point mesh;
Aspect Ratio=10-16; WMLES

Mesh Refinement data not available

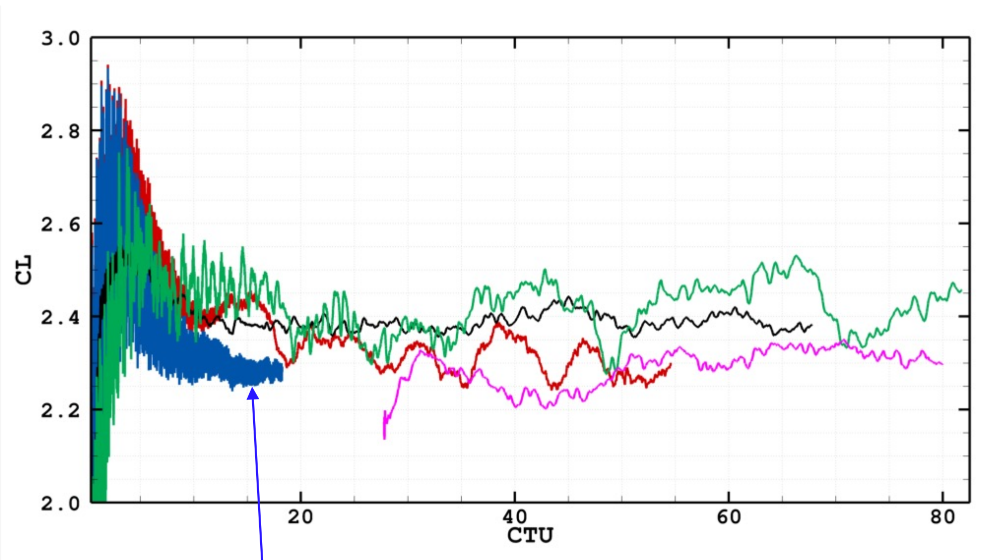
In WMLES, inboard separation is sensitive to:

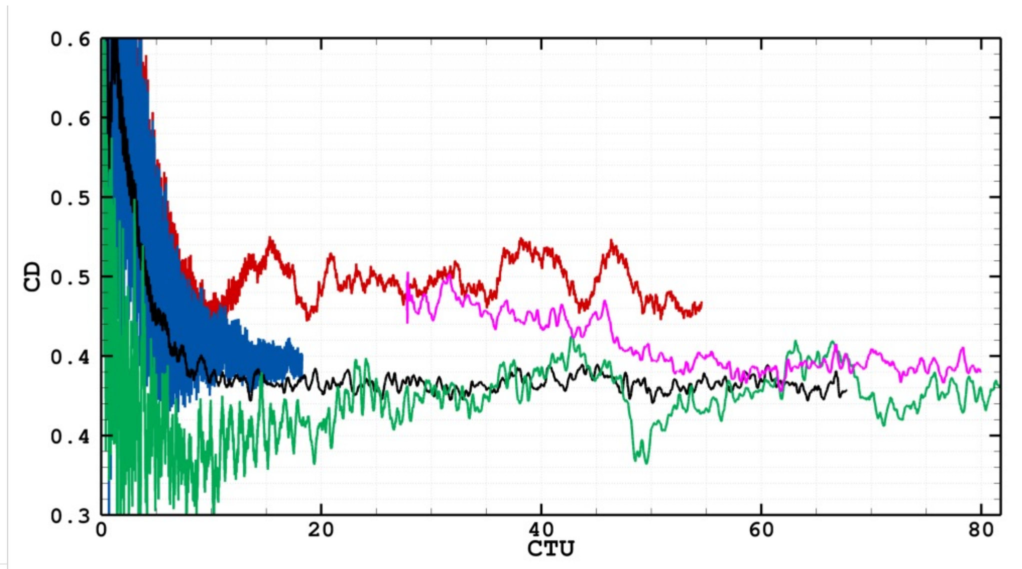
1. **Fuselage BL entering juncture – sensitive to transition/tripping near nose**
2. **Wing BL transition/tripping**

This is likely to be a fundamental difference between WMLES and RANS/HRLES

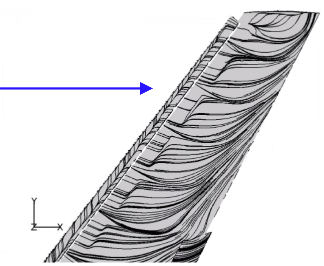
Both W-032 and W-021.1 report substantial separation in tunnel environment.

Time History at High AoA





W-031 does not show inboard separation but severely underpredicts outboard lift leading to large nose-up pitching moment



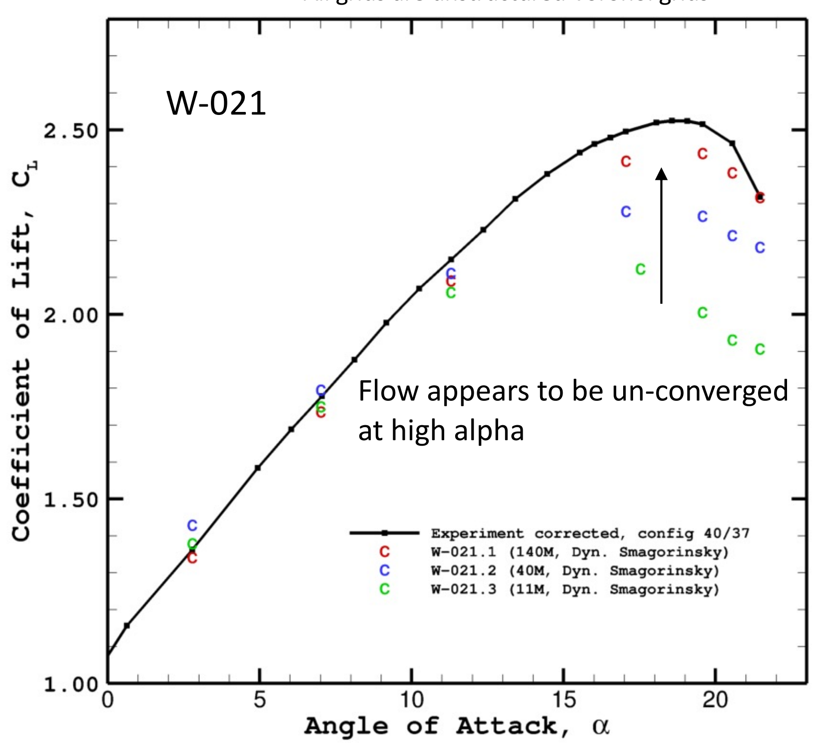
Green: W-032 Tunnel 19.9º(inboard separation occurs)
Red: W-020 FreeAir 21.5º(inboard separation occurs)
Pink: W-021 FreeAir 21.5º (inboard separation occurs)
Blue: W-031 FreeAir 21.5º(no inboard separation)
Black: W-32 FreeAir 21.5º(no inboard separation)

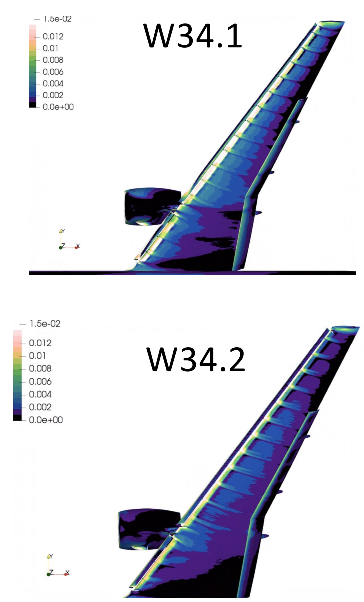
Grid convergence/sensitivity

AIAA SHAPING THE FUTURE OF AEROSPACE

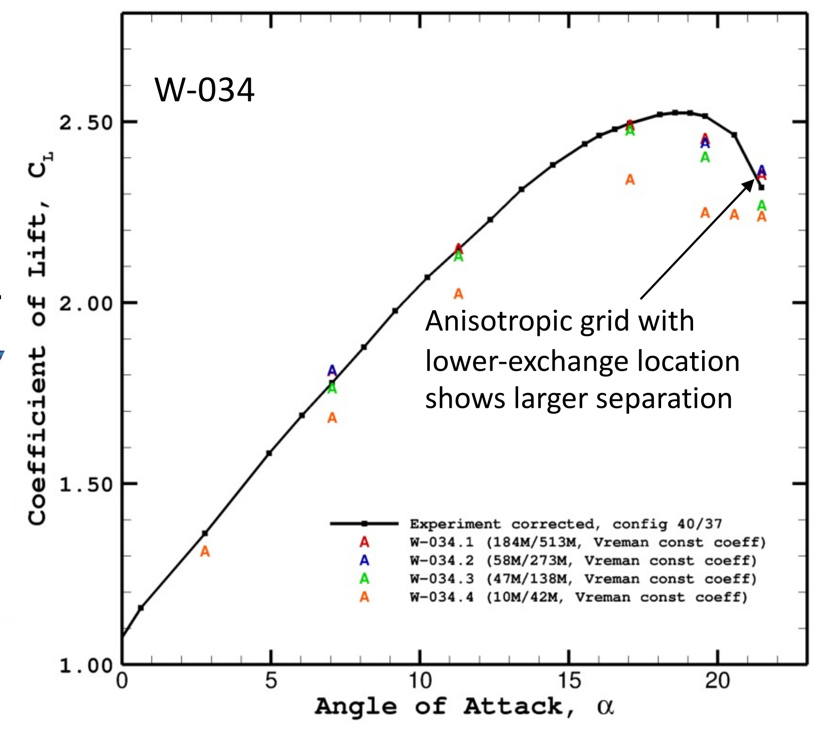
Free Air

All grids are unstructured Voronoi grids





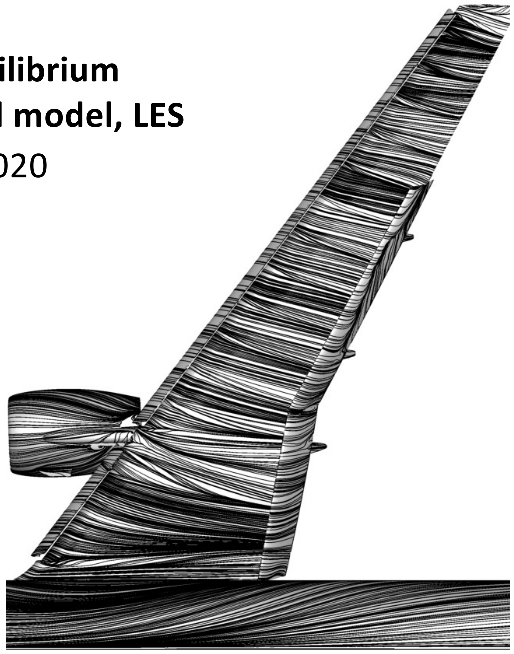
Green, Red : Isotropic Voronoi cells
Orange, Blue: Anisotropic grid (lower exchange location)



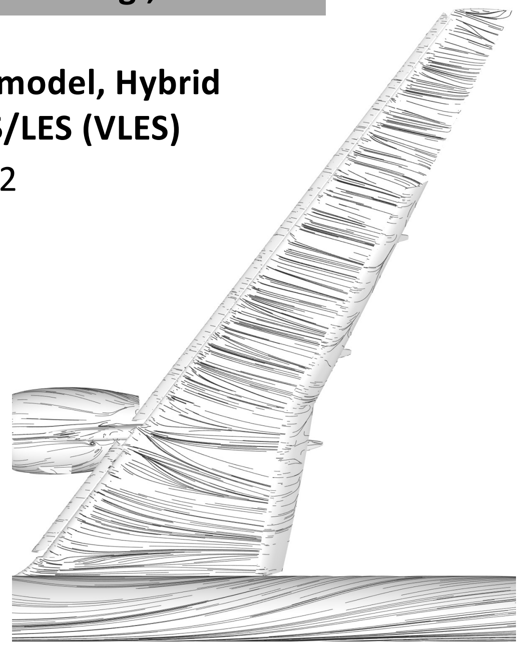
Wall model (effect of grid resolution)

AoA= 7.05deg., FREE AIR

Equilibrium wall model, LES
W-020

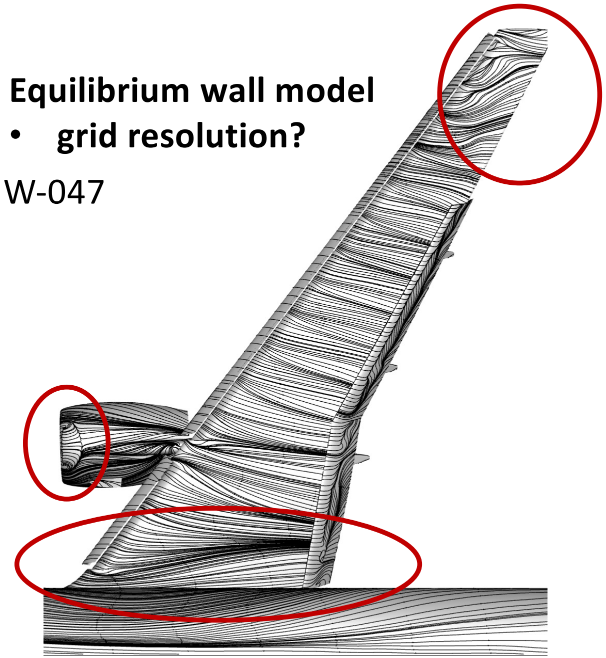


Wall model, Hybrid RANS/LES (VLES)
W-032



Equilibrium wall model
- **grid resolution?**

W-047

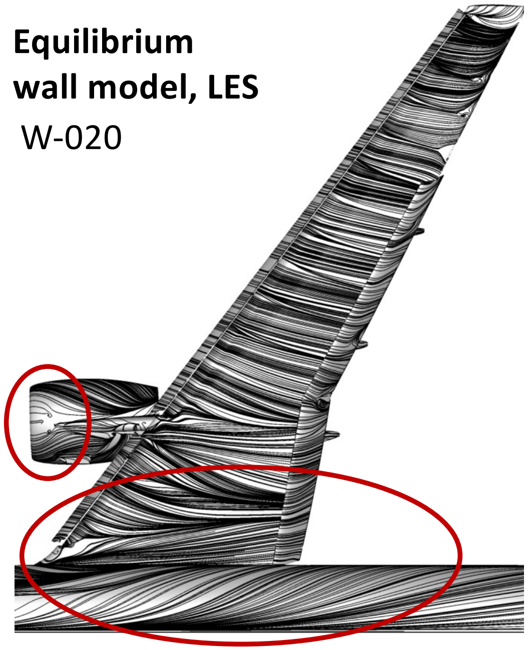


Submission ID	Mesh Topology and DoF	Wall-normal grid spacing	Aspect Ratio	WM – exchange location
W-020	300M Structured Curvilinear	2.5mm (up to 10%c); 5mm (after 10%c)	Min 1; Max 4; Nominally 2-3	2nd off-wall point (2 Delta)
W-032	474M Structured Cartesian	Approx. 10mm	1	0.5 Delta
W-047	13M DOFs/eq, FR/CPR P2, Uns	7.2 mm (21.5/3 mm)	Min 1; Max 71	Interface between the 1st and 2nd elements

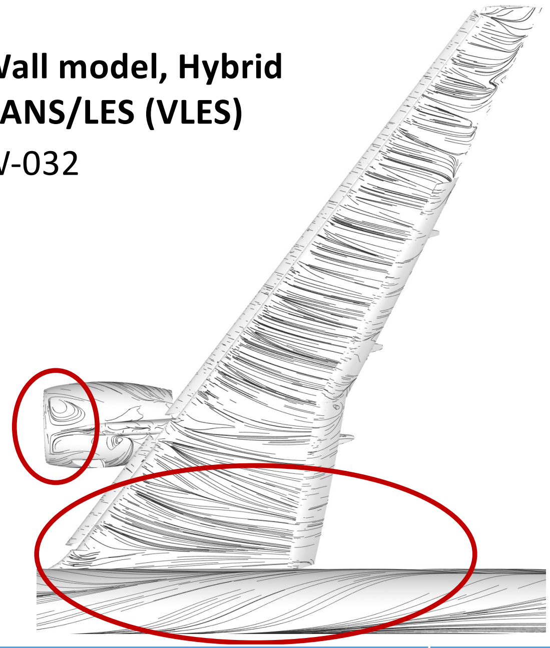
Wall model vs slip/inviscid walls

AoA= 17.05deg., FREE AIR

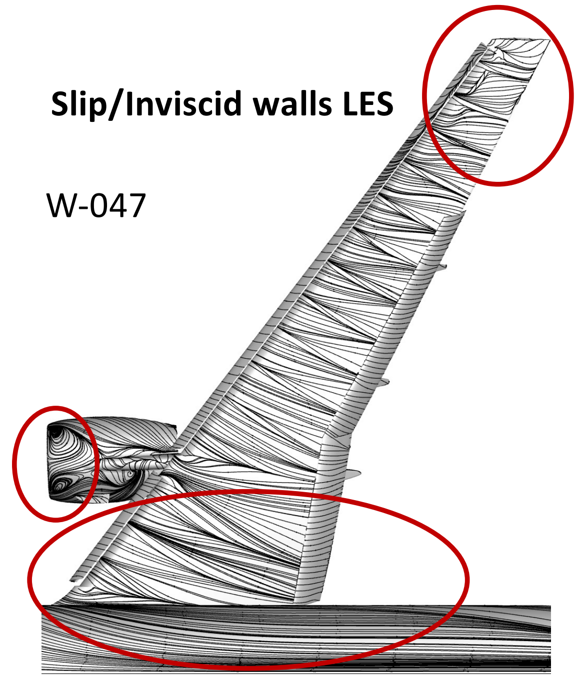
Equilibrium wall model, LES
W-020



Wall model, Hybrid RANS/LES (VLES)
W-032



Slip/Inviscid walls LES
W-047



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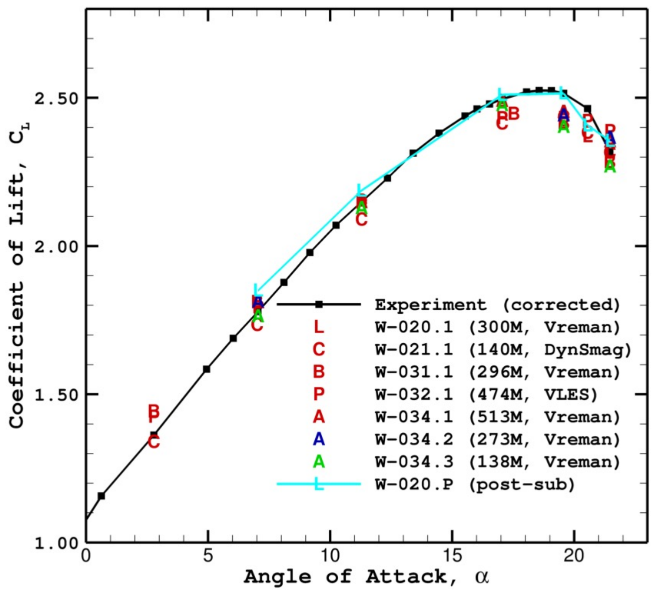
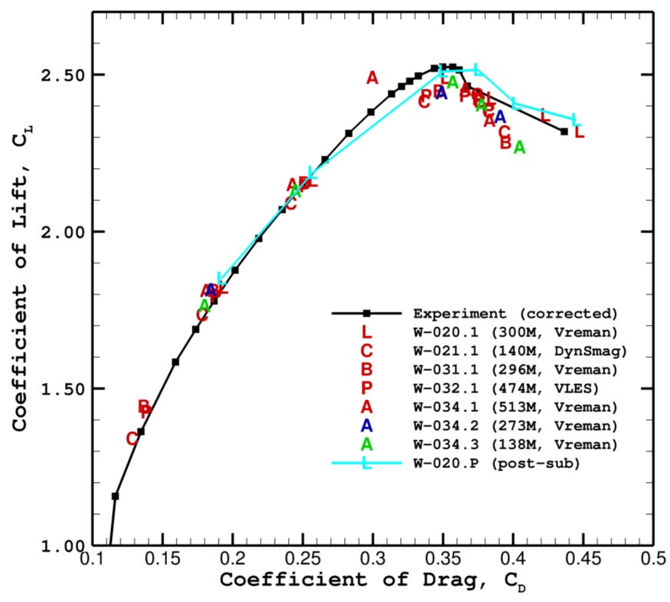
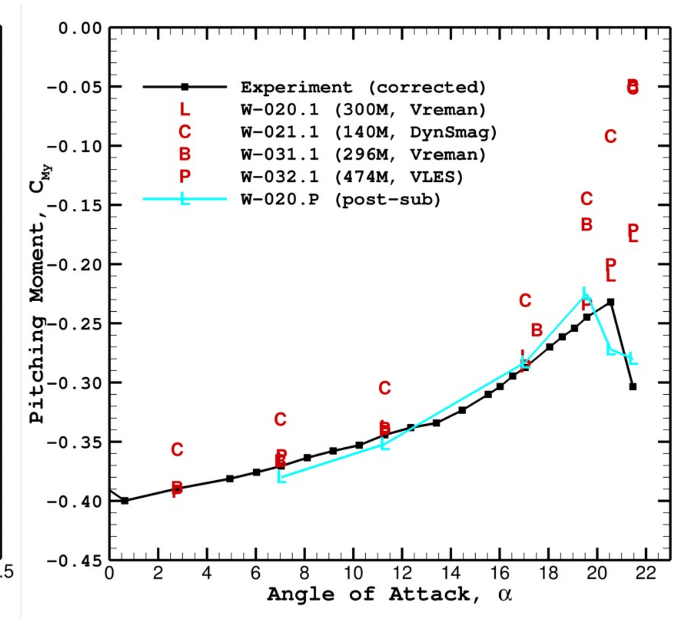
W-047	13M DOFs/eq, FR/CPR P2, Uns	7.2 mm (21.5/3 mm)	Min 1; Max 71	Interface between the 1^{st} and 2^{nd} elements

Basic CFD Results

Including Improvements Post-Submission Deadline – Free Air



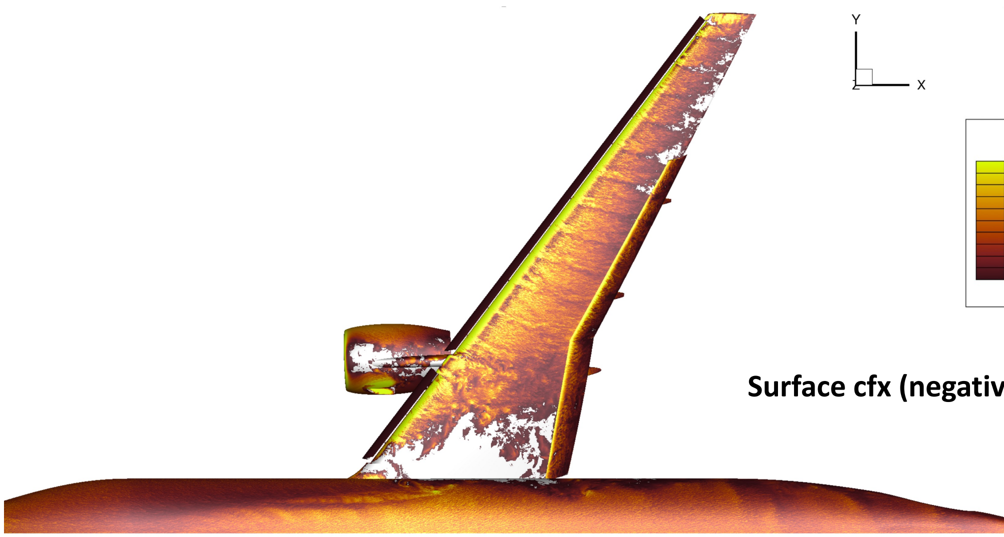




Angle of attack = 21.47deg

Including Improvements Post-Submission Deadline – Free Air

OLD WMLES (W-020.1)



NEW WMLES (W-020.P)

Surface cfx (negative values clipped)

Pitch break **was not captured because** there of excessive outboard separation causing loss-of-lift

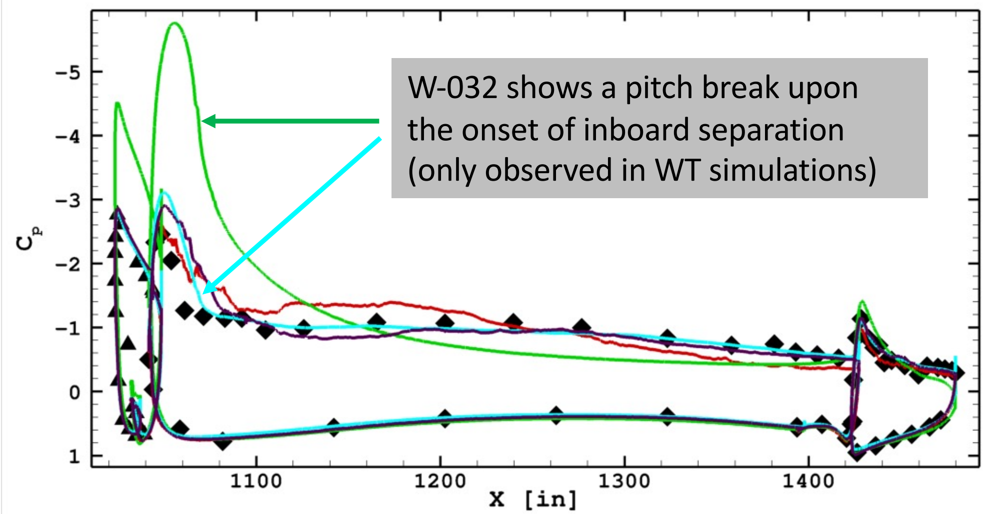
Pitch break **was captured because** there is no outboard separation (inboard stall occurs before outboard stall)

Question of pitch break (at 21.5deg)

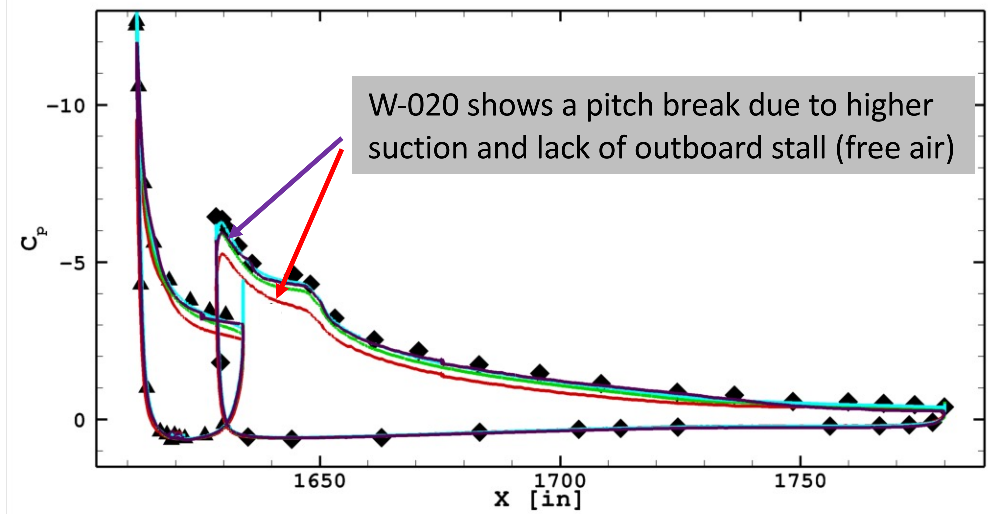
W-020.1 FreeAir (No pitch-break) - WMLES
W-020.P FreeAir (Pitch-break) – WMLES

W-032 FreeAir (No pitch-break) – LBM/VLES
W-032 Tunnel (Pitch-break) – LBM/VLES

Inboard, Row A



Outboard, Row G



Key Questions

Proposed in December 2020

1. **How sensitive are the integrated forces and moments (e.g., lift, drag, pitching moment coefficients) to the computational grid? (a) Will we be able to show convincing convergence with respect to the grid? (b) Can we define a credible process for verifying that the results are sufficiently converged, and what exactly would that process be?** While at least 2 groups (W-021, W-034) are investigating grid convergence and more have planned to, the notion of grid convergence needs to be revisited. Grid refinement has two distinct consequences: a) Flow gradients are better resolved, b) Numerical transition and thin leading edge boundary layers are altered.
2. **How do we handle the very thin boundary layer (BL) at the leading edge in a sufficiently accurate yet affordable manner?** No team is planning to treat the leading-edge laminar boundary layers accurately. All submissions assume a fully turbulent BL with numerical transition to turbulence. The need to accurately capture thin leading-edge BLs remains to be established at high Reynolds numbers.
3. **Will some kind of implicit time-stepping be necessary at realistic Reynolds and Mach numbers?** While some teams (W-034, W-047, W-030) are using implicit time stepping, this is primarily necessitated by the discretization and/or mesh; not due to high Reynolds numbers or high Mach numbers. Implicit time-stepping might be needed if (a) we need to resolve very thin BL at the leading edge (b) we don't have control on grid quality. Needs to be investigated further.
4. **What are the factors limiting accuracy and/or computational cost, and what is the estimated gain (in accuracy and/or cost) from improvements to each factor?** Both cost and accuracy appear to be driven by the smallest geometric length scales which are of order 2.5mm for a 7m MAC. Grid refinement studies are likely to influence targeted grid refinements to reduce computational cost.
5. **Relevance of tripping used on the wing. Does tripping need to be explicitly represented, or numerical transition is sufficient?** All current submissions use numerical treatment for transition, although some groups (W-020) plan to evaluate explicit representation of tripping. The exact angle of attack for onset of inboard separation/instability is likely to be sensitive to treatment of transition.
6. **With the fuselage mounted on the tunnel wall, how important is it to characterize the tunnel boundary layer?** Majority of the groups (W-020, W-021, W-032, W-034) plan to study the model inside a wind tunnel with tunnel wall boundary layers. It is unclear at this time whether any group will do a parameter study of CL_{max} sensitivity to tunnel wall boundary layer characteristics.

Key Questions

Additional key questions are proposed:

7. **To what extent can we demonstrate that predicted inboard flow development is not affected by discretization error (spatial or temporal):**
    a. In free-air computations?
    b. In "in-tunnel" computations? (i.e., those including a representations the wind tunnel walls)

8. **In support of (7) above, how sensitive is the inboard separation to:**
    a. Numerical discretization? (e.g., how aggressive is the numerical stabilization needed by the discretization near CL_{max}?).
    b. Grid aspect ratio and wall-distance of the exchange location?
    c. Representation of transition to turbulence in the boundary layers?

9. **Following on from (7), above:**
    a. What is the nature of the predicted development of inboard separation around CL_{max}? (e.g., gradual or sudden; from where/how does it originate),
    b. To what extent is this modified by the presence of the wind tunnel walls (or by the assumptions made in modelling their effects)?

10. **Is WMLES able to provide a consistent explanation for the shape of the predicted total lift, drag and pitching moment characteristics near CL_{max}?**

11. **Can we begin to identify a minimum set of criteria required to use WMLES with confidence in high-lift applications?**

Future Plans

- Continue working on key questions (original and new ones)
- Discussions with RANS and Hybrid RANS/LES TFGs will continue
- Run High AoA cases longer > 70 CTU
- Run higher grid resolution to resolve some to discrepancies between submitted results
- Investigate the effects of grid resolution & numerical dissipation
- Investigate slip wall versus wall modeling
- Need to distinguish between the two wind tunnel effects;
  - fuselage boundary layer, stand-off, and resulting horseshoe vortex
  - wind tunnel blockage
- More detailed wind tunnel measurements (i.e., Juncture Flow Experiments) might be helpful.
  - If fuselage boundary influences the inboard separation, some experimental data is need for the fuselage boundary layer
  - Infrared images to guide WMLES calculations for transition on un-tripped surfaces