Wall-Modeled Large Eddy Simulation Method for Unstructured-Grid Navier-Stokes Solvers

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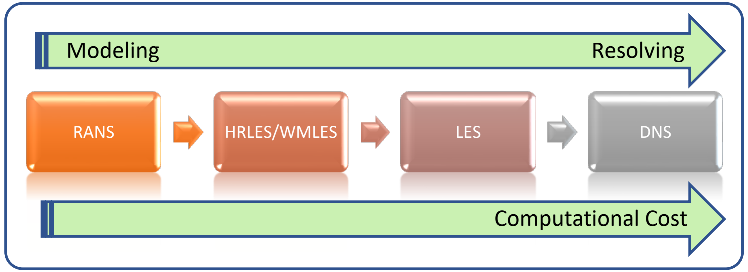
AIAA SciTech Forum 2023

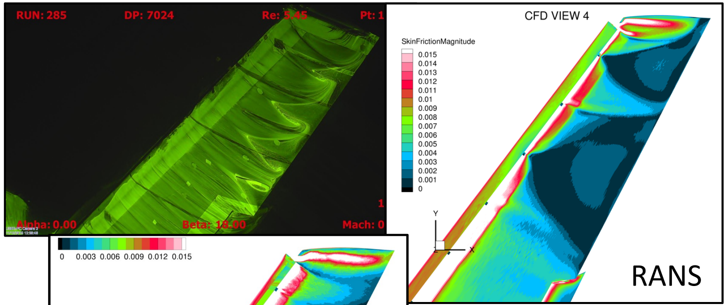
January 23, 2023

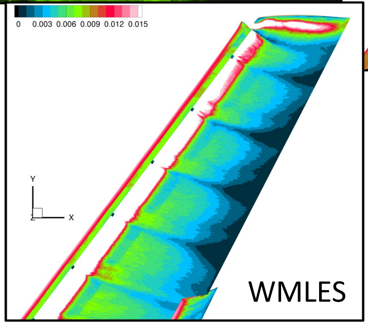
Motivation

- **Achieving the Goal of Certification by Analysis Relies on Accurate Computational Methodologies**
  - Predictive capabilities for high-lift flows near maximum lift conditions
  - Scale-resolving methods for turbulent flows
    - ✓ Hybrid Reynolds-Averaged Navier-Stokes/Large Eddy Simulation(HRLES), Wall-Modeled LES (WMLES)
    - ✓ LES, Direct Numerical Simulation (DNS)
  - More resolved physics, but higher computational cost
  - Significant increase in computational power enables scale-resolving methods for practical turbulent flows



- **Fourth High-Lift Prediction Workshop (HLPW-4)[1] at AIAA SciTech 2022**
  - RANS exhibited excessive outboard separation at high angles of attack
  - HRLES and WMLES demonstrated better agreement with experiments
  - NASA CFD code, FUN3D, predicted maximum lift within 2% of the experimental value[2]





Oil flow and samples of RANS and WMLES solutions from AIAA Paper 2022-3295

[1] NASA and AIAA, "4th High-Lift Prediction Workshop," , https://hiliftpw.larc.nasa.gov/, Last access 11/10/2022.
[2] Wang, L., et al., "Wall-Modeled Large-Eddy Simulations for High-Lift Configurations using FUN3D", AIAA Paper 2022-1555, 2022.

Objectives

Establish Best Practices

- *WMLES for complex high-lift configurations*
- *Suitable grid metrics*
- *Strategic mesh refinement and assessment of solutions*
- *Solver parameters*

Assess Finite-Element WMLES Solver

- *Evaluate finite-element solutions for representative flows*
- *Compare solution accuracy and consistency*

Study Reynolds Number Effects

- *Assess WMLES capabilities of capturing Reynolds number effects*
- *Examine key aerodynamic characteristics*

Computational Fluid Dynamics Code FUN3D

Unstructured-grid, node-centered Navier-Stokes solver discretized in space on mixed-type elements

Finite-Volume Discretization

- Second-order accurate in space
  - Inviscid fluxes based on unstructured monotonic upstream scheme for conservation laws (*UMUSCL*) and least-square gradients
  - Viscous fluxes are cell-based gradient approximation
- Explicit and implicit time integration schemes of various orders of accuracy
  - Optimized second-order backward difference formula (BDF2opt) used in this work
- Defect correction with multicolor point-iterative linear solver
- Hierarchical adaptive nonlinear iteration method (HANIM)[3] with adaptive CFL control

Finite-Element Discretization

- Second-order accurate spatial discretization
  - Linear basis functions based on stabilized Petrov Galerkin[4]
- Implicit time integration schemes
  - Second-order accurate, two-stage implicit Runge-Kutta (SDIRK) used in this work
- GMRES linear solver[5] with adaptive CFL control

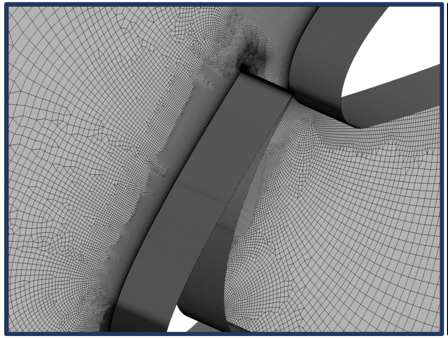
✓ LES solved in interior using Vreman subgrid scale model
✓ Boundary flux closure based on equilibrium wall model with Spalding's law
✓ Exchange location corresponds to first point off wall
✓ Exact linearizations of wall model to solve implicit system

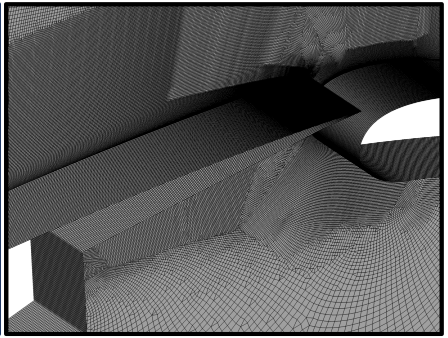
[3] Wang, L., et al., "Improvements in Iterative Convergence of FUN3D Solutions," AIAA Paper 2021–0857, 2021.
[4] Anderson, W. K., et al., "Stabilized Finite Element in FUN3D," Journal of Aircraft, Vol. 55, No. 2, 2018, pp. 696–714.
[5] Wood, S. L., et al., "Sparse Linear Algebra Toolkit for Computational Aerodynamics,", AIAA Paper 2020-0317, 2020.

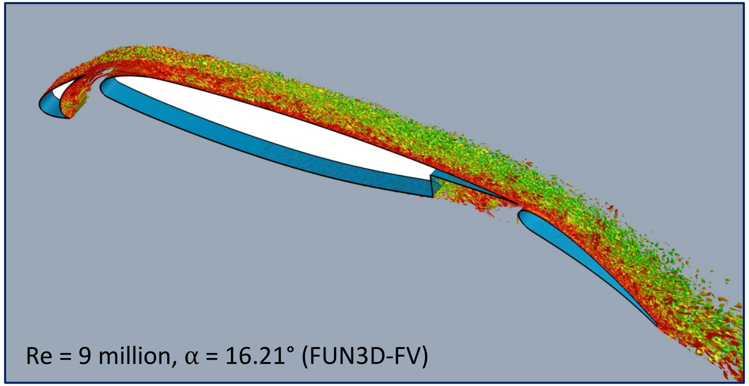
30P30N Multielement Airfoil

M_∞	Re	α
0.2	5,000,000	8.12°, 16.21°
	9,000,000	8.10°, 16.21°

- 17 million points and 16.9 million mixed-type elements
- Extruded in spanwise direction with 44 parallel planes (0.04*c*)
- Farfield BC at 100*c* and periodic sidewalls
- Wall normal spacing of Δy_w^+ ~ 100 (Re =9M) and 60 (Re = 5M)
- Aspect ratio: Δx : Δz : Δy ~ 3 : 3 : 1
- Time step corresponding to 2,000 steps per CTU (convective time unit)
- WMLES solutions computed by FUN3D-FV with defect-correction solver
- Data from LTPT wind tunnel tests and RANS solutions computed on a 2D grid used as references
- Sample results shown for pressure distributions, boundary-layer profiles, and effects of Reynolds number (details in paper)



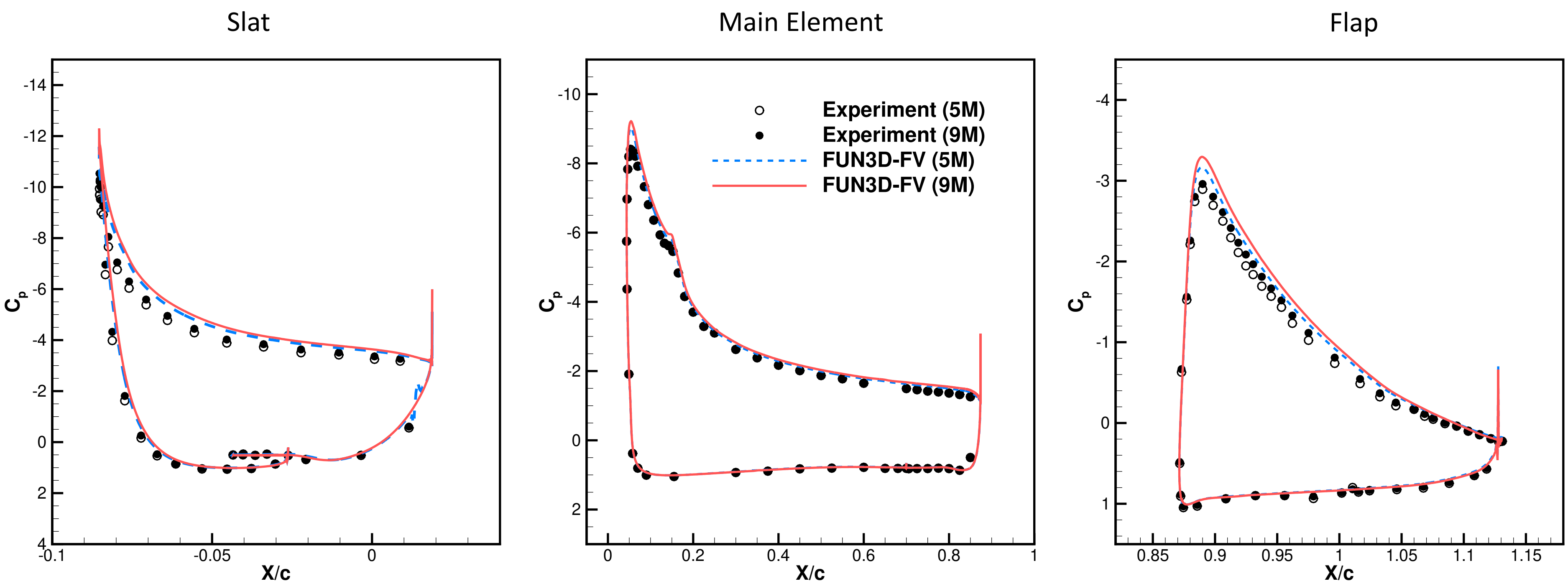




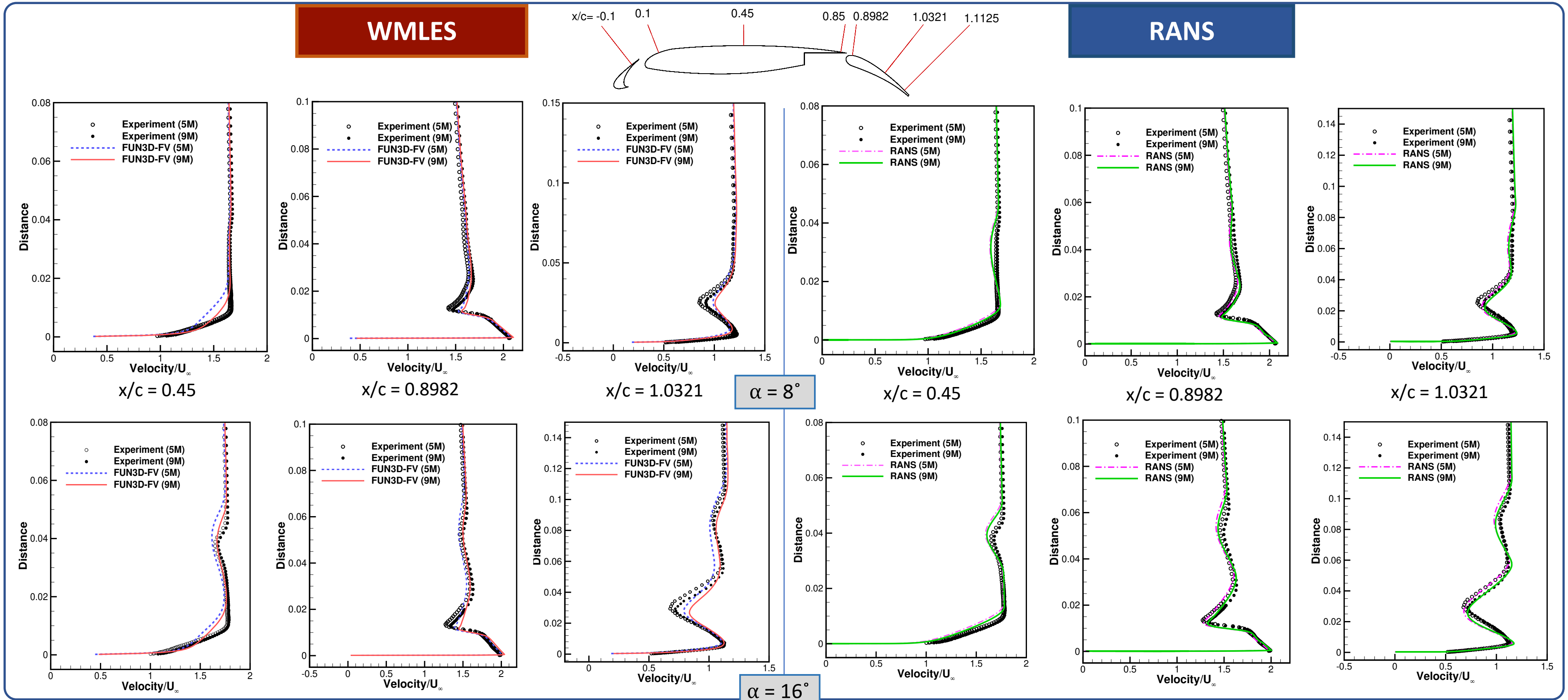
Isosurfaces of q-criterion colored by vorticity magnitude

Surface Pressure Distributions (α = 16˚)

WMLES



Mean Velocity Profiles

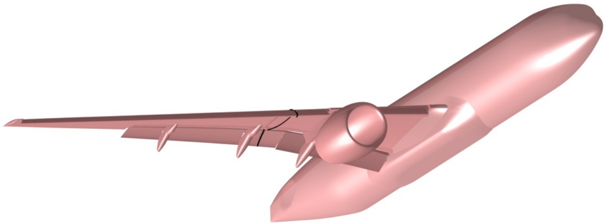


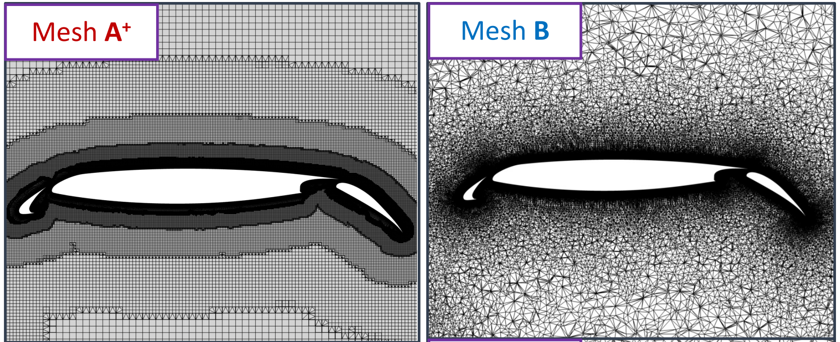
NASA High-Lift Common Research Model (CRM-HL)

M_∞	Re	α (wall corrected)
0.2	5,490,000	7.05°, 11.29°, 17.05°, **19.57**°, 20.55°, 21.47°, *22.00*°

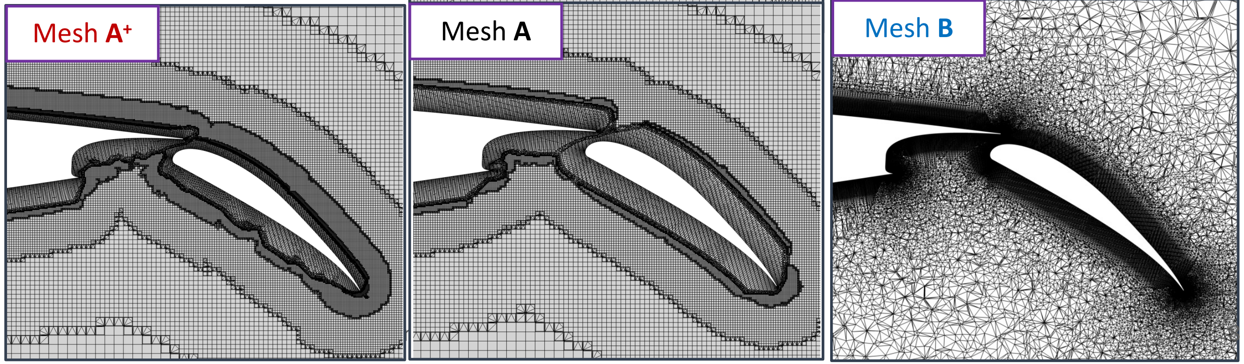
Metrics	Mesh A+	Mesh A	Mesh B
Points	555 M	419 M	156 M
Cells	1.12 B	812 M	475 M
Surface points	**10.8 M**	7.4 M	5.0 M
Nominal Δy_w^+	100	100	100

- Landing configuration at 40°/37° inboard/outboard flap deflection
- **Free air** simulations for half-span model with symmetry BC at *y* = 0 and farfield at 100 MAC (mean aerodynamic chord = 275.8")
- Time step corresponding to 1000/2000 steps per CTU
- Mesh A+ obtained finer spacing on upper surface of wing and flap
- FUN3D-FV WMLES on Meshes A+, A and B[2]
- FUN3D-FE WMLES on Mesh B



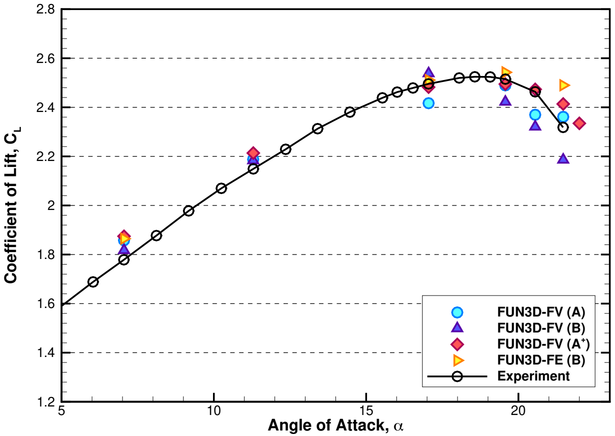


Mesh Slices at y = 483.5"

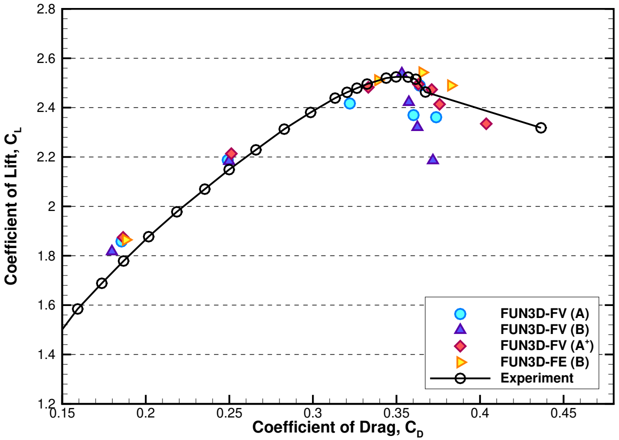


[2] Wang, L., et al., "Wall-Modeled Large-Eddy Simulations for High-Lift Configurations using FUN3D", AIAA Paper 2022-1555, 2022.

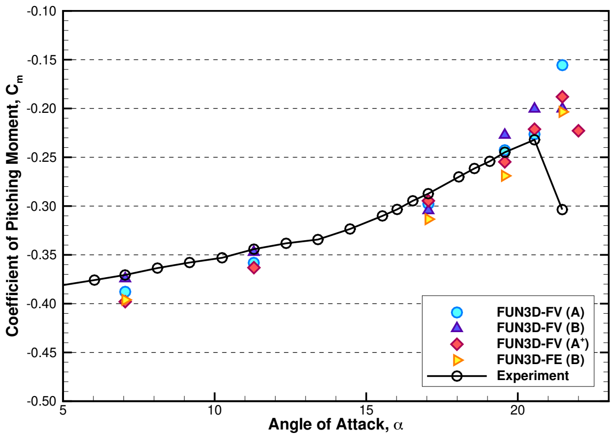
Time-Averaged Forces and Moments



Lift vs. α



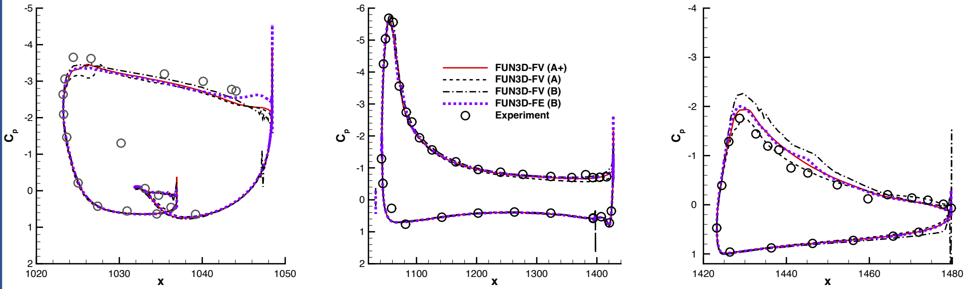
Lift vs. drag



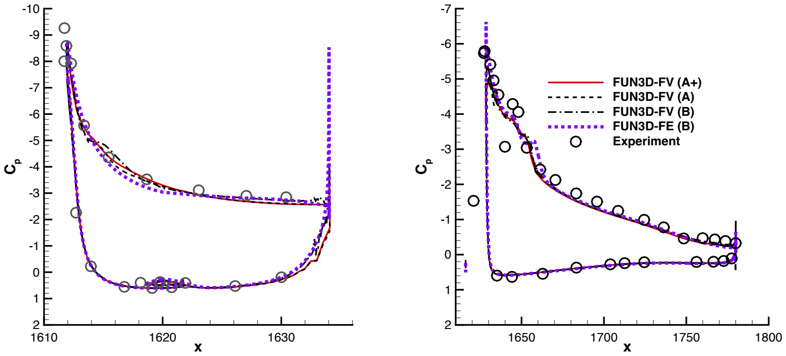
Pitching moment vs. α

- Time-averaged WMLES solutions compared with wall-corrected experimental data
- Predictions of maximum lift within 1% of experimental value by FUN3D-FV on Mesh A^+ and FUN3D-FE on Mesh B
- Improved agreement in lift and drag predictions obtained with FUN3D-FV on Mesh A^+ at 17.05˚ and 20.55˚
- A “pitch-break” phenomenon observed at 22.0˚ with FUN3D-FV on Mesh A^+

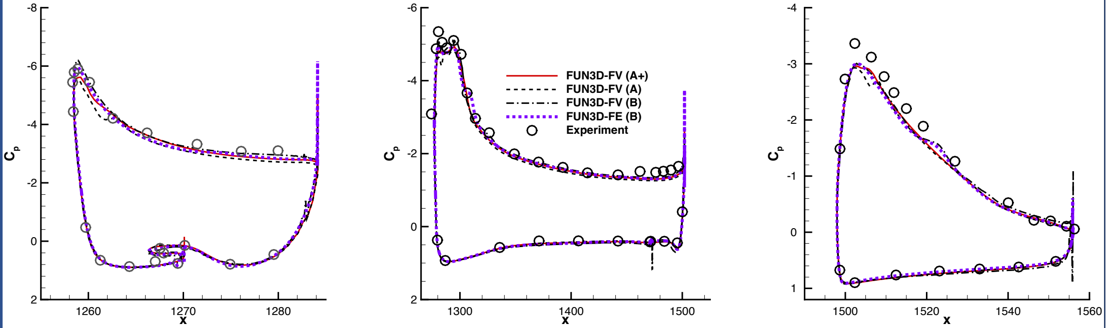
Surface Pressure Distributions (α = 17.05˚)



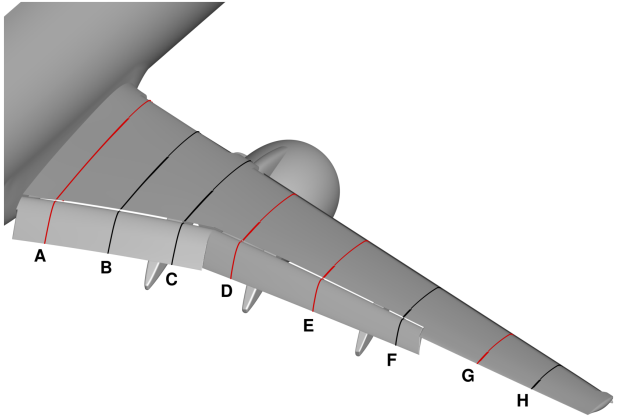
Station **A**



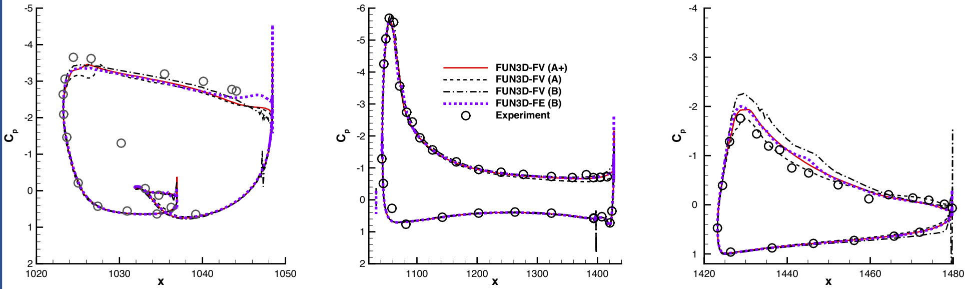
Station **G**



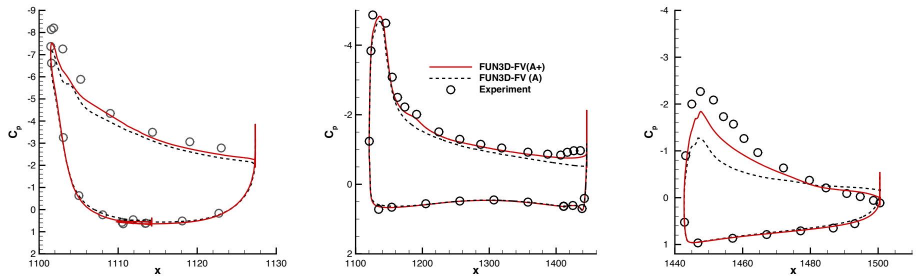
Station **D**



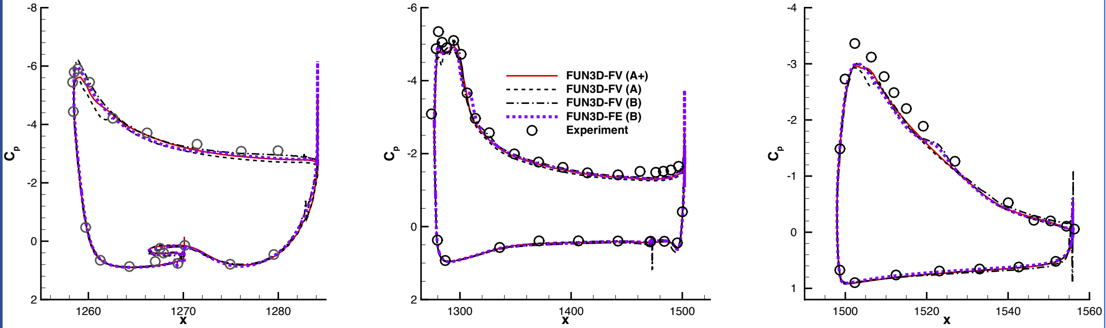
Surface Pressure Distributions (α = 17.05˚)



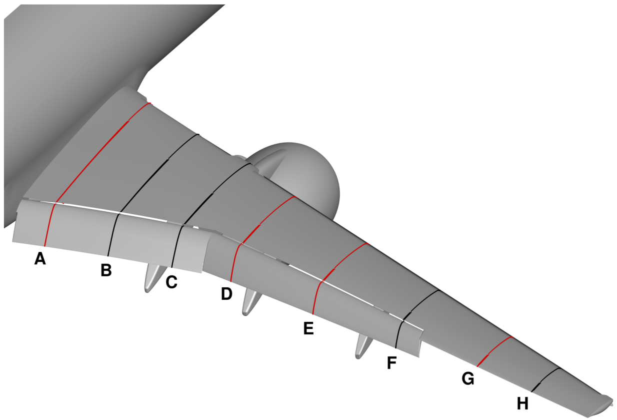
Station **A**



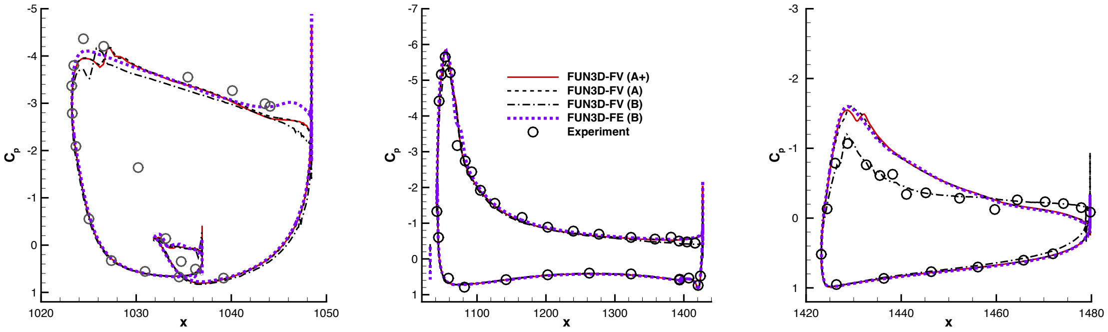
Station **B**



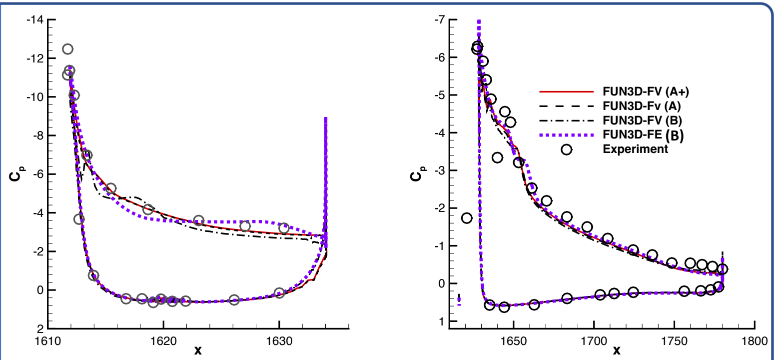
Station **D**



Surface Pressure Distributions (α = 19.57˚)



Station **A**



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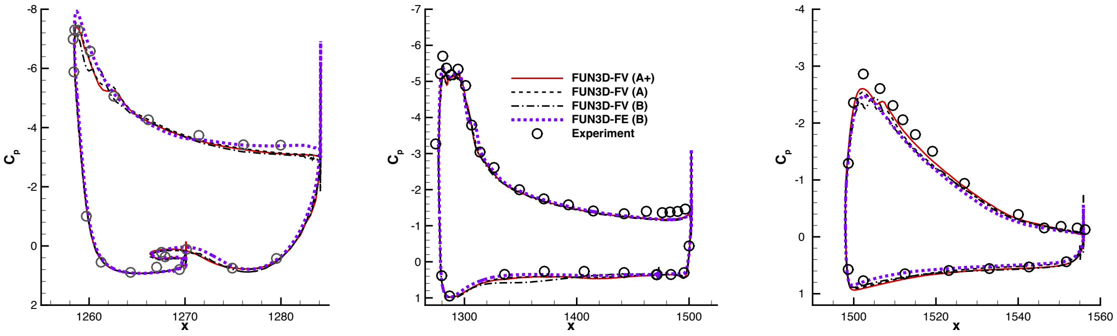

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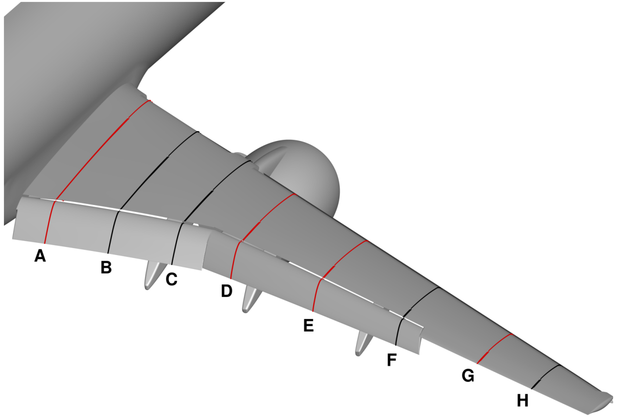
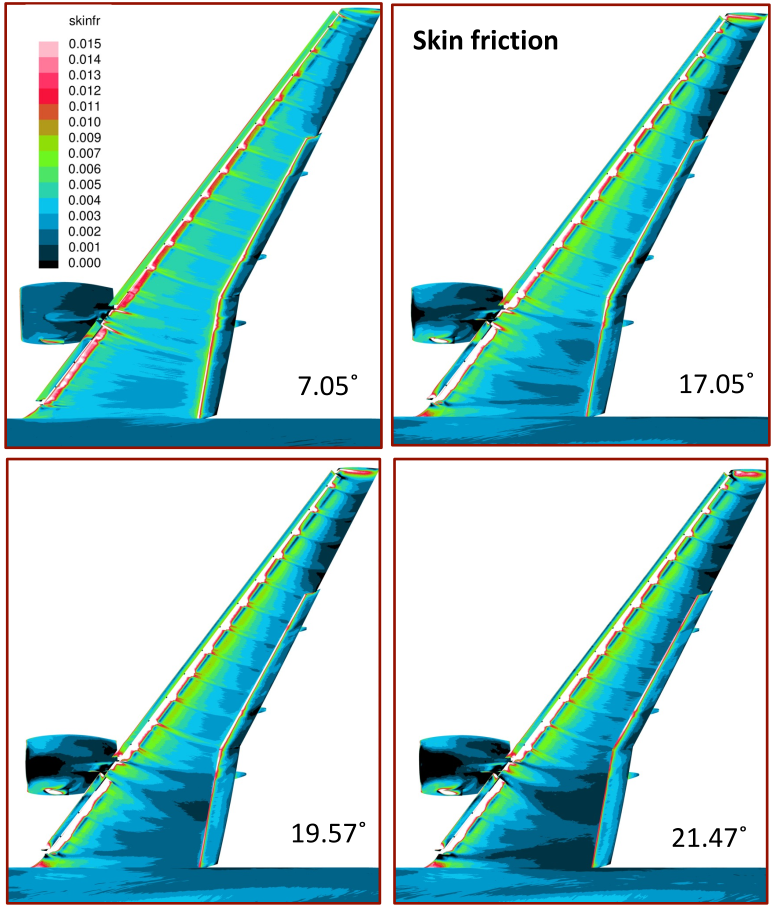
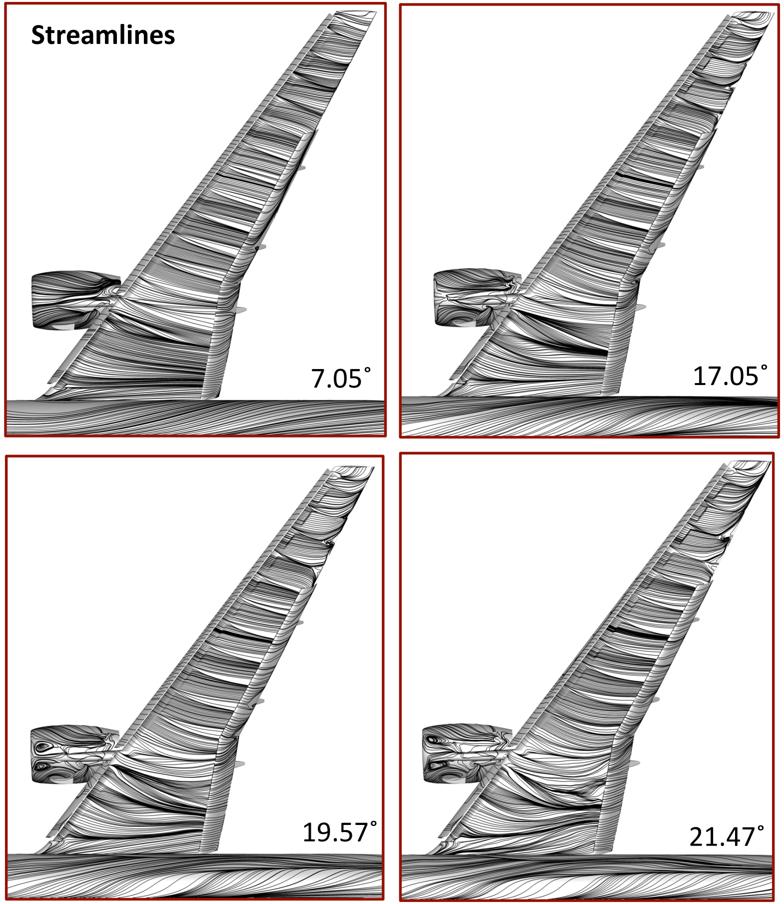
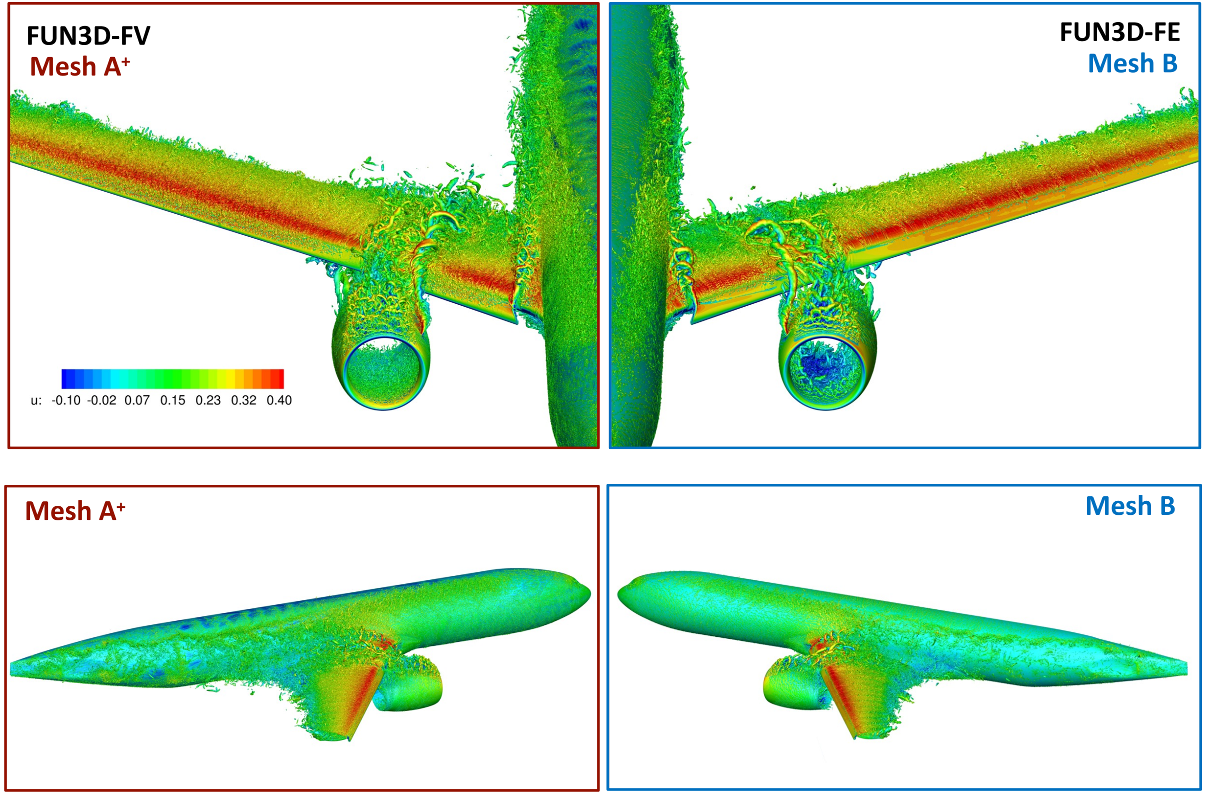


Time-Averaged Flowfield Visualization (FUN3D-FV, Mesh A$^+$)

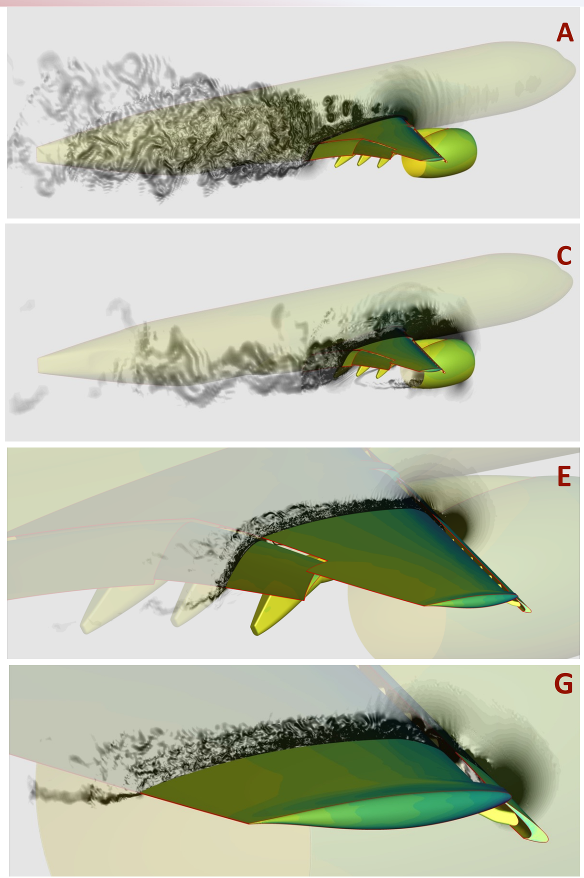




Instantaneous Flowfield Visualization (α = 21.47˚)



Isosurfaces of q-criterion colored by streamwise velocity



Density-gradient magnitude (FUN3D-FV, Mesh A$^+$)

Conclusions

- WMLES capability has been implemented in FUN3D FV and FE solvers
- WMLES methodology has been evaluated for high-lift configurations
  - Multielement 30P30N airfoil at different Reynolds numbers for 8˚ and 16˚
    - Capturing small flowfield variations due to variations of Reynolds number
  - NASA High-Lift Common Research Model at a range of angles of attack
    - Free-air simulations conducted with half-span model on three computational grids
    - FUN3D-FV and FUN3D-FE show qualitatively consistent solutions
    - Integrated aerodynamic forces, moments, and pressure distributions agree well in large range of angles of attack
    - Critical angle of attack corresponding to $C_{L,max}$ predicted accurately, with less than 1% difference with experiment
    - Improved lift and drag predictions at $\alpha = 17.05^\circ$ and $\alpha = 20.55^\circ$ on refined grid, Mesh A^+, using FUN3D-FV
    - Nose-down moment at $\alpha = 21.47^\circ$ is not strong enough but the "pitch break" is exhibited at $\alpha = 22.0^\circ$
- Future Work
  - More study on canonical flows
  - Conduct free-air and in-tunnel simulations for other CRM-HL configurations in the ecosystem

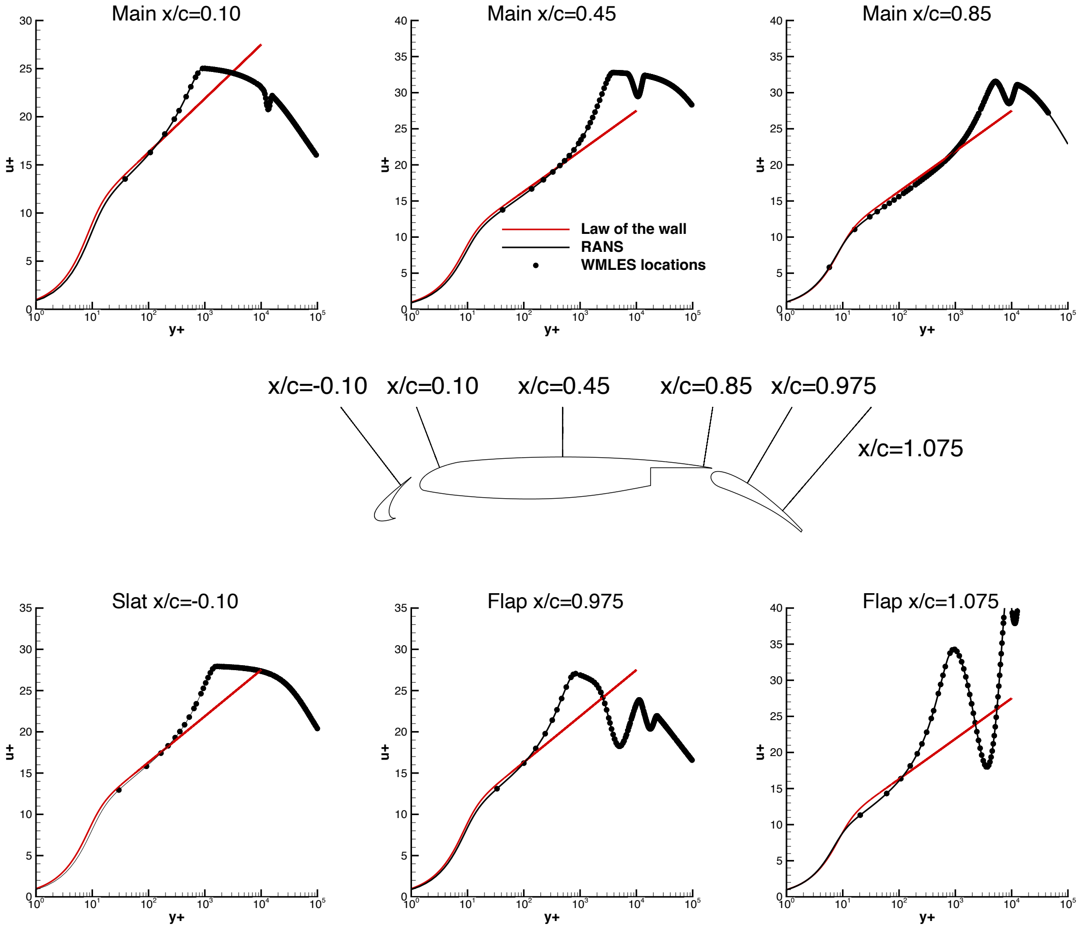
Acknowledgments

This research is sponsored by the NASA Transformational Tools and Technologies (TTT) Project of the Transformative Aeronautics Concepts Program under the Aeronautics Research Mission Directorate (ARMD).

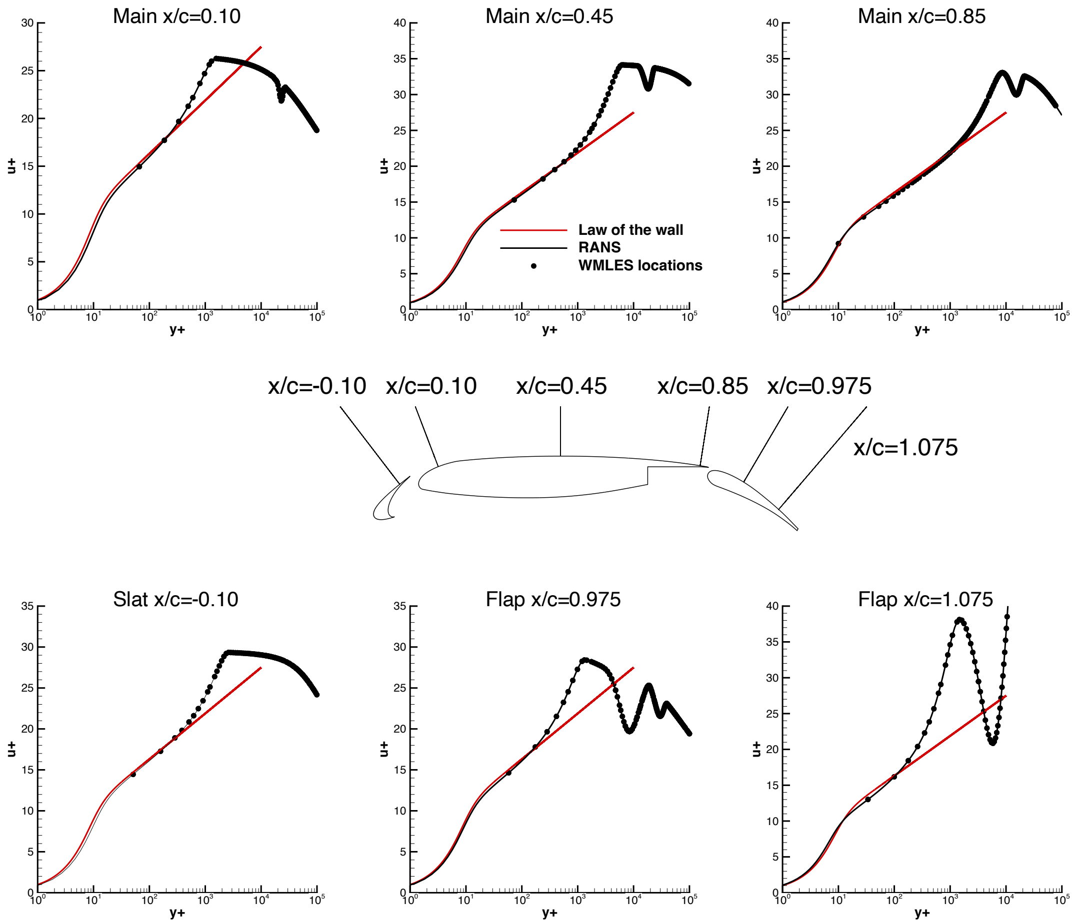
The authors would also like to thank Aaron Walden and Gabriel Nastac from NASA Langley Research Center, Langley GEOmetry LABoratory (GEOLAB), and the NASA High-End Computing (HEC) program for support of computational resources.

Backup Slides

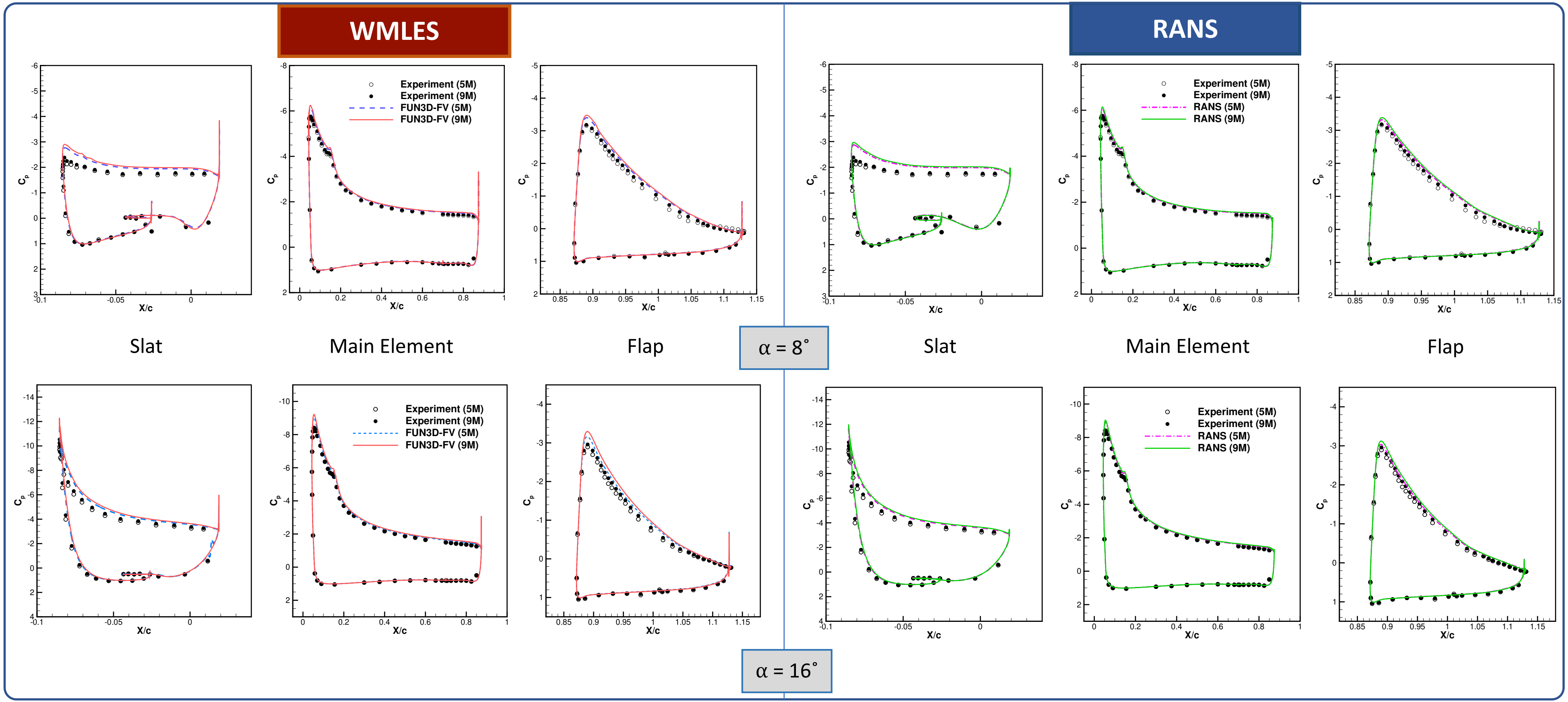
Point Distributions of WMLES Grid for 30P30N (Re = 5M, α = 16˚)



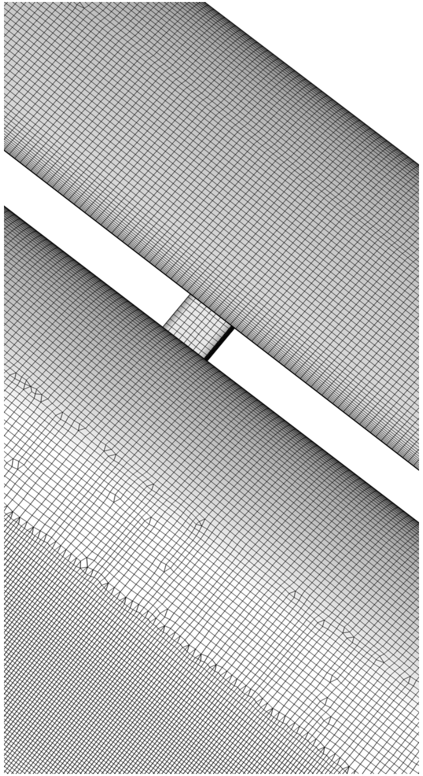
Point Distributions of WMLES Grid for 30P30N (Re = 9M, α = 16˚)



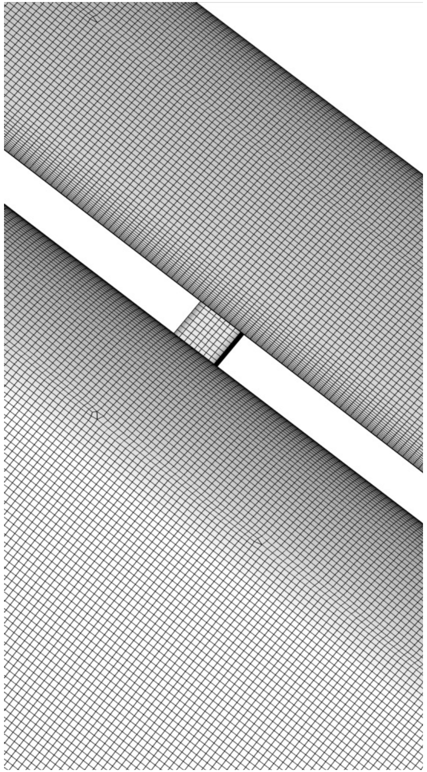
Surface Pressure Distributions



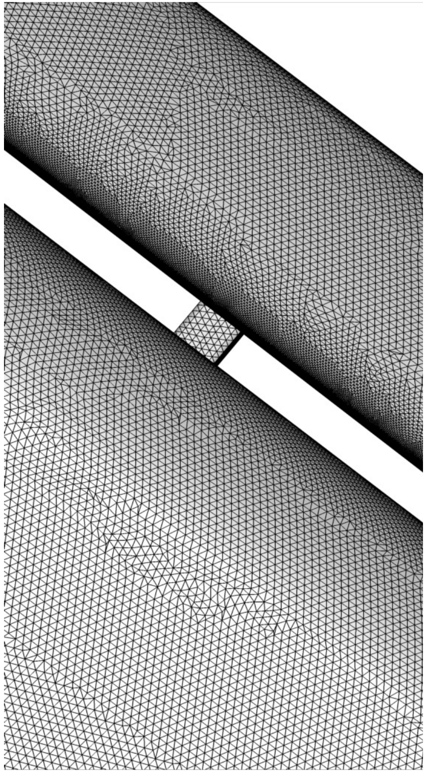
Computational Grids for NASA CRM-HL



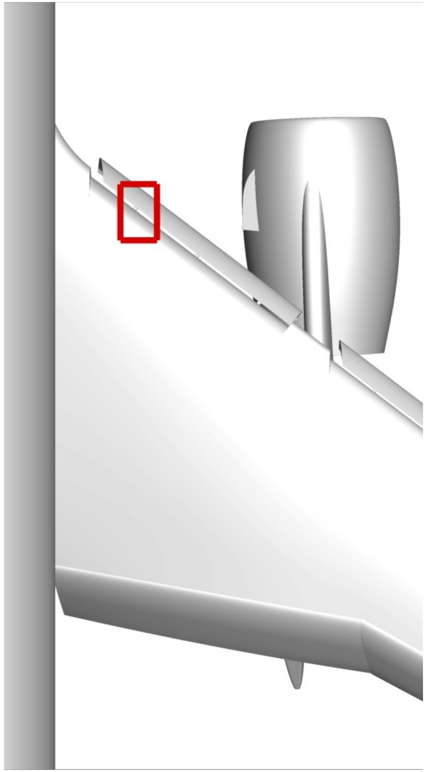
Mesh A^{+}



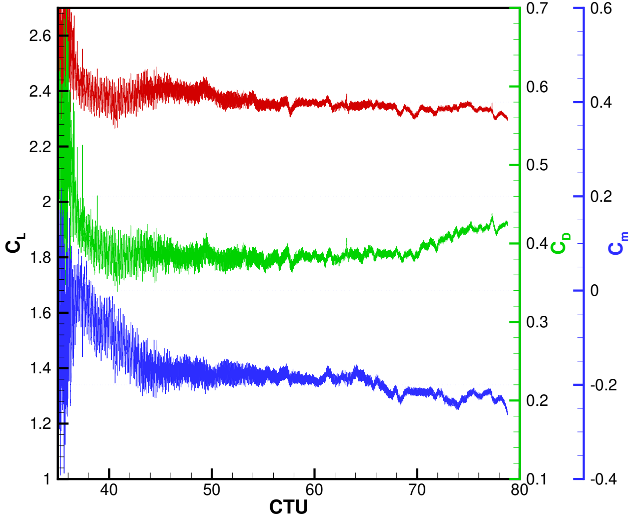
Mesh A



Mesh B



FUN3D-FV WMLES for NASA CRM-HL at α = 22°



Convergence of force and moments