

Large Eddy Simulations of High-Lift Common Research Model in the NTF Wind Tunnel at Flight Scale Reynolds numbers

Aditya S. Ghate, Jordan B. Angel, Gaetan K. W. Kenway, Man Long Wong, and Cetin C. Kiris
Volcano Platforms Inc., 422 Portage Ave, Palo Alto, CA 94306, U.S.

Immersed boundary Wall-Modeled Large Eddy Simulations (WMLES) of the High-Lift Common Research Model (HL-CRM) at a variety of Reynolds numbers up to a flight Reynolds number of $Re_{MAC} = 30 \times 10^6$ are performed using grids of sizes up to 2.5×10^9 cells. The simulations attempt to model the flow observed in the recent National Transonic Facility (NTF) wind tunnel at NASA Langley Research Center using the 5.2% scale half-span, floor-mounted model. Reasonable grid-convergence is achieved at all three Reynolds numbers studied, systematic differences between the experiment and the simulations still persist for the floor-mounted 5.2% model with simulations predicting a higher CL_{max} value compared to the experiment. Furthermore, simulations show a strong sensitivity to the model Reynolds number, while the experiment does not. Additional experiments and companion CFD studies utilizing full-span geometry mounting are needed to shed light on this anomalous Reynolds number behavior observed.

I. Introduction

Accurate computational prediction of aerodynamics seen on conventional aircraft with swept medium/high aspect ratio wings in high-lift configurations (take-off/landing) is notoriously challenging [1]. The flowfield seen in such configurations is dominated by the strong interplay between turbulent boundary layer flow separation, a variety of off-body vortex tubes and complex wake-boundary layer merges along with large pressure gradients [2]. This problem has been the focus of four past AIAA High Lift Prediction Workshops (HLPW), and the large scatter seen in submissions [3] underscores the need for a systematic evaluation of the current state-of-the-art Computational Fluid Dynamics (CFD) tools to understand potential benefits that are offered by different methodologies. This is particularly important to enable analysis-based compliance for aircraft certification; this goal has been envisaged in numerous programmatic objectives over the next two decades [4–6] as well, being highly desired by all airframe manufacturers in order to meet the emerging constraints imposed by climate change mitigation [7]. Following recent successes of scale-resolving techniques [8–13], this paper is focused on evaluating Volcano ScaLES, a newly developed Wall-Modeled Large Eddy Simulations (WMLES) solver [14–19] for its ability to:

- 1) Simulate high-lift aerodynamics on models observed in highly-complex slotted wind-tunnel tests - a flow characterized by exceptionally disparate length and time-scales due to the disparities between model scale and the tunnel scale.
- 2) Simulate Reynolds numbers effects, particularly to gauge the feasibility of WMLES at predicting flight-scale Reynolds number flows.

The recent experiments at the National Transonic Facility (NTF) at NASA Langley Research Center by Langston et al. (2025) [20] are used as a benchmark. Figure 1 shows the geometry simulation using ScaLES. Note that the desired Reynolds number (*variable*) and a Mach number of 0.2 inside the test section are obtained by choosing appropriate stagnation conditions at the inlet and allowing a carefully tuned Proportional–Integral–Derivative (PID) controller to determine the back-pressure applied at the outlet. Table 1 details the list of simulations performed at the Reynolds numbers that were studied.

The remainder of this paper is outlined as follows. In Section 2, we provide some brief description of Volcano ScaLES - the software utilized in this study. In Section 3, a grid-topology optimization and refinement study is performed on the free-air geometry in order to obtain the optimal grid-system for use for in-tunnel simulations. Section 4 describes the wind-tunnel initialization strategy that addresses the massive range of time-scales required to resolve for Large Eddy Simulations (LES) of this problem along with the tunnel+model unified grid system utilized. Section 5 covers the technical results obtained, while Section 6 summarizes them.

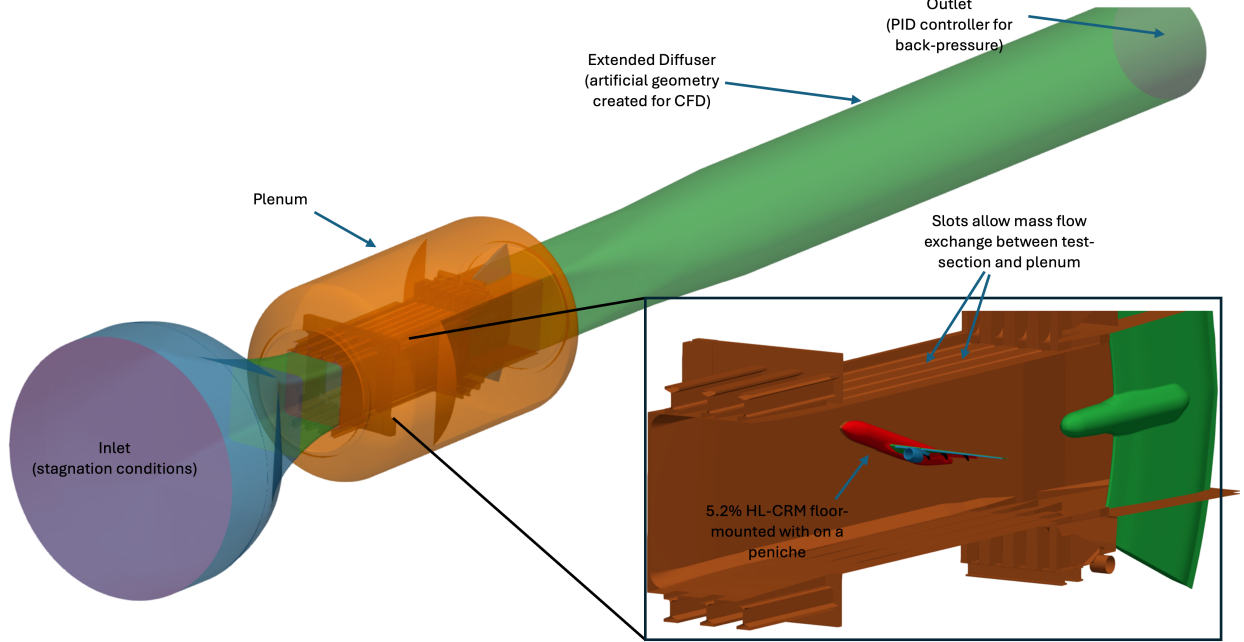


Fig. 1 Schematic showing the NTF-geometry and the HL-CRM model simulated

Table 1 Summary of test-cases (Reynolds numbers) simulated along with the grid sizes used for the 5.2% floor mounted model. a: Coarse and Medium resolution grids utilized a single NVIDIA 4xA100 node at the NAS facility at NASA Ames Research Center, while the Fine resolution grids used a single NVIDIA 8xL40S server. b: $\Delta x_{\min}$ is based on a full-scale model geometry with a 7 m mean aerodynamic chord (MAC). c: experimental data from the NTF facility are utilized for comparisons.

	NTF Data ^a	Reynolds Number	Volcano <u>ScaLES</u>	Grid Level ^a	$\Delta x_{\min}$ (mm) ^a	Cell Points (billions)	Angle of Attack								Total # of cases	
							6°	10°	14°	16°	18°	19°	20°	22°		
	X	5.4x10 ⁶	Freeair	Medium	4	1.01	x	x	x	x	x	x	x	x	8	
			WT installed	Coarse	5	0.894	x	x	x	x	x	x	x	x	8	
			WT installed	Medium	4	1.4	x	x	x	x	x	x	x	x	8	
			WT installed	Fine	3.25	2.15	x				x	x			3	
		16x10 ⁶	Freeair	Medium	4	1.01	x	x	x	x	x	x	x	x	8	
			WT installed	Coarse	5	0.894	x	x	x	x	x	x	x	x	8	
			WT installed	Medium	4	1.4	x	x	x	x	x	x	x	x	8	
	X	30x10 ⁶	Freeair	Medium	4	1.01	x	x	x	x	x	x	x	x	8	
			WT installed	Coarse	5	0.894	x	x	x	x	x	x	x	x	8	
			WT installed	Medium	4	1.4	x	x	x	x	x	x	x	x	8	
			WTinstalled	Fine	3.25	2.15	x				x	x			3	
			TOTAL												78	

II. Volcano ScaLES

A. Numerical Formulation

Volcano ScaLES solves the compressible Navier–Stokes equations using a nominally 4th order spatially accurate finite difference discretization with favorable Kinetic Energy and Entropy Consistency properties making it suitable for LES over a vast range of flow regimes. The viscous flux discretization utilizes a mix of 4th order and 2nd order discretizations with high spectral bandwidth thereby allowing further robustness for high Reynolds number flows without

additional numerical dissipation via the inviscid flux numerical operator in turbulence resolving regions. Physics-based numerical sensors that are functions of local velocity gradients as well as pressure and density fluctuations allow for spatio-temporally localized use of limiters needed to capture flows with discontinuities such as shocks and steep density gradients. A key convenience afforded by the use of Cartesian grids with unit aspect ratio is the use of explicit time-stepping scheme even in flows involving highly complex geometries; the perfectly isotropic grid cells near the geometry (see Figure 2) do not introduce any numerical stiffness associated with complex grid topologies. There are other significant advantages of Cartesian meshes including significantly reduced memory requirements for storing the grid as well as efficient and high accuracy in the underlying numerical formulation. The popular Strong Stability Preserving (SSP) variant of the classical 3rd order Runge–Kutta scheme developed by Gottlieb & Shu [21] is utilized for all the work presented in this paper.

Geometries are represented in the numerical formulation using an immersed boundary algorithm capable of enforcing inviscid no-penetration boundary conditions as well as viscous skin friction with appropriate Reynolds number asymptotic properties using an equilibrium wall-model. The wall-model that provides a shear-stress constraint at the wall uses solution information interpolated via probing at a fixed distance of $3\Delta/2$ into the fluid away from walls. All simulations presented in this work utilize the dynamic Smagorinsky model [22] to model the subgrid-scale stresses.

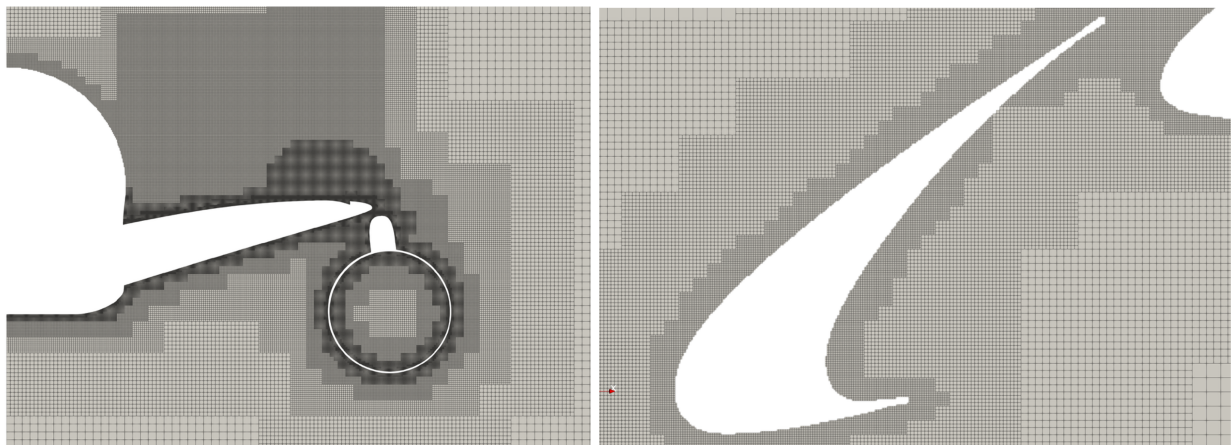


Fig. 2 Typical Cartesian Octree grids used in Volcano ScaLES.

B. Computational Architecture

Motivated by the need to fully exploit all available resources on modern GPUs, Volcano ScaLES is written exclusively in C++17 and CUDA. On simulations involving non-canonical geometries such as those considered in this paper, we achieve approximately 30% of peak FLOPs on compute-oriented devices along with nearly perfect (>95%) weak scaling efficiency from 1 to 8 GPUs (the number of GPUs per node). Unlike most CFD codes, the majority of the computations are compute-bound and we achieve high performance even in graphics-oriented, bandwidth-restricted devices, such as the Nvidia RTX 4090, Nvidia A10g or the Nvidia L40S. The combination of Cartesian methods and an explicit time stepping scheme yields extremely low memory requirements: ScaLES can simulate between 8.5 and 10 million cells per gigabyte of GPU memory depending on the complexity of the configuration. Simulations containing between 400 and 500 million cells are routinely performed on desktop computers containing just two RTX 4090 GPUs with 24 Gb of memory each. The ability to fully exploit more price efficient GPU hardware such as the Nvidia L40S accelerators on AWS, significantly lower the cost of large eddy simulations to a level that is practical for use in an industrial setting.

III. Grid Topology Optimization

In order to optimize the grid points and maintain computationally tractable total grid sizes, initial test simulations were conducted to determine the refinement regions at a variety of angles of attack. The $Re_{MAC} = 5.49 \times 10^6$ case was considered at $\alpha = 6^\circ$, $\alpha = 14^\circ$ and $\alpha = 19^\circ$ in free-air in order to focus the grid sensitivity on the model. Surface grid resolutions were obtained using criteria such as curvature-induced pressure variations, boundary layer thickness as well as tendency to separate, and a surface topology depicted in Figure 3 was achieved with finest resolution used on the

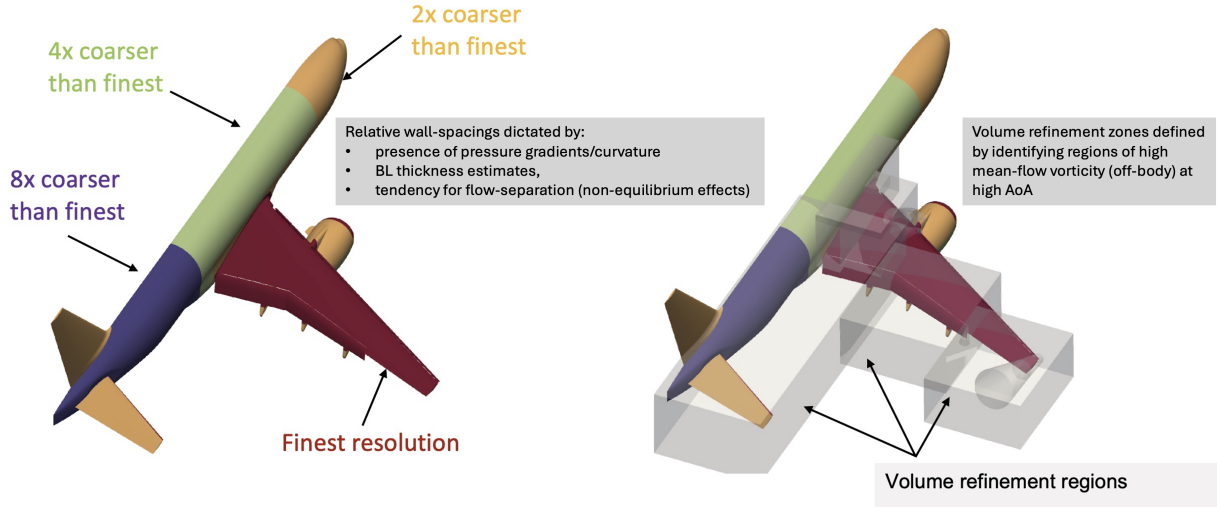


Fig. 3 Surface (left) and volume (right) refinement topologies showing relative spacings in different parts of the geometry.

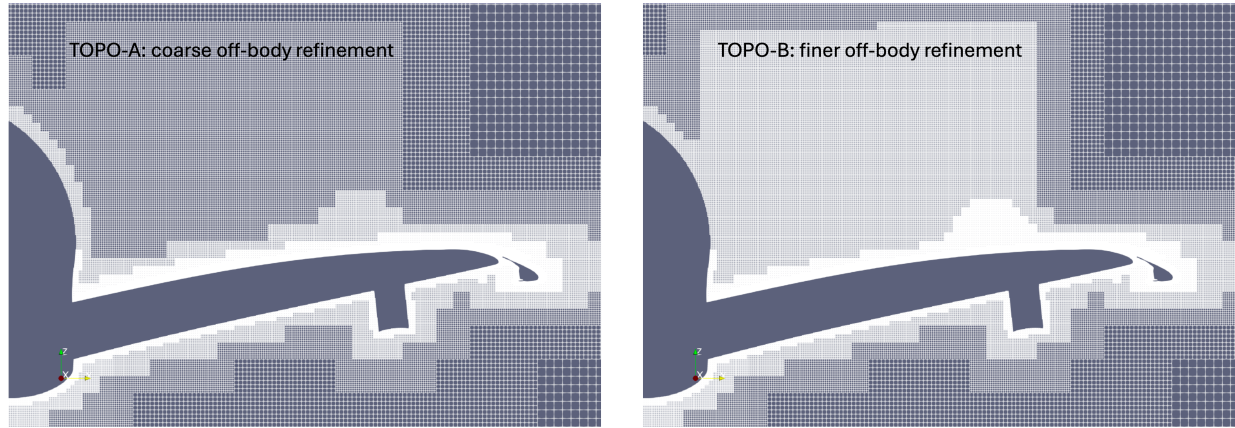


Fig. 4 Cross-sections of the grids for the two grid topologies with sequences of 6 consistently refined grids used to study mesh and topology sensitivity for the HL-CRM model.

main element (suction side), the slat (both sides) and the flaps (suction side). Finest resolution was also used on leading edge of the nacelle to capture the thin transitional boundary layer at the lip. Volume refinement zones were also utilized to capture off-body vorticity generated by the chine-vortex and tip vortices created at various cutouts as well as flap, slat and main-element tips. While the location of these refinement regions is straightforward to determine, the resolution needed inside the regions is not obvious. As such, two topologies, topoA and topoB, were generated where the relative resolution inside the volume refinement region was varied (see Figure 4). For each of the two topologies, a sequence of 6 uniformly refined grids was generated with details provided in Table 2. Figures 5 through 7 show the lift obtained on the grids broken down into component-wise lift for further insights. Several observations follow -

- 1) At $\alpha = 6^\circ$, little sensitivity is seen between the two topologies. The finest two resolutions appear to reach grid convergence for both component-wise lift and total lift with some minor sensitivities left on the slat.
- 2) Similarly for $\alpha = 14^\circ$, no sensitivity is observed between the two topologies and reasonable grid convergence is observed for grid spacing around 4 mm.
- 3) For the CLmax case at $\alpha = 19^\circ$ some sensitivity is observed between the two topologies, especially at coarser grid levels of around 5 – 8 mm. TopoB utilizing finer off-body refinement predicts a noticeably higher CLmax. Further insight can be obtained by studying the skin friction for the L5 grid level (see Figure 8). Coarser volume grid in TopoA results in a weaker boundary layer downstream of the pylon whereas improved resolution in the

Table 2 Grid statistics for the two grid topologies used to study mesh and topology sensitivity for the HL-CRM model.

Grid Level	Dx_{min} (mm) Full Scale	Dx_{min} (mm) Model Scale	TOPO-A Grid Points (M)	TOPO-B Grid Points (M)
L0	10.986	0.0225	130	134
L1	8.789	0.0180	199	208
L2	7.031	0.0144	305	323
L3	5.625	0.0115	469	506
L4	4.500	0.0092	722	790
L5	3.600	0.0074	1,124	1,261

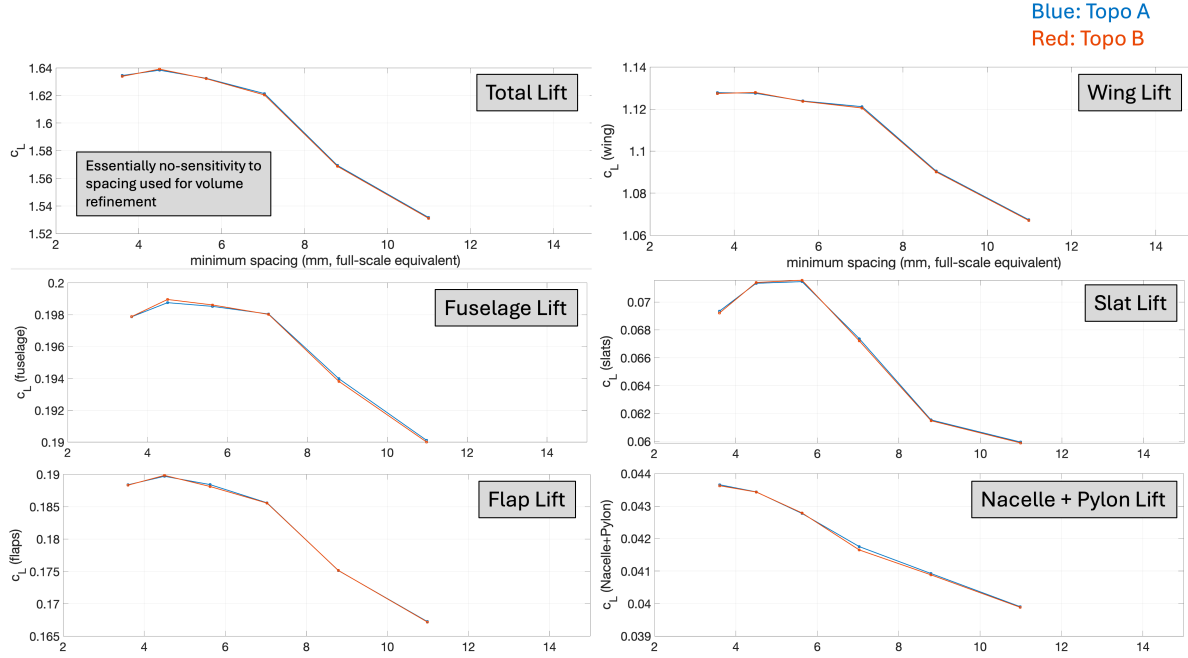


Fig. 5 Grid convergence and topology sensitivity for $\alpha = 6^\circ$.

chine vortex for TopoB alleviates this artificial boundary layer weakness.

This refinement study highlights the importance of off-body grid resolution to capture the physics near CL_{max} . Furthermore, it suggests that reasonable grid convergence may be obtained at resolutions closer to 4 mm corresponding to approximately 1700 points across the mean aerodynamic chord. These best practices are subsequently used for in-tunnel simulations discussed in the next section.

IV. Wind-tunnel startup strategy

The primary challenge associated with in-tunnel LES is the disparity in spatial and temporal time-scales seen in turbulent eddies occurring on the model and those seen inside the wind-tunnel. As an example, the turbulence time-scales occurring on the model are no longer than 0.025s (5-10 Convective Time Units (CTUs)) while those seen in the tunnel diffuser are at least 50-100 times longer. Furthermore, the simulation time required for the floor-boundary layer to equilibrate is at least two orders of magnitude larger than the time needed for the wing-boundary layer to equilibrate. As such, a multi-resolution strategy is needed to simulate this multi-timescale problem. Additional complication is added by the need for variable back-pressure for each case simulated (varies with both α and Re_{MAC}). A PID controller is used to address this second challenge; the controller coefficients were tuned once using a coarse grid and then frozen for all test cases discussed in this paper. We use three precursor simulations (see Figure 9) to *start* the tunnel followed by the

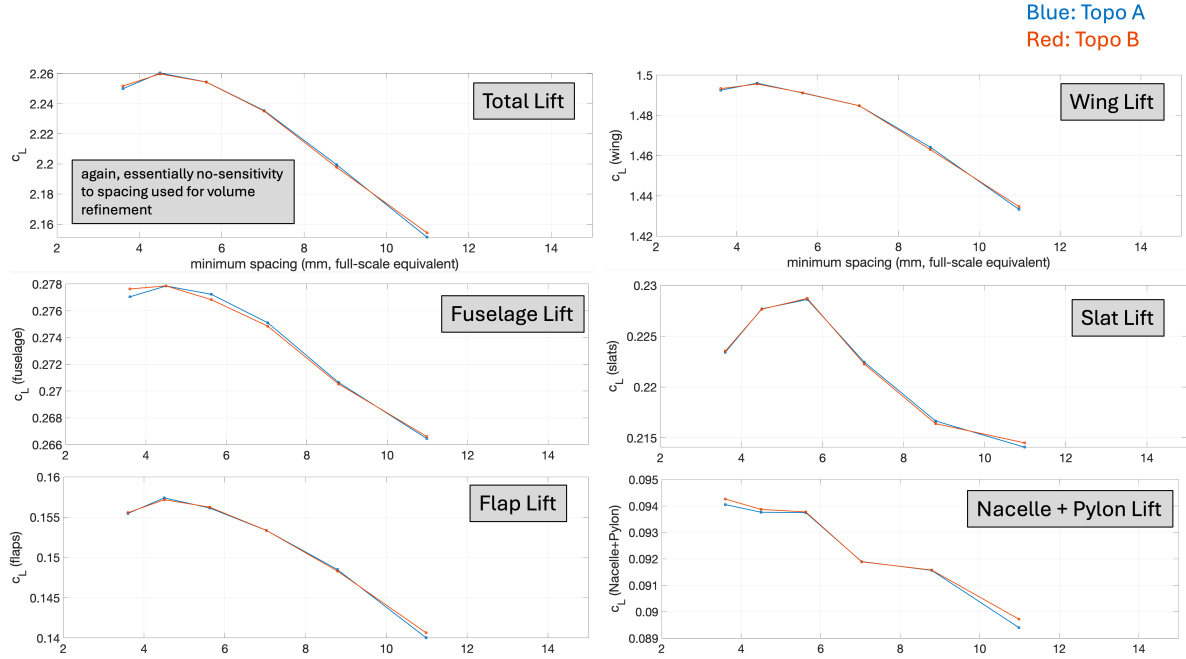


Fig. 6 Grid convergence and topology sensitivity for $\alpha = 14^\circ$.

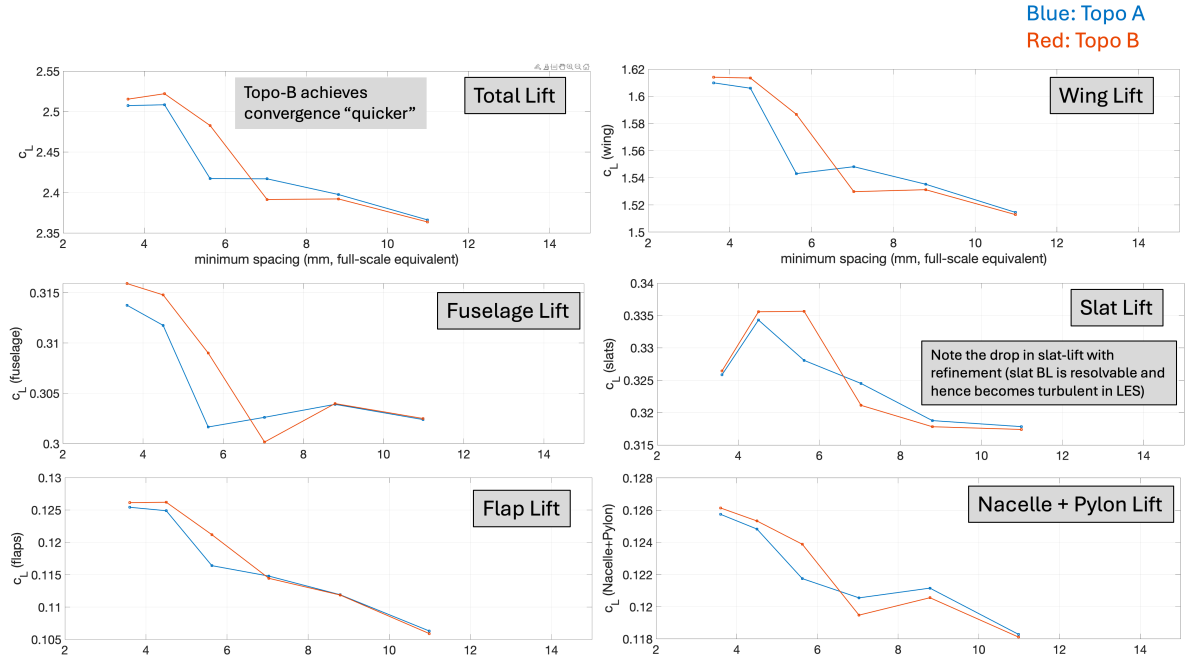


Fig. 7 Grid convergence and topology sensitivity for $\alpha = 19^\circ$.

target grid (either "coarse", "medium" or "fine") resolution which is then run as long as needed for the aerodynamic loads to reach a statistically stationary state. Appropriate grid resolution is utilized for the test section: a) the tunnel floor boundary layer is captured with at least 10-20 grid points (see Figure 11 and 12), and b) at least 10-15 grid points are used in the narrowest part of the test-section slots to allow sufficient resolution for capturing the mass-flow exchange that occurs between the test section and the plenum once the model is aerodynamically loaded. Figure 10 shows the flow inside the test section on the medium grid once the entire flow (tunnel and model) has reached an equilibrium state.

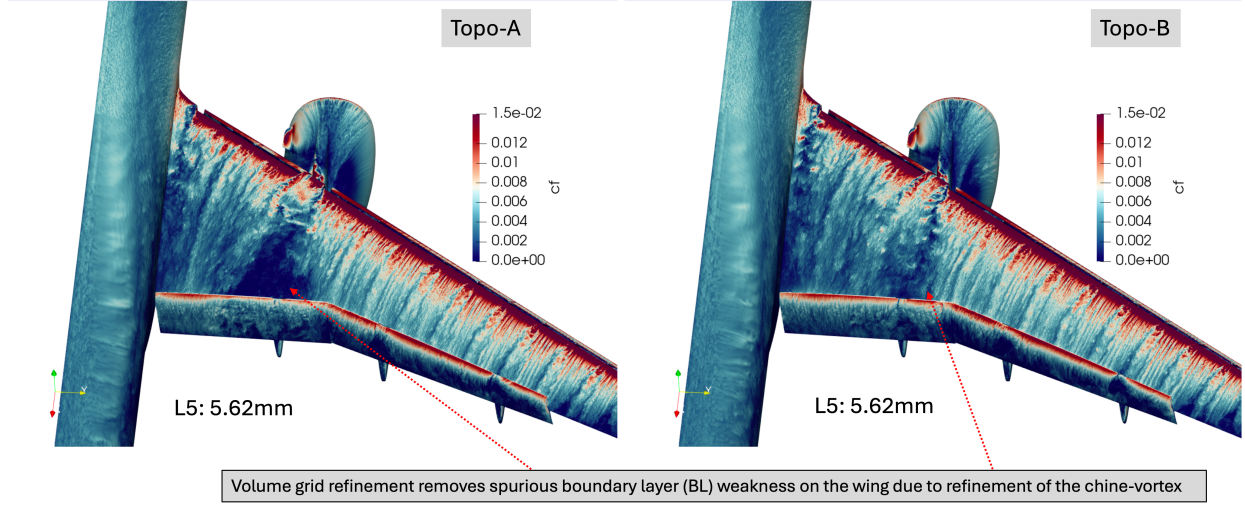


Fig. 8 Instantaneous skin friction coefficient compared between a coarse grid (L4) for the two-distinct grid topologies showing sensitivity of surface boundary layer weakness to the resolution used for the chine-vortex.

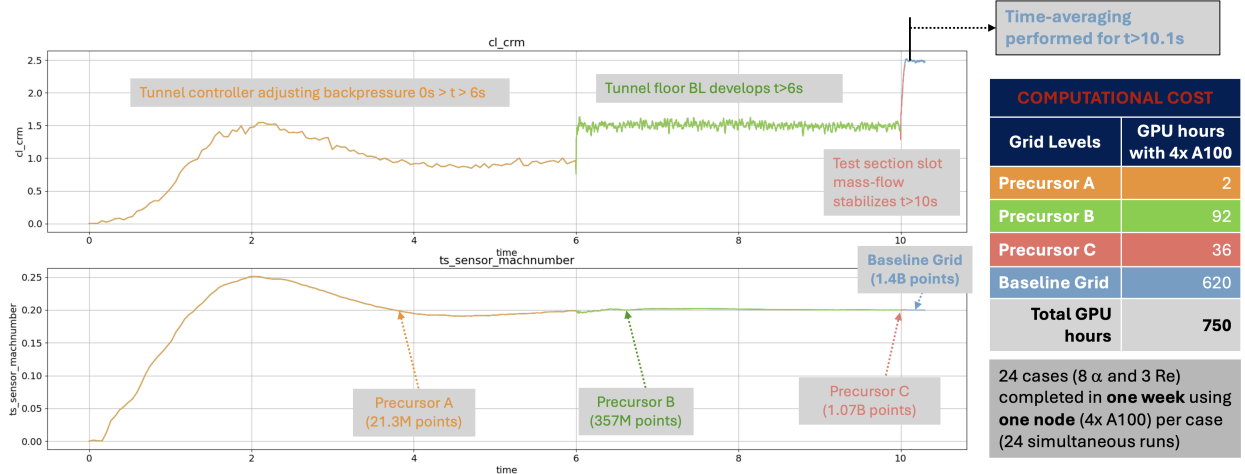


Fig. 9 History of test section Mach number and lift on the model for the sequence of four grids leading up to the medium grid simulation. Computational cost of each simulation in terms of GPU-hours is also reported.

V. Results and Discussions

A. Integrated Forces and Moments

We begin the discussion of the results by first considering the integrated force and moment coefficients for all cases shown in Figures 13 through 17. The following observations can be made based on these integral quantities:

- 1) Medium and fine grids produce essentially identical loads at all angles of attack and Reynolds numbers. This is consistent with the grid requirements suggested by the free-air grid resolution study discussed in Section 3. The LES results shown in Figure 13 show a clear offset at all angles of attack when the Reynolds number is increased from 5.49×10^6 to 30×10^6 .
- 2) For the $Re_{MAC} = 5.49 \times 10^6$ case shown in Figure 14, a clear offset is seen in pitching moment with LES predicting a more nose-up moment compared to the experiment. This overprediction is more noticeable at lower angles. Interestingly, the pitch break is predicted at the correct angle of attack by the simulations which suggest that it occurs at $\alpha = 19^\circ + \epsilon$ consistent with the experiment. However, the CL_{max} value seen in LES (2.5) is higher than that seen in the tunnel (2.4).

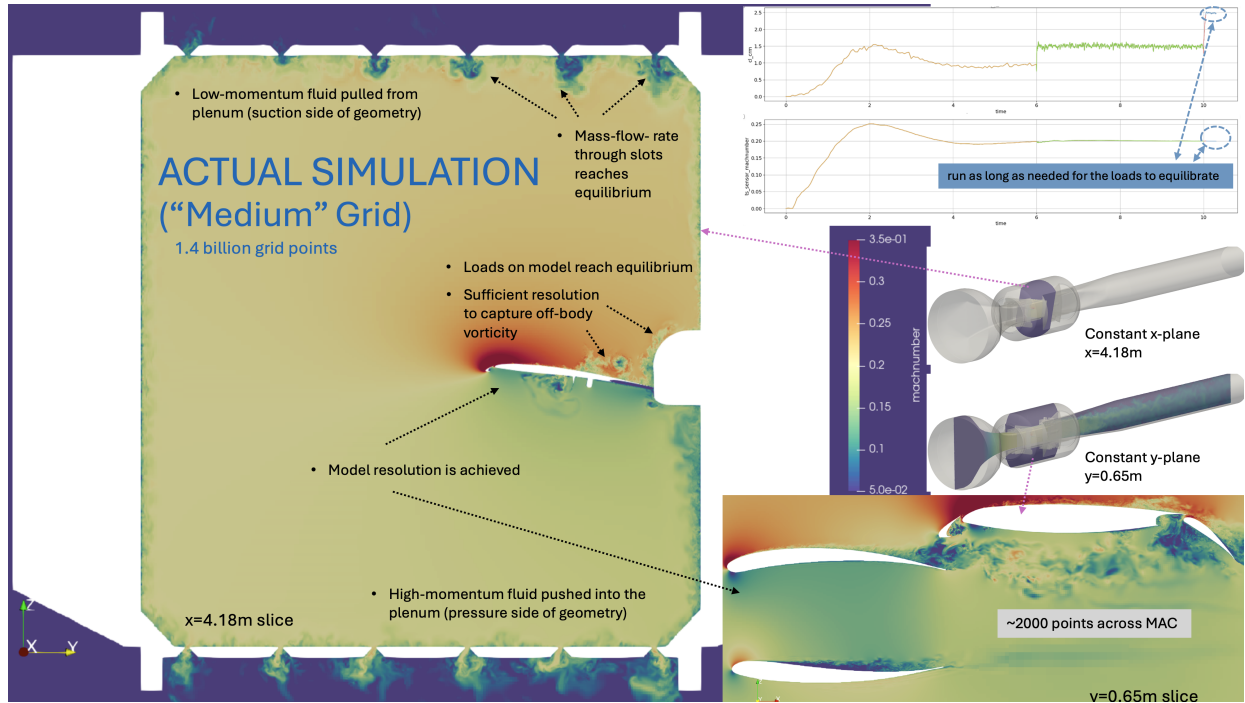


Fig. 10 Cross-section of the test-section obtained for the medium grid at $\alpha = 18^\circ$ for $Re_{MAC} = 5.49 \times 10^6$.

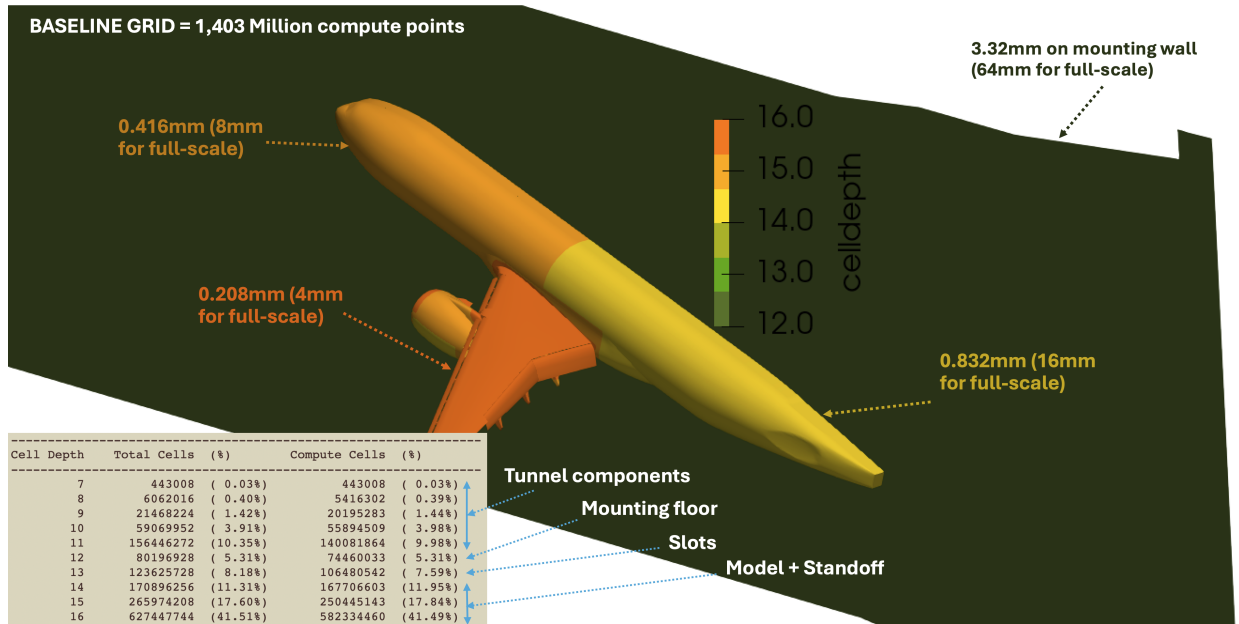


Fig. 11 Model and tunnel spacings for the medium resolution grid.

- 3) For the $Re_{MAC} = 30 \times 10^6$ case shown in Figure 15, a clear offset is seen in CL for all angles of attack. Interestingly, the pitching moment shows excellent agreement; this is incidental and likely to be due to error cancellations.
- 4) All three simulated Reynolds numbers are shown in Figure 16 for the medium grid and plotted against the experimental data at the two extreme Reynolds numbers. It is clear that while LES shows a monotonic increase in CL at all α , the experimental data shows little to no sensitivity to Reynolds number. However, note that LES

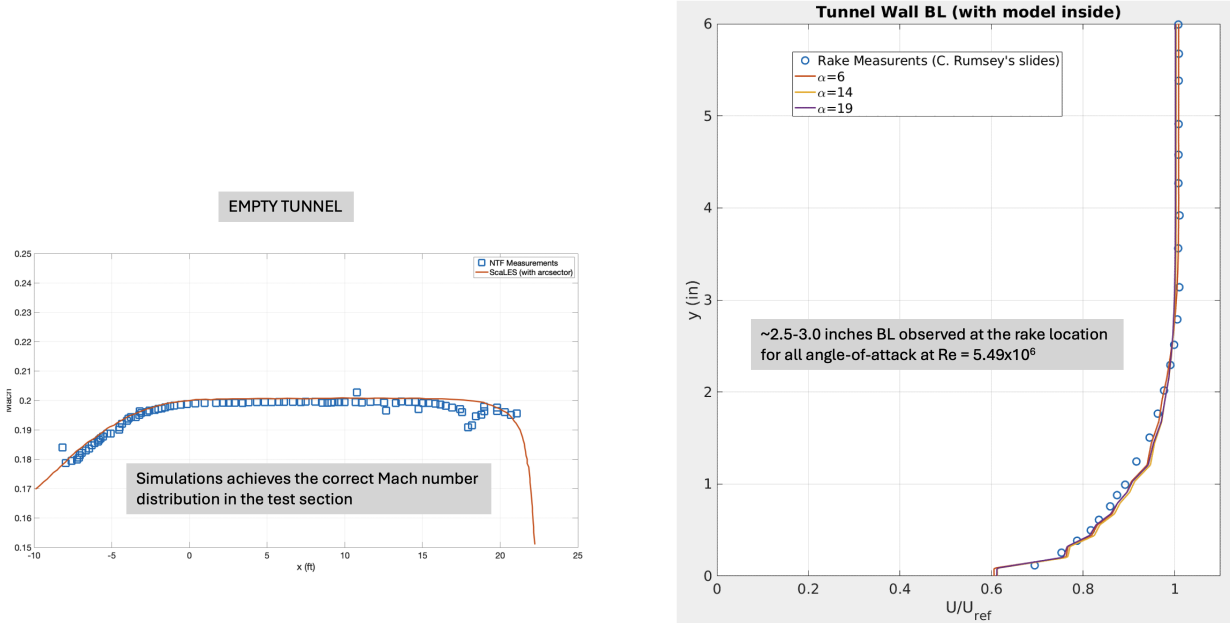


Fig. 12 Velocity profiles obtained for empty tunnel and floor boundary layer profile obtained at the rake location with the model in the tunnel at several angles of attack.

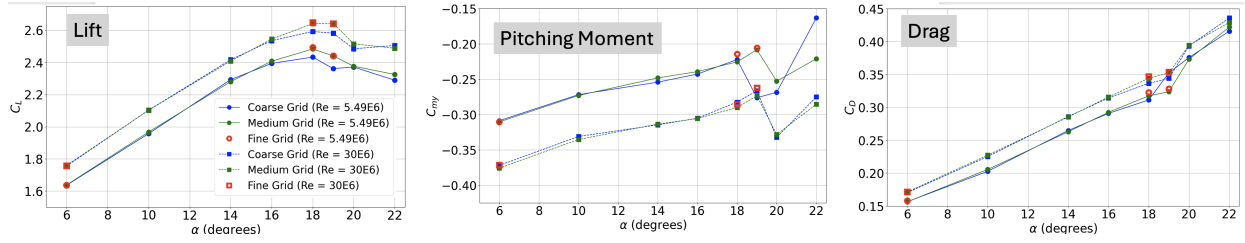


Fig. 13 Force and moment coefficients for all three grid levels shown for the two Reynolds numbers.

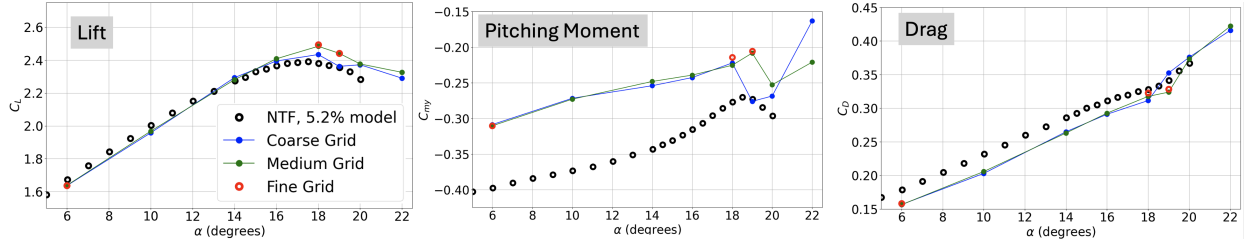


Fig. 14 Force and moment coefficients for all three grid levels shown for $Re_{MAC} = 5.49 \times 10^6$ compared with the experiment.

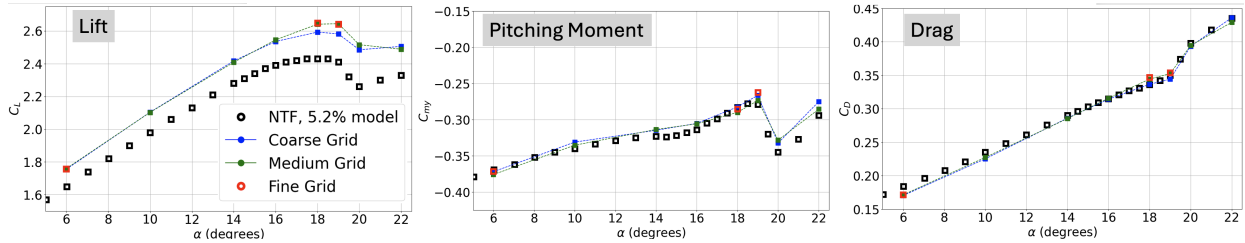


Fig. 15 Force and moment coefficients for all three grid levels shown for $Re_{MAC} = 30 \times 10^6$ compared with the experiment.

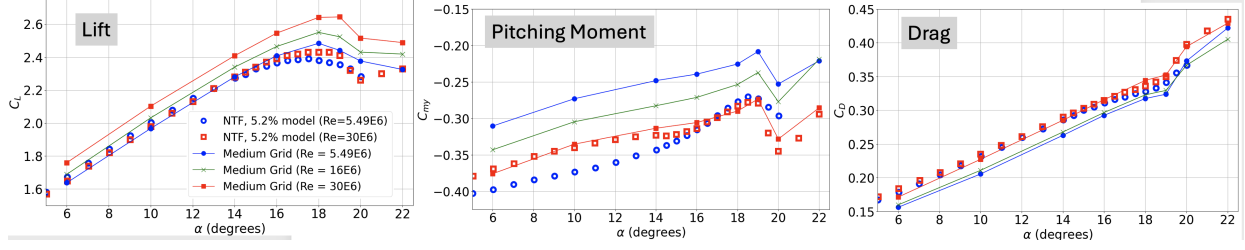


Fig. 16 Medium grid force and moment coefficients for three Reynolds numbers with comparisons to the experiment.

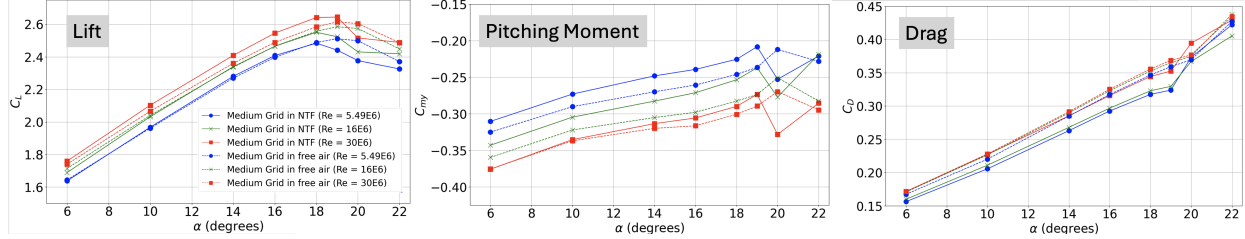


Fig. 17 Medium grid force and moment coefficients for three Reynolds numbers showing comparisons between in-tunnel and free-air configurations.

predicts the correct onset of pitch break at both Reynolds numbers compared to the experiment.

- 5) Finally, the difference between free-air and in-tunnel case is shown in Figure 17 for the three Reynolds numbers on the medium resolution grid. It is interesting to note that the onset of stall occurs approximately 1.5° - 2° lower for the in-tunnel configuration compared to the free-air configuration. While the CL differences between in-tunnel and free-air cases are low, the in-tunnel cases show a substantially lower CD and a more nose-up pitching moment.

B. High- α conditions

The CL_{max} condition is expected to occur at around $\alpha = 18^{\circ}$ and $\alpha = 19^{\circ}$, and so we attempt to correlate the observations made for integrated forces and moments with flow features observed on the geometry by considering the surface streamlines and pressure coefficients extracted at 9 spanwise stations. Several interesting observations are found:

- 1) The surface streamlines at $\alpha = 18^{\circ}$ are shown for the three different grids in Figure 18. Neither of the three grids show any onset of side-of-body separation occurring at wing root; however, separation is observed both on the flap as well as on the outboard wing. Medium and fine resolution grids show essentially identical separation with some small differences remaining on the outboard flap. Upon inspection of pressure coefficient, excellent agreement between the fine-grid and the experiment is noted on mid- and out-board wing, slats and flaps. However, the wing-root region in LES shows a noticeably higher suction; this is consistent with the higher CL_{max} observed in LES compared to the experiment. Nonetheless, all spanwise stations except for station A show excellent agreement in predicted C_p for $Re_{MAC} = 5.49 \times 10^6$.
- 2) The sensitivity of the flap and outboard wing separation to Reynolds number is next reported in Figure 19. Simulations show a decreasing separated flow region on the outboard wing with increasing Reynolds numbers; however the flap separation triggered by the flap fairings does not appear to be very sensitive to Reynolds number.
- 3) The pressure coefficients for $\alpha = 18^{\circ}$ at $Re_{MAC} = 30 \times 10^6$ shown in Figure 20 provide some insight into the large CL_{max} overprediction observed for the higher Reynolds number. The larger suction near wing-root is consistent with the observation made for the lower Reynolds number case; however the pressure coefficient at every other station shows a small over-prediction in contrast to the lower Reynolds number case.
- 4) Next the differences between in-tunnel and free-air cases at CL_{max} are highlighted using C_p for $Re_{MAC} = 30 \times 10^6$ in Figure 21. The only two stations that show meaningful differences are the most-inboard stations A and B. The free-air simulations show a large side-of-body lift compared to the in-tunnel case; this is consistent with the presence of horse-shoe vortex formed by the juncture flow interactions between the tunnel floor and the model

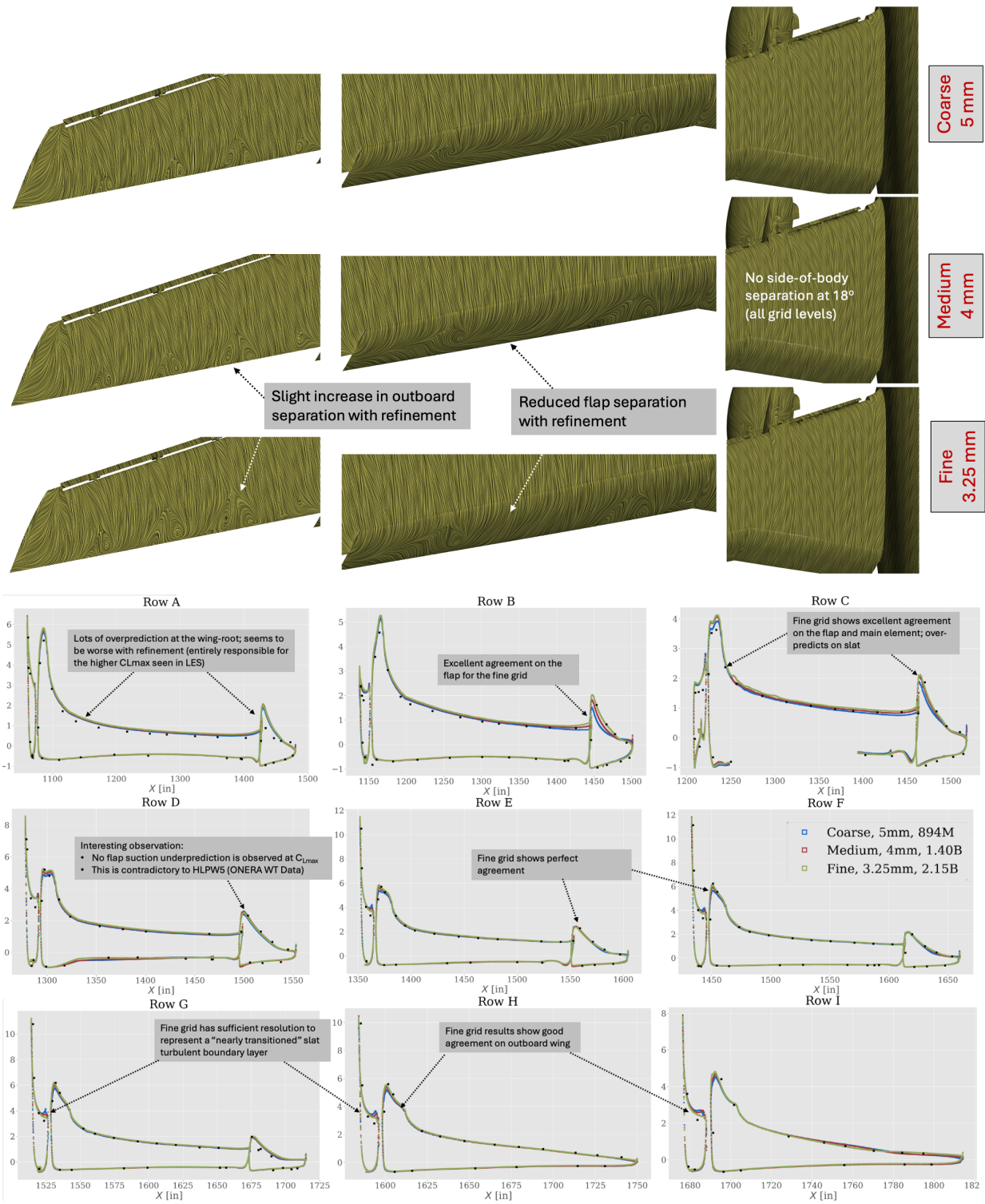


Fig. 18 Streamlines and pressure coefficients shown for the three grid levels for $\alpha = 18^\circ$ at $Re_{MAC} = 5.49 \times 10^6$ compared with the experiment.

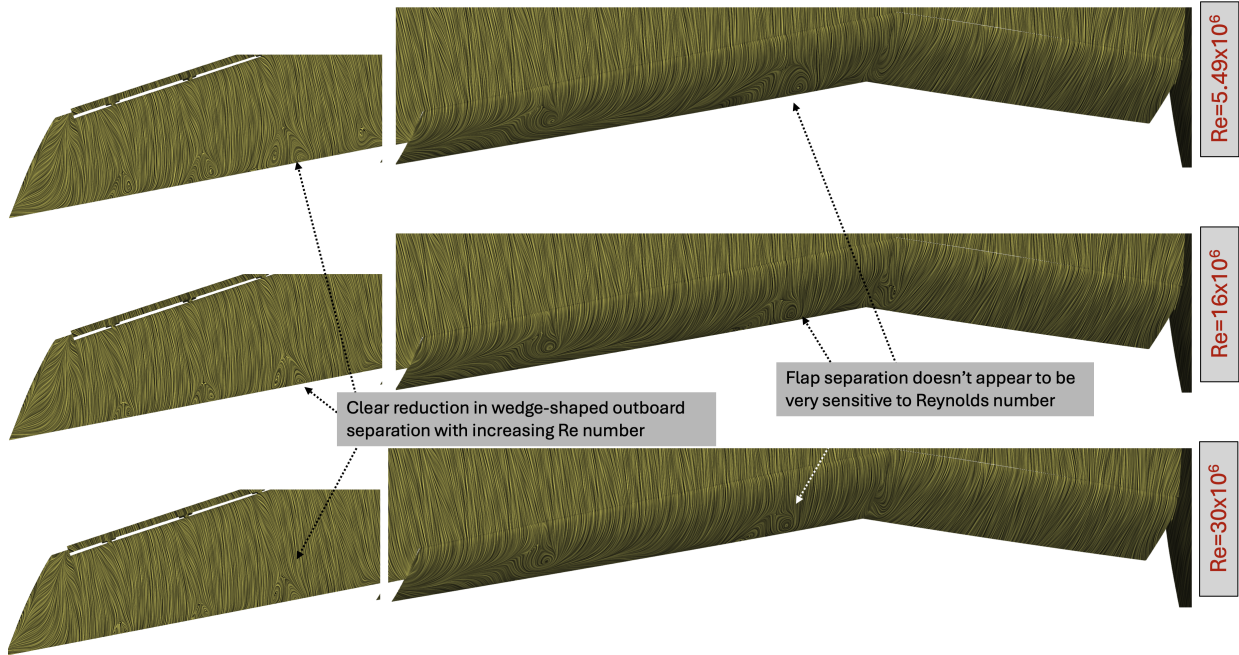


Fig. 19 Surface streamlines at $\alpha = 18^\circ$ showing Reynolds number sensitivities for separation observed on the flaps and on the outboard wing.

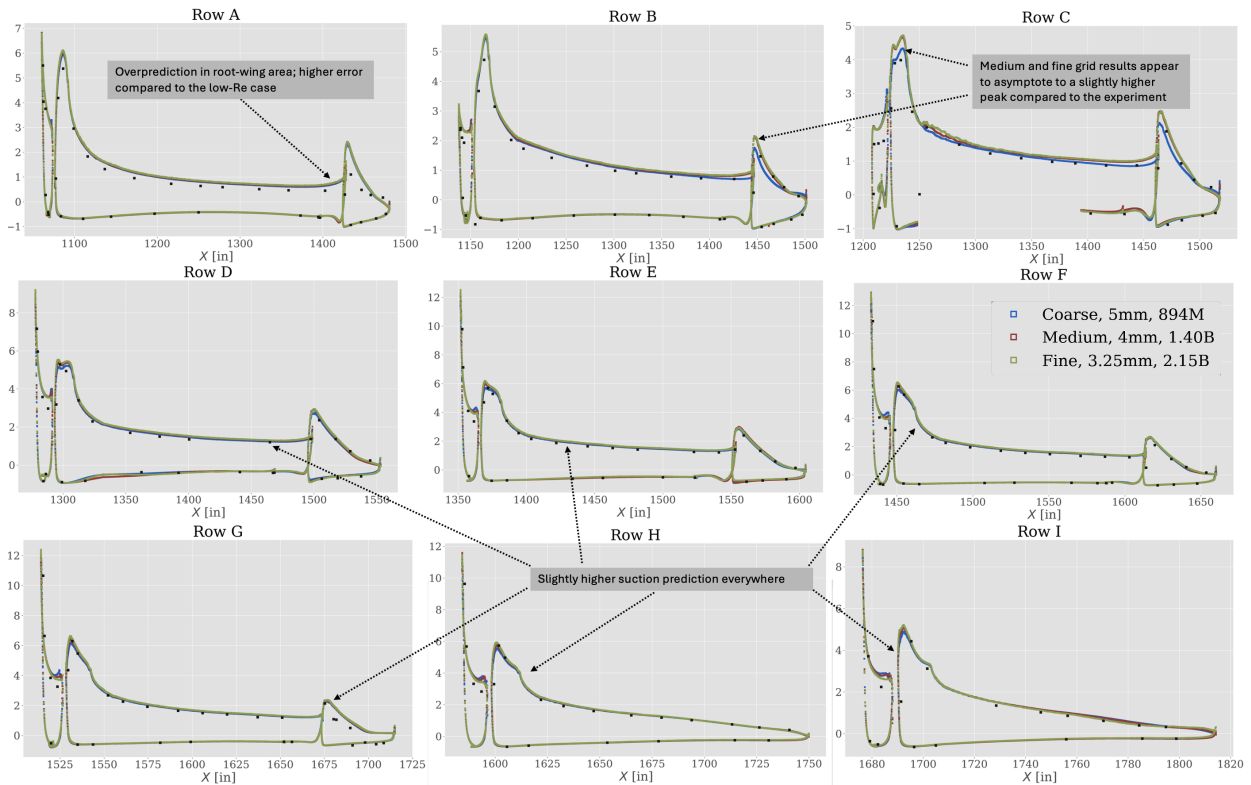


Fig. 20 Pressure coefficients shown for the three grid levels for $\alpha = 18^\circ$ at $Re_{MAC} = 30 \times 10^6$ compared with the experiment.

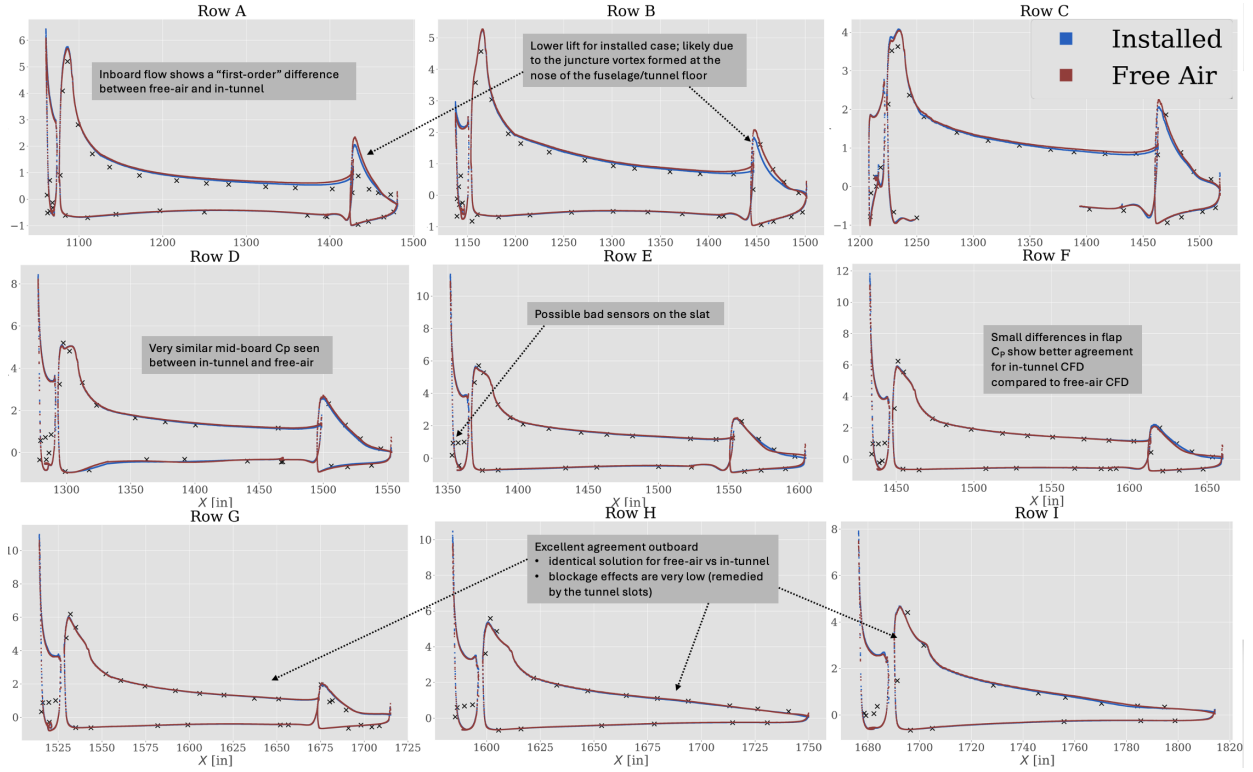


Fig. 21 Pressure coefficients shown for $\alpha = 18^\circ$ at $Re_{MAC} = 5.49 \times 10^6$ comparing the in-tunnel (installed), free-air and experimental data.

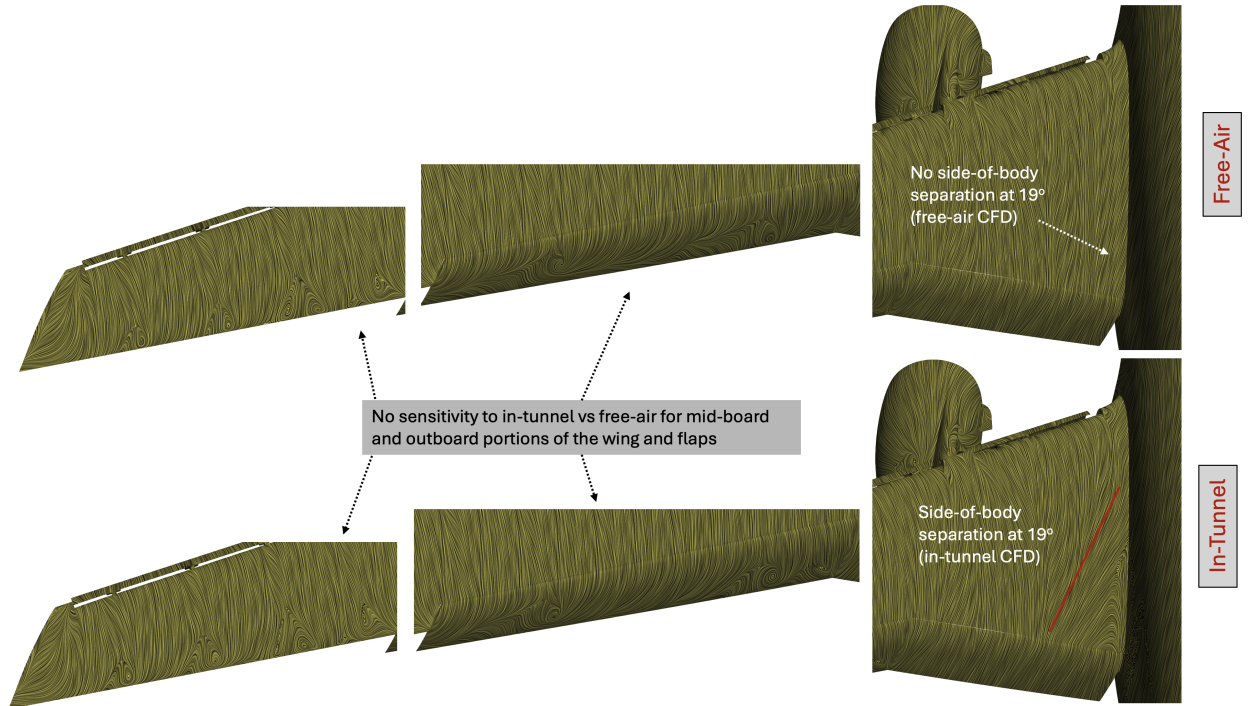


Fig. 22 Surface streamlines comparing free-air vs in-tunnel simulations on the medium grid at $\alpha = 19^\circ$ at $Re_{MAC} = 5.49 \times 10^6$.

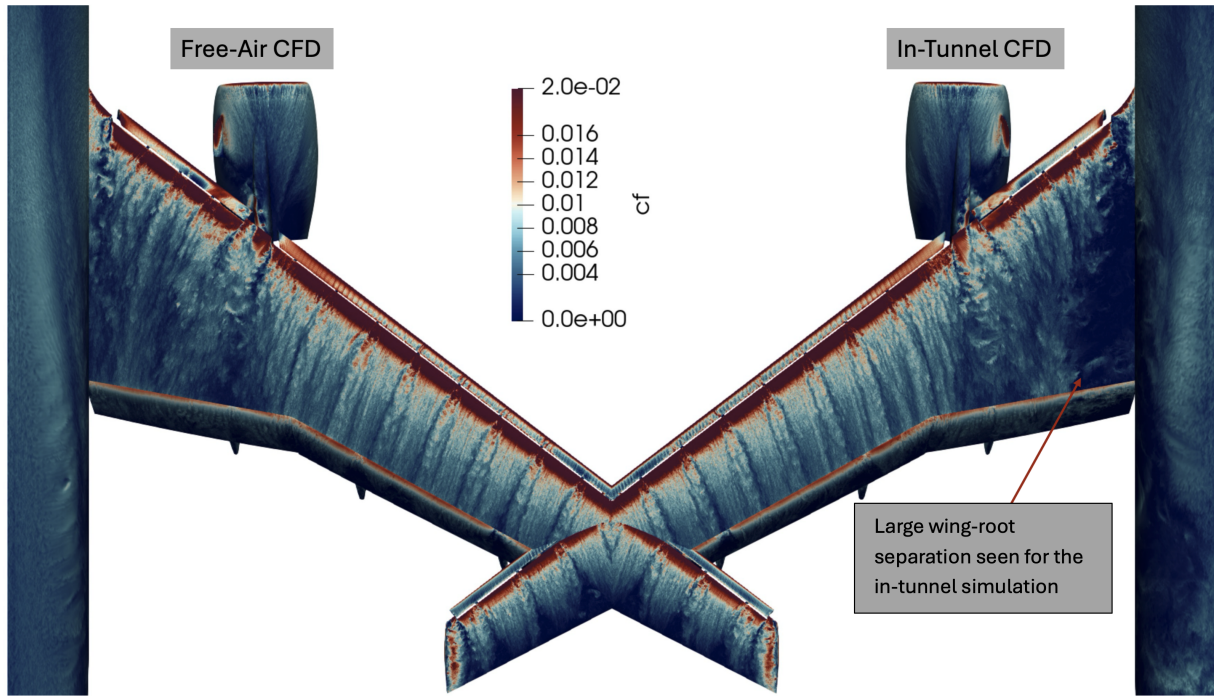


Fig. 23 Instantaneous skin friction for $\alpha = 19^\circ$ at $Re_{MAC} = 5.49 \times 10^6$ comparing in-tunnel and free-air simulations.

fuselage/peniche which alters the irrotational flow field occurring at the side-of-body.

- 5) The earlier onset of stall for in-tunnel simulations compared to free-air simulations observed in integrated loads and moments can now be explained by considering the surface streamlines at $\alpha = 19^\circ$ in Figure 22. The in-tunnel simulations show onset of wing-root separation while free-air cases do not show any separation. Instantaneous skin friction shown in Figure 23 shows that the two configurations attain nearly identical surface flow on the majority of the wing except for the wing-root region. While the free-air simulations show some boundary layer weakness, the in-tunnel simulations experience complete juncture flow separation leading to massive loss-of-lift on the inboard wing.

C. Low- α condition

As noted in the recently concluded 5th High-Lift prediction workshop (HLPW-5), the lowest angle studied, $\alpha = 6^\circ$ poses a significant challenge for configurations with extended flaps [23]. The following observations can be made based on the various simulations run at $\alpha = 6^\circ$.

- 1) Figure 24 shows the streamlines for the $Re_{MAC} = 5.49 \times 10^6$ condition on the 3 grids that were studied. Both medium and fine resolution simulations show essentially identical flap separation patterns with some minor sensitivity limited to the inboard flap.
- 2) Considering the pressure coefficients in Figure 25, one can see the lack of grid sensitivity, which is largely consistent with the little sensitivity reported in CL and CMY. However, note that the large excess pitching moment observed in the simulations is not easily understood from the C_p comparisons. Perhaps some of this over-prediction of the moment could be explained by the systematic underprediction of suction on the outboard portions of the wing (see Row G for example). Interestingly, the fine resolution simulation shows larger midboard flap separation which appears to be consistent with the experiment as seen in terms of the C_p at Rows E and F.
- 3) Moving on to the $Re_{MAC} = 30 \times 10^6$ condition, a largely similar qualitative agreement between medium and fine resolution simulations is observed for flap separation, as shown in Figure 26. The pressure coefficients shown in Figure 27 again confirm the lack of grid resolution sensitivity. Additionally, the over-prediction of the integrated CL discussed earlier is again not very obvious from the C_p comparisons. One potential source is

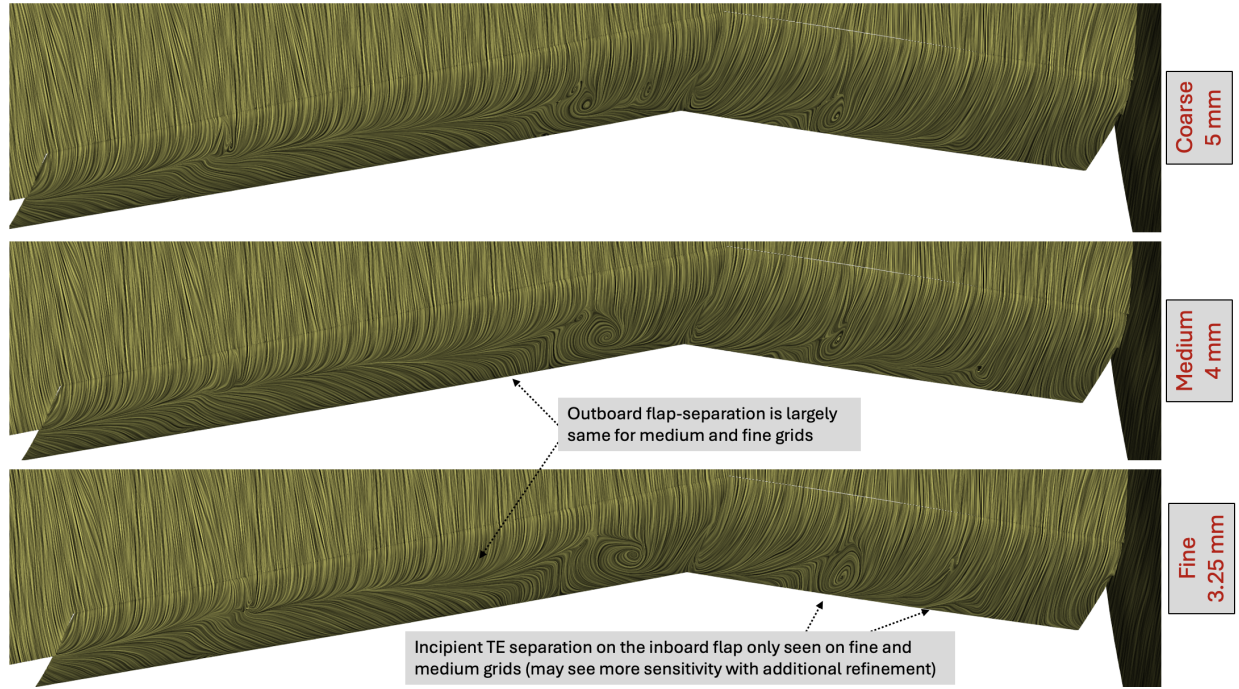


Fig. 24 Time-averaged flap streamlines for $\alpha = 6^\circ$ at $\text{Re}_{\text{MAC}} = 5.49 \times 10^6$ in-tunnel simulations on the three grid levels.

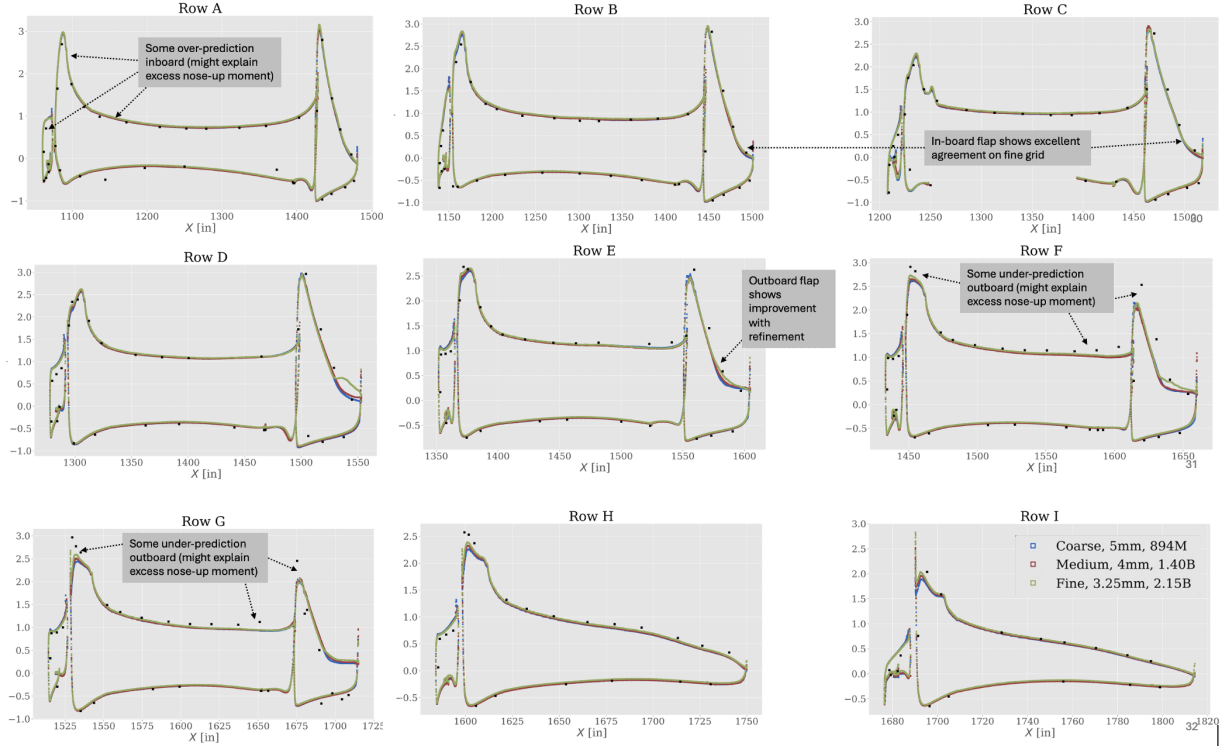


Fig. 25 Pressure coefficients shown for the three grid levels for $\alpha = 6^\circ$ at $\text{Re}_{\text{MAC}} = 5.49 \times 10^6$ compared with the experiment.

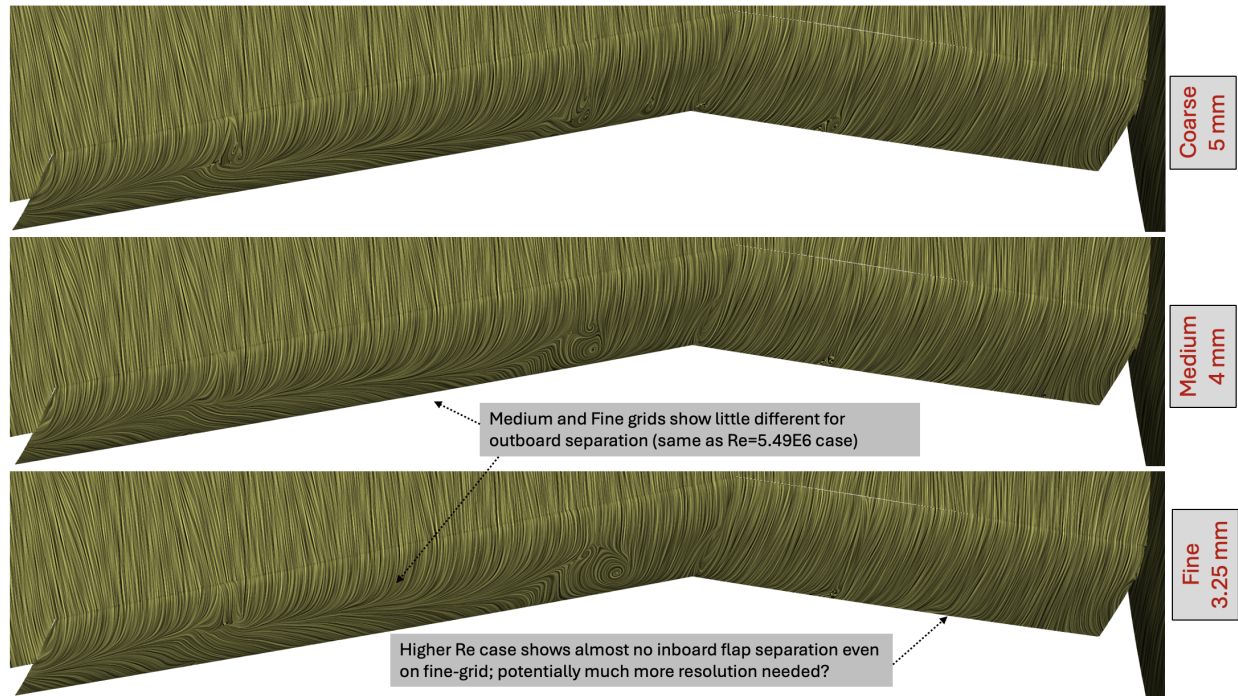


Fig. 26 Time-averaged flap streamlines for $\alpha = 6^\circ$ at $Re_{MAC} = 30 \times 10^6$ in-tunnel simulations on the three grid levels.

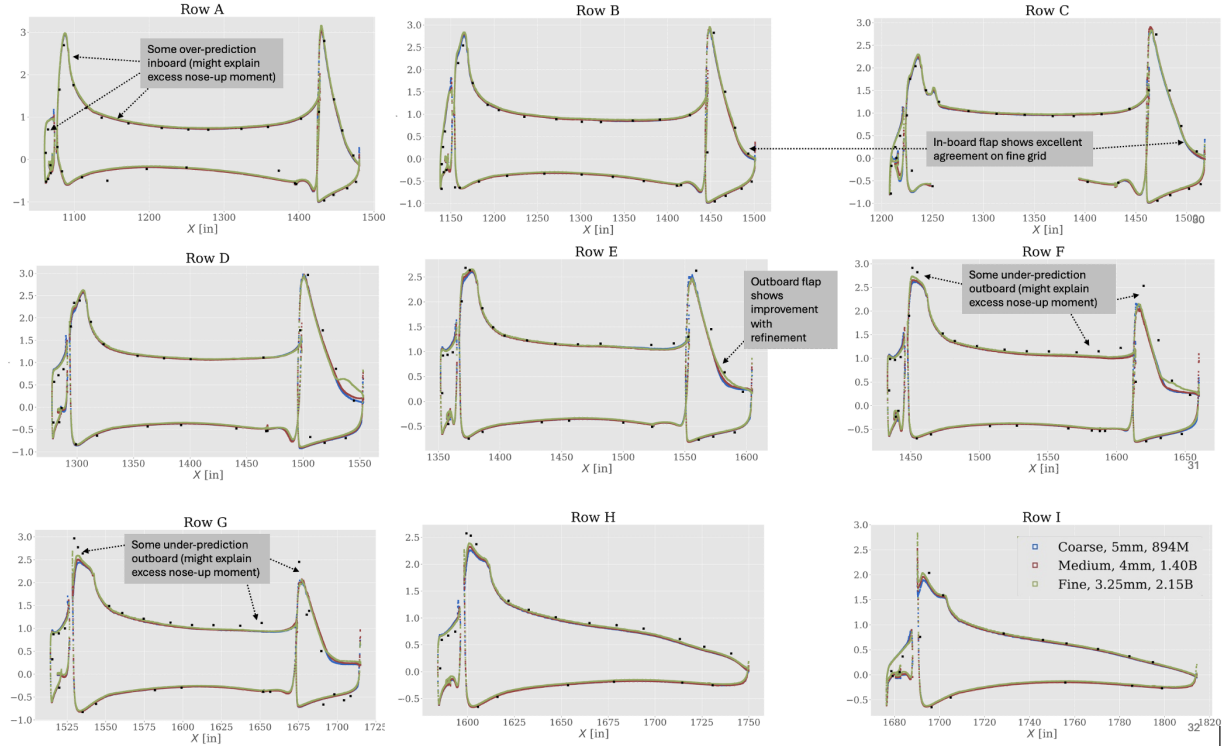


Fig. 27 Pressure coefficients shown for the three grid levels for $\alpha = 6^\circ$ at $Re_{MAC} = 30 \times 10^6$ compared with the experiment.

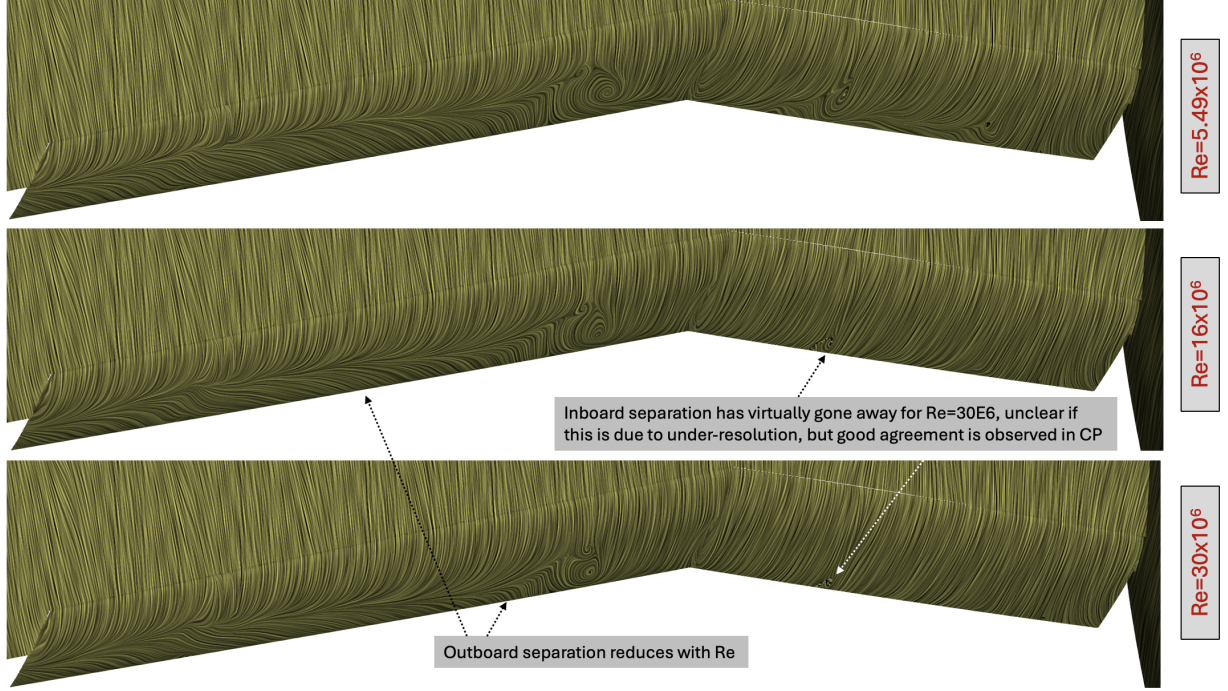


Fig. 28 Time-averaged flap streamlines for $\alpha = 6^\circ$ for the three Reynolds numbers studied on the medium resolution grid.

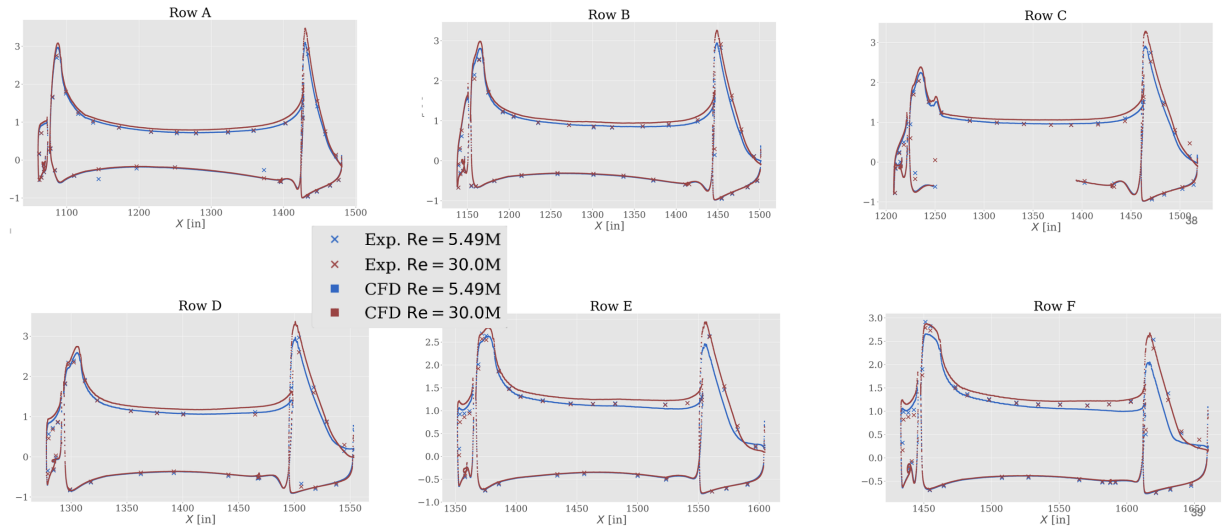


Fig. 29 Pressure coefficients shown for the medium resolution grid for $\alpha = 6^\circ$ at two different Reynolds numbers compared with the experiment.

the overprediction of slat suction at virtually all rows, somewhat reminiscent of an angle-of-attack offset. The simulation C_p appears to be consistent with what one could expect to see in the experiment at a slightly higher angle of attack.

- 4) The flap separation patterns are shown for all three simulated Reynolds numbers in Figure 28. The most noticeable attribute is the reduction in overall flap separation with an increasing Reynolds number. This reduction in flap separation has a clear upstream effect as is seen in terms of increased suction on the overall wing, slat and flap as shown in Figure 29. However, the C_p values measured in the experiment show essentially no sensitivity to

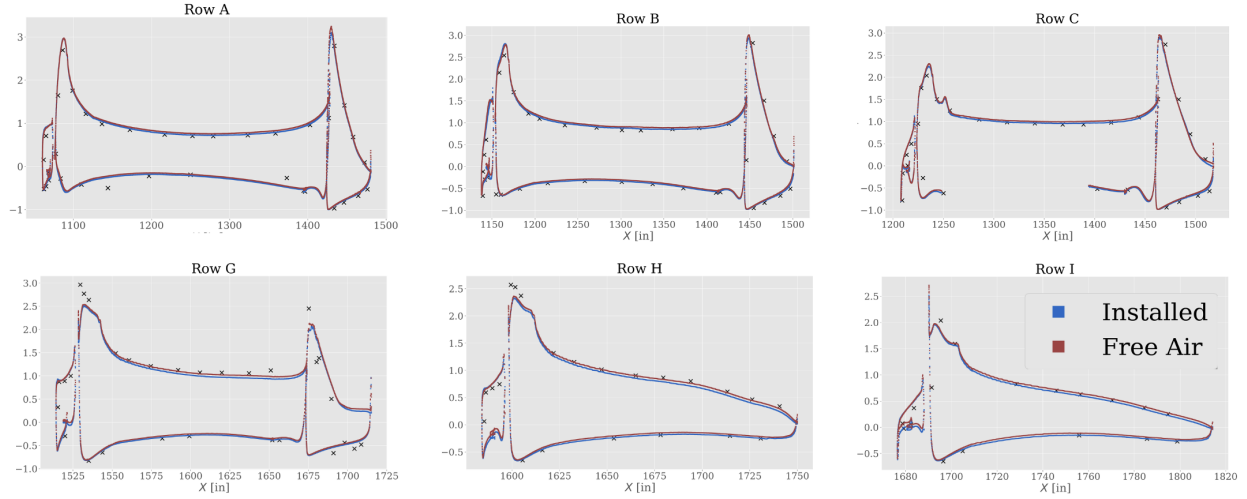


Fig. 30 Pressure coefficients showing the difference between free-air and in-tunnel simulations on the medium resolution grid for $\alpha = 6^\circ$ at $Re_{MAC} = 5.49 \times 10^6$.

Reynolds number. The C_p comparisons do not help explain the inconsistent pitching moment behavior observed between the experiment and CFD at low angles of attack. There appears to be a clear trend - simulations that agree with the experiment in CL, tend to overpredict the pitching moment compared to the experiment (as is the case for $Re_{MAC} = 5.49 \times 10^6$), while simulations that over-predict the CL are consistent with the experiment for pitching moment (as is the case for $Re_{MAC} = 30 \times 10^6$), with C_p comparisons offering no additional insight into these discrepancies.

- 5) Perhaps a more interesting comparison at low- α can be made by comparing the C_p obtained between the free-air and tunnel configurations. As noted previously, for $Re_{MAC} = 5.49 \times 10^6$ condition at $\alpha = 6^\circ$, essentially identical CL was obtained; however, the free-air simulation predicted a noticeably more nose-down pitching moment. By comparing the pressure coefficients in Figure 30, we gain some possible insight; there appears to be a small offset in the C_p curves between the free-air and in-tunnel simulations. While the in-tunnel simulation C_p values agree very well with the experiment measurements at the three inboard-stations, there is a clear under-prediction of suction on the three outermost stations. This is consistent with the excess nose-up moment seen in the LES with essentially identical total integrated lift.

VI. Summary

Results from high-lift CRM LES performed using Volcano ScaLES were discussed. These simulations differ from numerous prior studies, in two ways a) several Reynolds numbers were studied, and b) simulations were performed for wall-mounted 5.2% model inside the highly complex NTF wind tunnel. While reasonable grid convergence is observed in LES at all Reynolds numbers, several systematic differences between experimental observations and simulations persist. Of note is the lack of agreement between the experiment and the CFD at higher Reynolds numbers. LES was unable to capture the unexpected Reynolds number sensitivities observed at both high and low angles of attack and hence this counterintuitive finding from the NTF experiments remains a mystery. Among multiple possible speculative explanations is the possibility of model deformation in the experiment which was not modeled in CFD. Many of these discrepancies in integrated forces and moments were inconsistent with agreement seen in pressure coefficients; this aspect requires additional collaborative investigation between CFDers and experimentalists.

To end on a more positive note, the simulations correctly predict the onset of inboard stall and the subsequent pitch-break at both Reynolds numbers and show CL_{max} and stall separation patterns that are largely consistent with oil flow observations taken from prior experiments of this CRM-HL geometry. Additionally, in this paper, time-accurate WMLES conducted using explicit time-stepping discretization was shown to be a very effective tool for studying wall-mounted model physics in-tunnels, even though the problem encompasses a very wide range of disparate spatio-temporal scales.

VII. Acknowledgements

This work was performed under the NASA Cooperative Agreement NSSC24M0204. Computational resources from NASA's Advanced Supercomputing Division (NAS) at NASA Ames Research Center were utilized to complete the simulations discussed. Experimental data were kindly provided by Dr. Mujeeb Malik (NASA Langley Research Center).

References

- [1] Clark, A. M., Slotnick, J. P., Taylor, N. J., and Rumsey, C. L., "Requirements and challenges for CFD validation within the High-Lift Common Research Model ecosystem," *AIAA AVIATION 2020 FORUM*, 2020, p. 2772.
- [2] Rumsey, C. L., and Ying, S. X., "Prediction of high lift: review of present CFD capability," *Progress in Aerospace Sciences*, Vol. 38, No. 2, 2002, pp. 145–180.
- [3] Rumsey, C. L., Slotnick, J. P., and Woeber, C. D., "Fourth High-Lift Prediction/Third Geometry and Mesh Generation Workshops: Overview and Summary," *Journal of Aircraft*, 2023, pp. 1–18.
- [4] Slotnick, J., Khodadoust, A., Alonso, J., Darmofal, D., Gropp, W., Lurie, E., and Mavriplis, D., "CFD vision 2030 study: a path to revolutionary computational aerosciences," 2013.
- [5] Slotnick, J. P., and Mavriplis, D., "A Grand Challenge for the Advancement of Numerical Prediction of High Lift Aerodynamics," *AIAA Scitech 2021 Forum*, 2021, p. 0955.
- [6] Slotnick, J., and Heller, G., "Emerging opportunities for predictive CFD for off-design commercial airplane flight characteristics," *Proceedings of the 54th 3AF International Conference on Applied Aerodynamics*, 2019, pp. 25–27.
- [7] Hasan, M. A., Mamun, A. A., Rahman, S. M., Malik, K., Al Amran, M. I. U., Khondaker, A. N., Reshi, O., Tiwari, S. P., and Alismail, F. S., "Climate change mitigation pathways for the aviation sector," *Sustainability*, Vol. 13, No. 7, 2021, p. 3656.
- [8] Kiris, C. C., Ghate, A. S., Duensing, J. C., Browne, O. M., Housman, J. A., Stich, G.-D., Kenway, G., Fernandes, L. S., and Machado, L. M., "High-lift common research model: RANS, HRLES, and WMLES perspectives for CL_{max} prediction using LAVA," *AIAA SciTech 2022 Forum*, 2022, p. 1554.
- [9] Ghate, A. S., Kenway, G. K., Stich, G.-D., Maldonado, D., and Kiris, C. C., "A wall-modeled LES perspective for the high lift common research model using LAVA," *AIAA Aviation Forum and Exposition 2022*, 2022, p. 3434.
- [10] Ashton, N., Batten, P., Skaperdas, V., and Eberhardt, S., "Towards best-practices for Hybrid RANS-LES simulations of high-lift aircraft geometries," *AIAA AVIATION 2022 Forum*, 2022, p. 3524.
- [11] Browne, O. M., Housman, J. A., Kenway, G. K., Ghate, A. S., and Kiris, C. C., "Numerical Investigation of CL_{max} Prediction on the NASA High-Lift Common Research Model," *AIAA Journal*, Vol. 61, No. 4, 2023, pp. 1639–1658.
- [12] Goc, K., Bose, S. T., and Moin, P., "Large eddy simulation of the NASA high-lift common research model," *AIAA SciTech 2022 Forum*, 2022, p. 1556.
- [13] Konig, B., Duda, B. M., and Laskowski, G. M., "Lattice Boltzmann Simulations for the 4th AIAA High-Lift Prediction Workshop Using PowerFLOW," *AIAA Aviation 2022 Forum*, 2022, p. 3433.
- [14] Ashton, N., Ghate, A., Kenway, G., Angel, J., Long Wong, M., and Kiris, C. C., "Immersed Boundary Wall-Modelled Large Eddy Simulations for the 5th High-Lift Prediction Workshop," *AIAA SCITECH 2025 Forum*, 2025, p. 0888.
- [15] Angel, J. B., Ghate, A. S., Kenway, G. K. W., Wong, M. L., and Kiris, C. C., "Immersed Boundary Wall-Modelled Large Eddy Simulations for Automotive Aerodynamics," *AIAA Aviation 2024 Forum*, 2024.
- [16] Angel, J. B., Wong, M. L., Kenway, G., Ghate, A., and Kiris, C. C., "Validation of Immersed Boundary Wall-Modelled Large Eddy Simulations with F-16XL Flight Data," *AIAA AVIATION FORUM AND ASCEND 2024*, 2024, p. 4374.
- [17] Kenway, G. K. W., Ghate, A. S., Browne, O. M. F., Wong, M. L., Angel, J. B., and Kiris, C. C., "Immersed Boundary Wall-Modelled Large Eddy Simulations of a Generic Hammerhead Payload Fairing," *AIAA Aviation 2024 Forum*, 2024.
- [18] Wong, M. L., Ghate, A. S., Kenway, G. K. W., Angel, J. B., and Kiris, C. C., "Immersed Boundary Wall-Modelled Large Eddy Simulations of Straight Wings with Three-Dimensional Ice Accretion," *AIAA Aviation 2024 Forum*, 2024.

- [19] Wong, M. L., Ghate, A. S., Kenway, G. K. W., Angel, J. B., and Kiris, C. C., “Immersed Boundary Wall-Modelled Large Eddy Simulations of Subsonic Jet Flows and Acoustics,” *AIAA Aviation 2024 Forum*, 2024.
- [20] Langston, S., Winski, C. S., and Rivers, M. B., “Reynolds Number Effects on a 5.2%-Scale High Lift Common Research Model,” *AIAA SCITECH 2025 Forum*, 2025, p. 1514.
- [21] Gottlieb, S., and Shu, C.-W., “Total variation diminishing Runge-Kutta schemes,” *Mathematics of computation*, Vol. 67, No. 221, 1998, pp. 73–85.
- [22] Germano, M., Piomelli, U., Moin, P., and Cabot, W. H., “A dynamic subgrid-scale eddy viscosity model,” *Physics of Fluids A: Fluid Dynamics*, Vol. 3, No. 7, 1991, pp. 1760–1765.
- [23] Kiris, C. C., Ghate, A., and Angel, J., “High Lift Prediction Workshop 5: Wall-Modeled Large Eddy Simulations Technology Focus Group Summary,” *AIAA SCITECH 2025 Forum*, 2025, p. 0049.