

Immersed Boundary Wall-Modeled Large Eddy Simulations for the 5th High-Lift Prediction Workshop

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A new Wall-Modelled Large Eddy Simulation (WMLES) framework, *Volcano ScaLES*, is evaluated on high-lift aircraft configurations as part of the fifth AIAA High Lift Prediction Workshop (HLPW-5). Excellent “blind” C_{Lmax} predictions are obtained for multiple configurations involving slats, flaps, and the nacelle, with errors less than 1 - 2% compared to the ONERA experimental data. Modest grid convergence is shown via a sequence of consistently refined grids, and some qualitative differences between the use of constant-coefficient Vreman and the dynamic Smagorinsky subgrid-scale models are reported. Utilization of appropriate mixed precision numerical formulations along with flow-optimized grids allow for highly efficient use of consumer-grade GPUs such as the Nvidia A10g. We show that even with grids using as many as 1.6 billion degrees of freedom, WMLES is cost-competitive with conventional steady-state RANS models. Reynolds number sensitivity study shows monotonically increasing lift going from a subscale Reynolds number of $Re_{MAC} = 5.49 \times 10^6$ to a flight-scale Reynolds number of $Re_{MAC} = 30 \times 10^6$ with reasonable grid convergence obtained at all three Reynolds numbers studied.

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 mergers 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, 4] 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 [5–7] as well, being highly desired by all airframe manufacturers in order to meet the emerging constraints imposed by climate change mitigation [8]. Following recent successes of scale-resolving techniques [9–17], this paper is focused on evaluating a newly developed immersed boundary Wall-Modelled Large Eddy Simulation (WMLES) framework, *Volcano ScaLES*, for prediction of high-lift aerodynamics. More specifically, the focus of this work is two-fold:

- **Prediction accuracy and numerical sensitivities:** Beyond simple comparisons between numerical simulations and available experimental data via studying the sensitivity to grid-resolution and refinement, we hope to additionally address the following aspects of WMLES.
 - 1) **Sensitivity to subgrid-scale (SGS) closures:** While constant coefficient scalar eddy viscosity models have some advantages in terms of implementation simplicity, the goal is to perform systematic studies comparing static coefficient Vreman model [18] with the Smagorinsky model with dynamically determined model coefficient [19].
 - 2) **Sensitivity to numerical precision:** The rapid growth in usage of GPUs for computation has led to revisiting the widely accepted practices such as usage of FP64 (double-precision) arithmetic for CFD. These choices were in most cases driven by the large aspect ratio $y^+ < 1$ grids needed for conventional Reynolds-Averaged Navier–Stokes (RANS) models. The use of isotropic grids such as the Cartesian octree grids employed in *ScaLES* provides an opportunity to leverage FP32 (single-precision) arithmetic in certain computational

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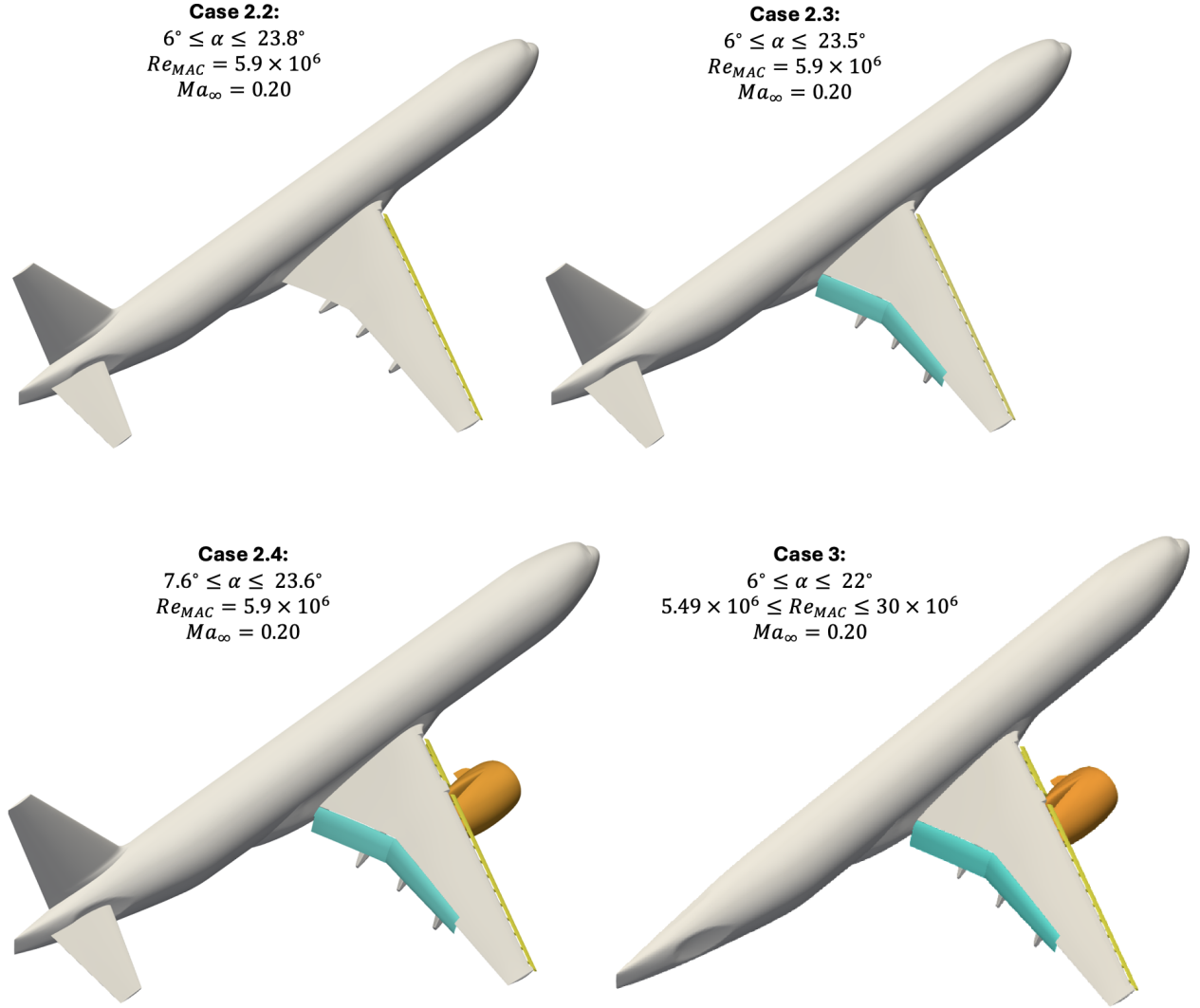


Fig. 1 The four CRM-HL configurations studied.

kernels thereby achieving substantially higher performance on consumer grade GPUs (as opposed to scientific GPUs) that typically have low GPU memory and are optimized for very high FP32 performance at the cost of FP64 performance. For example, x8 Nvidia H100 nodes are up to x3 higher more expensive than Nvidia L40s nodes * but typically offer less than x3 greater performance for mixed-precision CFD codes. However, as will be shown in subsequent sections of this paper, naive usage of single-precision arithmetic leads to inaccurate results, and appropriate mixed precision algorithms are essential.

- **Practical feasibility of the proposed approach for utilization by industry:** Beyond studying the scientific merits (accuracy, convergence, etc.) of the proposed approach, we also wish to evaluate the practicality of the approach, especially from the perspective of computational resources available to airframe manufacturers in 2024. Any approach requiring a large fraction of a Top10 supercomputer is simply not feasible in an industrial setting. On the other hand, consumer grade GPUs are readily available through commercial cloud infrastructure and is already being utilized by many airframe manufacturers. To this end, we wish to evaluate the financial viability of WMLES simulations for day-to-day usage by airframe manufacturers on readily available HPC infrastructure. Furthermore, an emphasis on automated, user guided and rapid grid generation is essential for industrial adoption

*Based upon on-demand Amazon EC2 pricing as per 8th Dec 2024 - <https://aws.amazon.com/ec2/pricing/on-demand/>

and is critical importance to subject-matter-experts lacking expertise on LES-nuances.

The present work follows some of the test cases highlighted in the fifth AIAA High Lift Prediction Workshop (HLPW-5)[20]. The experimental data used for reference are the wind tunnel tests conducted by Mouton et al. (2023) [21] in the ONERA Pressurized F1 Low-Speed Wind Tunnel. Three sub-cases involving component build-up are studied numerically: a) Wing-body + Slats (corresponding to Case 2.2 in HLPW5), b) Wing-body + Slats + Flaps (corresponding to Case 2.3 in HLPW5), and c) Wing-body + Slats + Flaps + Nacelle (corresponding to Case 2.4 in HLPW5). Each case is studied in a “blind” manner - ScaLES results were publicly presented to the HLPW-5 community in late 2023, prior to public release of the experimental data in early 2024. Figure 1 depicts the geometries simulated for each of the four test cases. All simulations are performed in *free-air* with symmetry boundary conditions applied at the center-plane ($y = 0$), in an effectively unconfined far-field domain ($-\infty < x < \infty$, $0 \leq y < \infty$, $-\infty < z < \infty$). As such, the free-air *corrected* variant of the wind-tunnel data is utilized for comparisons between the LES and the experiments in the cases where data is available. Free-stream Mach number for all cases is 0.2 and all simulations are initialized from free-stream conditions and run for sufficiently long simulated time (>70 CTUs in all cases) in order obtained a statically stationary flow with adequate time-averaging.

The remainder of this paper is outlined as follows - we begin with the description of the numerical algorithms used in Section 2. Section 3 considers grid-convergence for the three Cases 2.2 (wing+slat), 2.3 (wing+slat+flaps), and 2.4 (wing+slats+flaps+nacelle). Section 4 discussed sensitivity to SGS closure used, while Section 5 highlights the importance of using a mixed-precision formulation over a primarily single-precision (FP32) formulation. In Section 6, the sensitivity to Reynolds number is the focus following the Cases 3.2, 3.3, and 3.4 for HLPW-5. A brief summary of all the findings are provided in Section 7 to conclude the paper.

II. Simulation Details

A. Numerical Formulation

Volcano ScaLES solves the compressible Navier–Stokes equations using a nominally fourth-order spatially accurate finite-difference discretization with favorable kinetic energy and entropy consistency properties, making it suitable for large eddy simulations (LES) over a vast range of flow regimes. The viscous flux discretization utilizes a mix of fourth order and second 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. Use of such limiters was not needed for the Mach 0.2 cases being studied in this paper. A key convenience afforded by the use of Cartesian grids with unit aspect ratio is the feasibility of explicit time-stepping schemes even in flows involving highly complex geometries; the perfectly isotropic grid cells near the geometry do not introduce any numerical stiffness associated with complex grid topologies. The popular Strong Stability Preserving (SSP) variant of the classical third order Runge–Kutta scheme developed by Gottlieb and Shu [22] 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, where Δ is the local grid spacing. Additional numerical techniques to damp generation of spurious numerical noise at walls as well as at coarse-fine interfaces are also utilized. All simulations presented in this work utilize either the constant coefficient Vreman model [18], or the dynamic Smagorinsky model [23, 24] to model the SGS stresses.

The CFD solver has been validated using a sequence of WMLES applications including: a) subsonic jets [25], b) aerodynamics of iced straight wings [26], c) F-16XL aircraft aerodynamics [27], d) automotive aerodynamics [28], e) transonic vibroacoustics on hammerhead launch fairings [29], and f) missile aerodynamics [30].

B. Octree Cartesian Grid System

The Volcano ScaLES solver uses Cartesian grids generated with a recursive octree approach. Grids around practical configurations consist of an unstructured tree-of-cubes with millions of “boxes” each of which contain a structured grid of 4^3 or 8^3 cells. This method gives nearly all the computational advantages of structured grids while retaining the

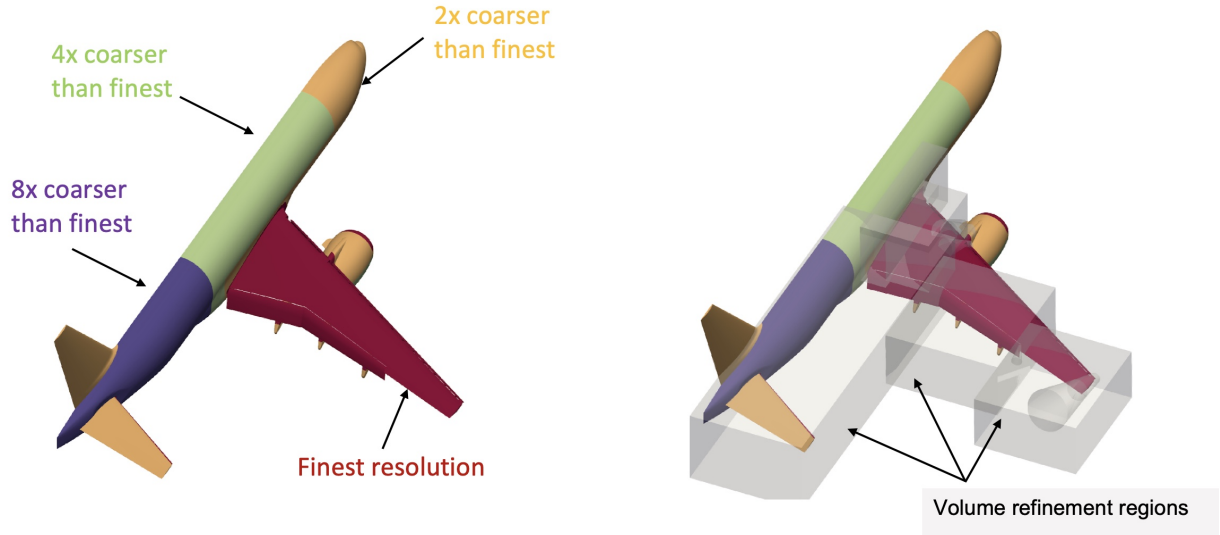


Fig. 2 Surface and volume refinement regions used in the WMLES octree Cartesian grid systems.

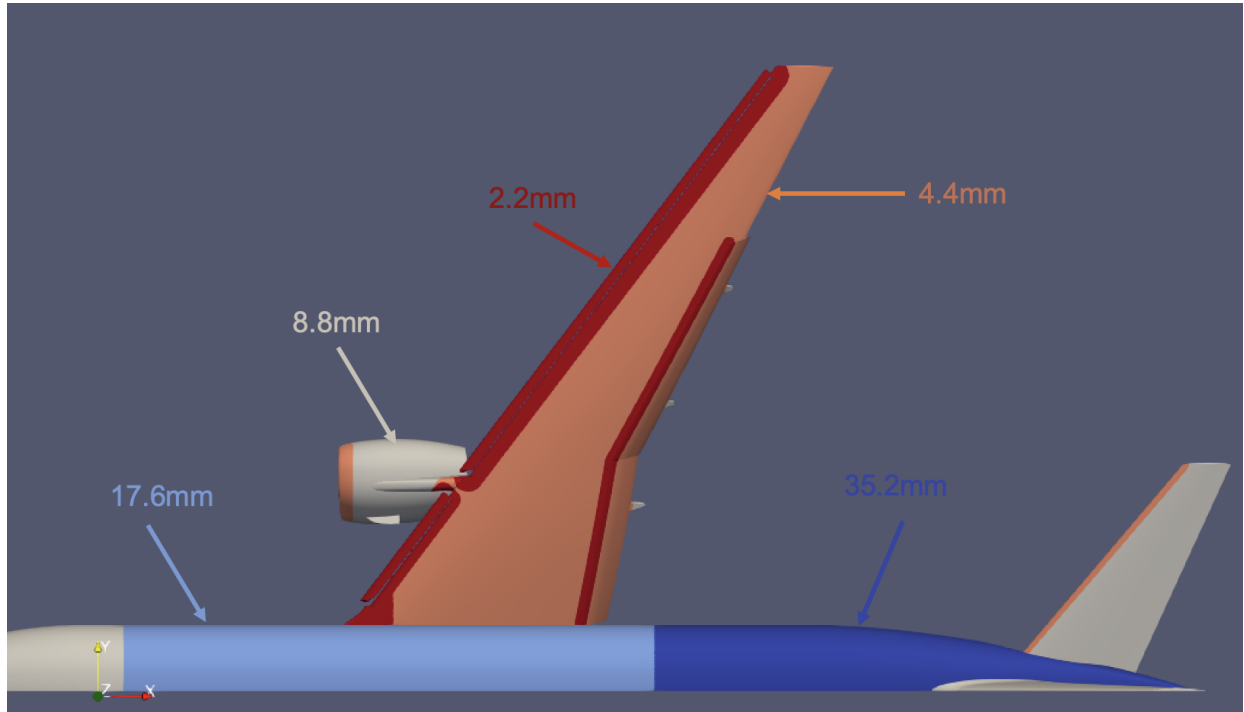


Fig. 3 Surface spacings for the “best-practice” grid.

ability to closely follow surfaces and minimize the number of “dead” cells inside the geometry. Typically, 90-95% of the total cells in a grid are compute cells, while the remaining ones are considered “dead” or “blanked” cells.

Due to the significant influence of off-body vorticity generated in high-lift configurations, optimal LES grids generated for these flows cannot be designed using purely boundary layer resolution metrics (such as points-per-delta and y^+). Additional refinement regions are needed to capture generation of vorticity in regions such as lift-element cut-outs (finite-span effects are highly prevalent at slats, flaps, and the pylon) and the intentional vortex generation elements such as the nacelle-chine. Relevant information on the grids utilized in this study is presented succinctly via Table 1, and Figures 2 and 4. A “best-practice” grid was constructed for all 6 test cases studied based on findings of the

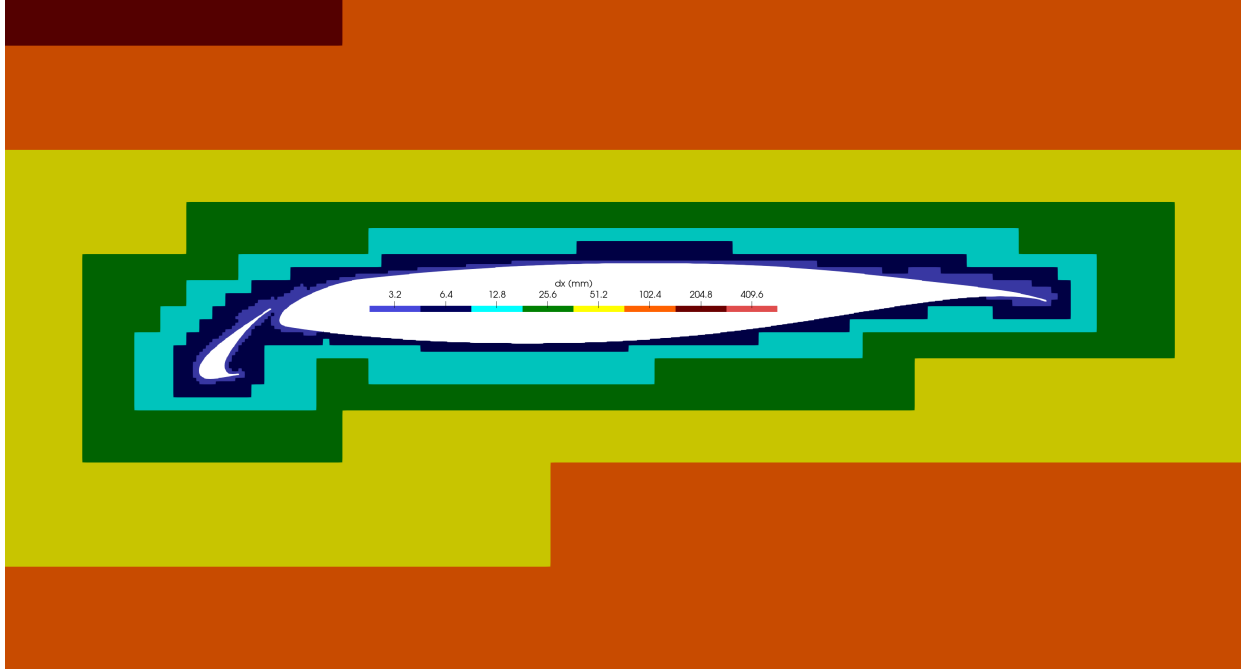


Fig. 4 Grid spacings depicted on a slice at $y = 25$ m plane for Case 2.4 fine-grid system.

Table 1 Grid resolutions studied for the three test cases. The grid spacings correspond to a full-scale aircraft geometry with a mean aerodynamic chord of approximately 7 m.

Case	Grid level	Minimum grid spacing	Total compute points
Case 2.2	Coarse	5 mm	352 million
	Medium	4 mm	544 million
	Fine	3.2 mm	1.094 billion
	Best-practice	2.2 mm	872 million
Case 2.3	Coarse	5 mm	400 million
	Medium	4 mm	622 million
	Fine	3.2 mm	971 million
	Best-practice	2.2 mm	1.030 billion
Case 2.4	Coarse	5 mm	436 million
	Medium	4 mm	678 million
	Fine	3.2 mm	1.058 billion
	Best-practice	2.2 mm	1.020 billion

grid-convergence study to obtain finer minimum spacings than the “fine” grid in critical regions while utilizing fewer total grid points. Figure 3 shows the surface topology of this “best-practice” grid. The volume refinement regions are re-used for “best-practice” grids without any changes. Figure 5 shows a representative plane to depict the geometry represented via an immersed boundary treatment with an octree grid topology. These volumetric refinements allow for robust resolution of instantaneous vorticity, as shown in Figure 6.

The following grid-generation strategy is employed within Volcano ScaLES for simulations of highly complex flows where it is difficult to make an a-priori assessment of grid-resolution requirements.

- 1) Test WMLES performed on coarse-uniformly surface refined grid to generate “flow-physics-describing” numerical

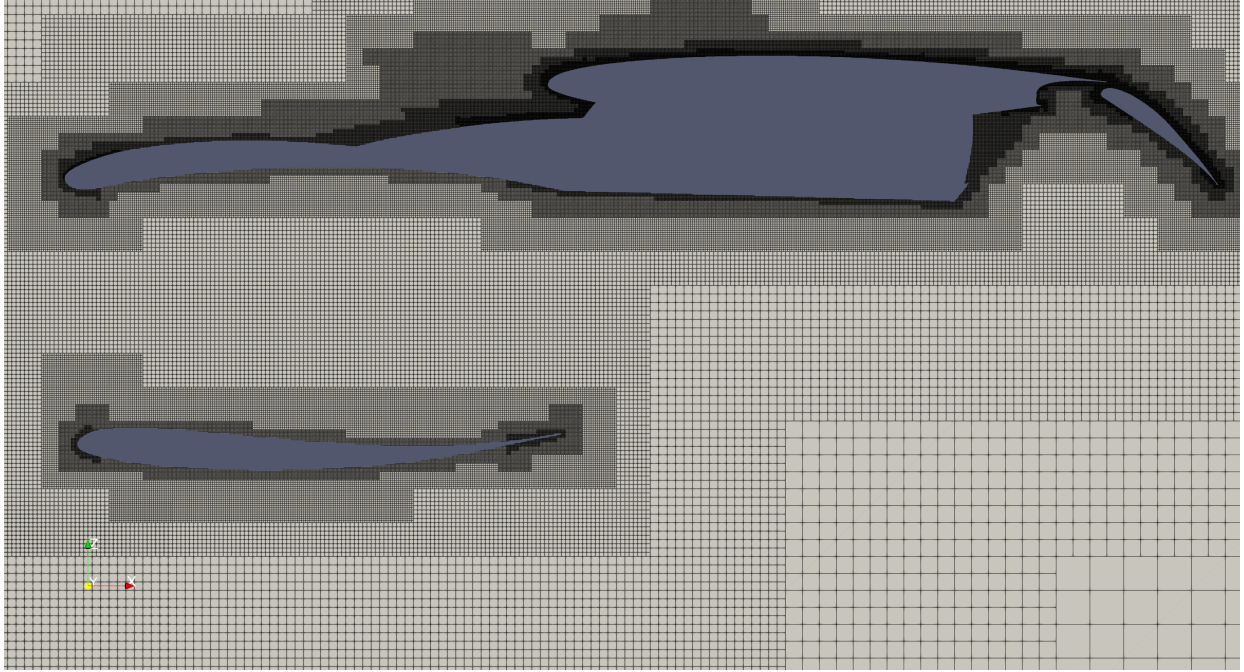


Fig. 5 Slice at $y = 10$ m showing the octree Cartesian grid topology along with immersed boundary representation of the geometry.

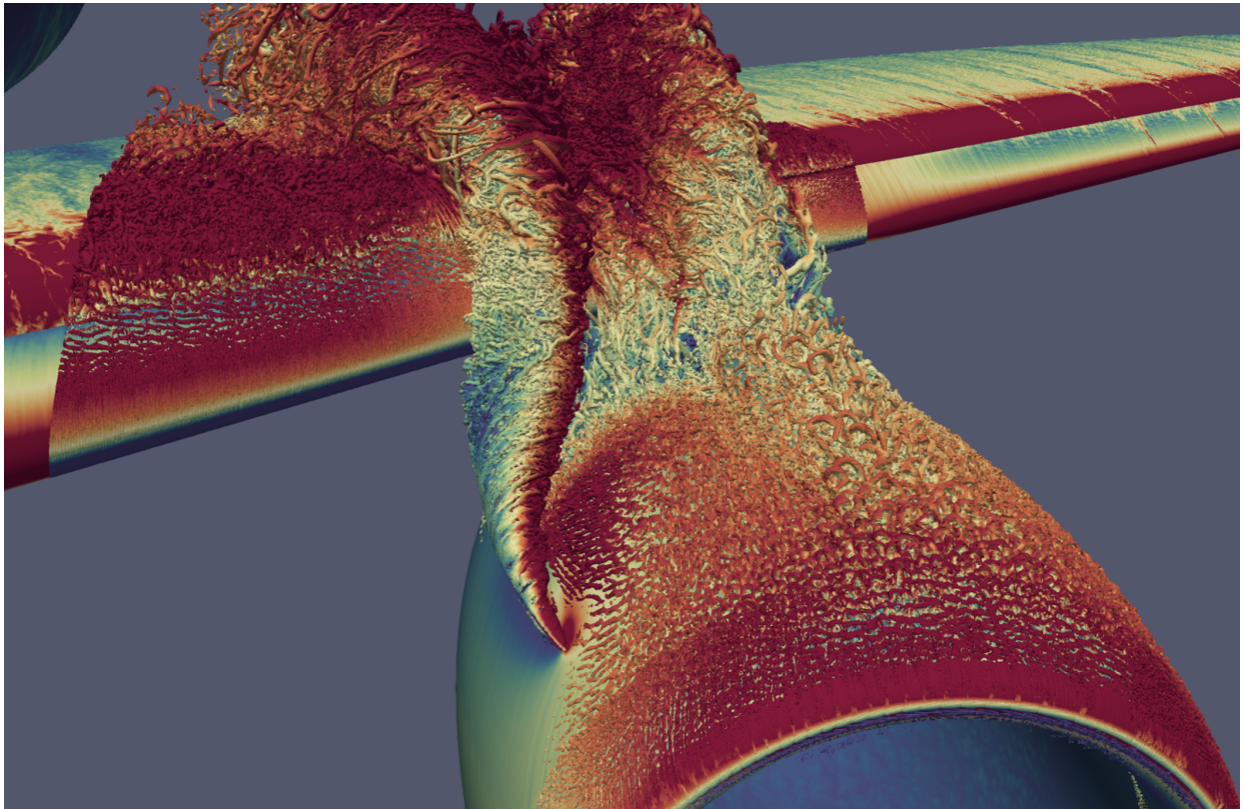


Fig. 6 Instantaneous snapshot of the flowfield depicting the chine vortex (using Q -criterion) and the surface skin-friction at $\alpha = 19.7^\circ$ for the Case 2.4 configuration.

sensors. These numerical sensors identify regions of the geometry where: a) additional boundary layer resolution is needed, b) steep-pressure gradients associated with irrotational flow require additional resolutions, and c) strong turbulence generation due to locally formed shear layers.

- 2) Numerical sensors guide the generation of the optimal grid topology - this *final* grid topology is depicted in Figure 2.
- 3) Family of consistently refined grid systems (labelled “coarse”, “medium”, and “fine”) are generated while maintaining the grid-topologies realized via the test simulation. The three grid-levels are summarized in Table 1.

The *test-simulations* performed were repeated for each angle of attack since the dominant flow physics changes substantially between the low and the high angles of attack. As such, the final grid topologies generated at the second step represent a compromise, resulting in a grid system that is slightly larger than an angle-specific optimized grid. The same is true for the “best-practice” grid, which is designed to be “optimal” for all angles of attack. Finally, the grids used in this Reynolds number study (Cases 3.2, 3.3, and 3.4) are essentially identical to the grids used for Case 2.4, but do not include the additional grid needed for the empennage.

C. 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 or Nvidia A10g. 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 A10g accelerators on AWS (Amazon EC2 g5 family of instances), significantly lowers the cost of LES to a level that is practical for use in an industrial setting. Two distinct numerical precision settings (herein referred to as mixed precision 1 and mixed precision 2) are available in ScaLES with the former can be considered an “essentially” single-precision algorithm while the latter utilizes FP64 in a limited way to minimize round-off error growth.

III. Grid Sensitivity Study for Cases 2.2, 2.3, and 2.4

In this section, simulations are conducted with the three consistently refined grids using the constant coefficient Vreman SGS model. Additionally, the “best-practice” grid is simulated using the dynamic Smagorinsky SGS model; this change in the SGS closure is informed by the sensitivity study presented in Section 4. The purpose of the “best-practice” simulation is to facilitate direct comparisons between the simulation and the ONERA WT data. Furthermore, the “best-practice” simulations utilize the more complex mixed precision 2 setting in ScaLES while the grid refinement study is performed using the simpler mixed precision 1 setting (primarily FP32); this change in precision is subsequently motivated in Section 5.

A. Case 2.2 Configuration

We begin the technical discussion by considering the simplest of the three configurations, the wing-body with an extended slat. Figure 7 shows the aerodynamic loads and the pitching moment for the three grids compared to the experimental data. Figures 8 and 11 compare the time-averaged surface streamlines obtained on the three grids for the two highest angles simulated. Figures 10 through 13 compare several relevant quantities of interest obtained on the “best-practice” grid with the experiment. Several interesting observations follow.

- 1) Little sensitivity in integrated aerodynamic forces is seen between the three grid levels at all angles of attack. The scatter in lift coefficients on the three grids at CL_{max} ($\alpha = 23^\circ$) is less than 1.5%. Interestingly, the fine grid shows a slight over-prediction of lift at $\alpha = 23.8^\circ$ by about 1.4%, with the error on the finest grid slightly larger than that on the coarsest grid.
- 2) Upon inspection of the surface streamlines (Figures 8 and 9), it appears that the side-of-body separation reduces with refinement. At $\alpha = 23.8^\circ$ the separation bubble at the wing-body junction is incipient on the fine grid. The trailing edge separation, as well as the wedge-shaped separation regions on the outboard portions of the

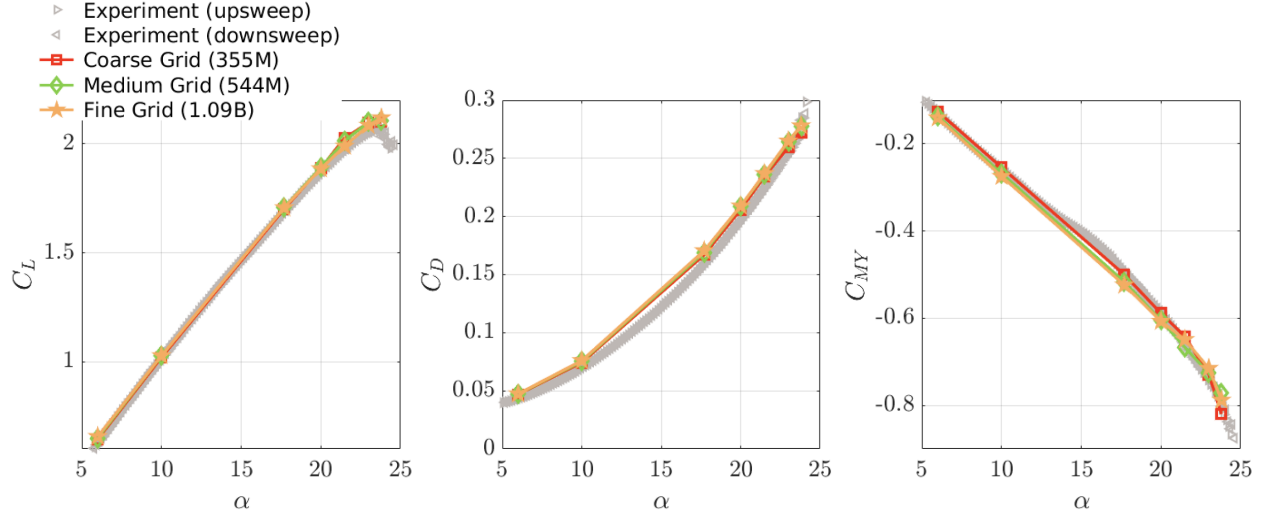


Fig. 7 Integrated forces and moments for the three grids for Case 2.2.

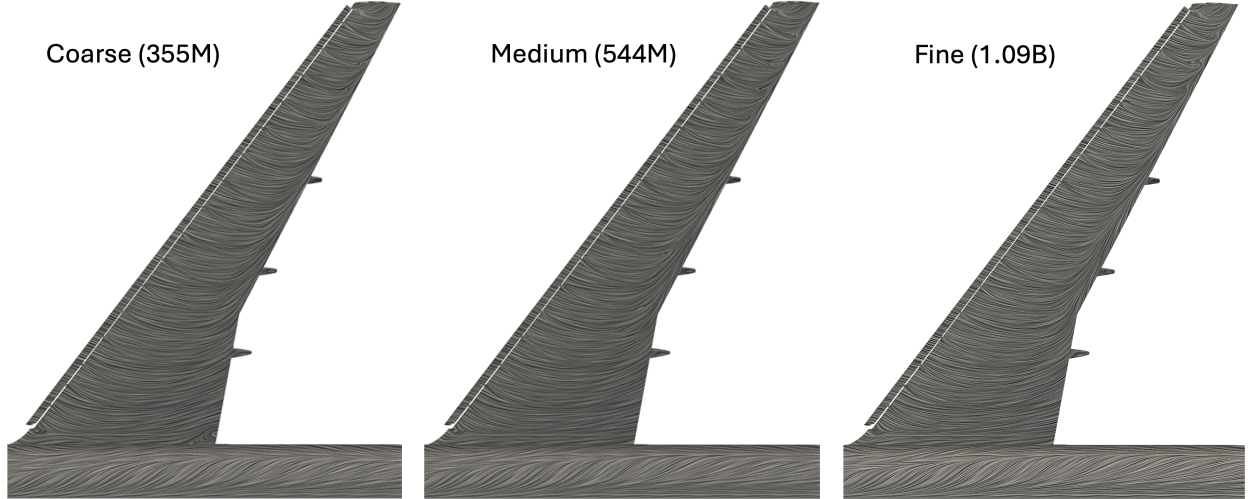


Fig. 8 Surface streamlines for Case 2.2 on the three grids at $\alpha = 23.0^\circ$.

wing, are essentially identical on all three grid levels; hence the slight increase in lift is primarily due to reduced side-of-body separation.

- 3) The “best-practice” grid appears to show much better agreement with the experiment for the C_L value predicted at $\alpha = 23.8^\circ$ (Figure 10), compared to the fine grid. This improvement is in large part due to the changes of SGS model and numerical precision that will be addressed later in Section 5.
- 4) Comparison of surface streamlines predicted by the “best-practice” simulation with the ONERA Wind Tunnel (WT) experiment (Figure 11) shows excellent agreement for both the side-of-body separation and the trailing edge separation seen outboard of the Yehudi break.
- 5) Some insight into the slightly nose-up pitching moment seen at high angles for the “best-practice” simulation can be obtained by considering the pressure coefficient along several spanwise stations. At $\alpha = 23.0^\circ$, the most inboard station (station A) shows a slight over-prediction of wing suction, while the outboard stations show a slight under-prediction of the wing section, most likely caused by small differences in the trailing edge separation observed. This suggests an inboard-outboard error cancellation leading to a very accurate lift but a more nose-up pitching moment. These observations are essentially the same for $\alpha = 23.8^\circ$, except the lift over-prediction is observed at station B instead of station A. This suggests that the size of the side-of-body separation predicted

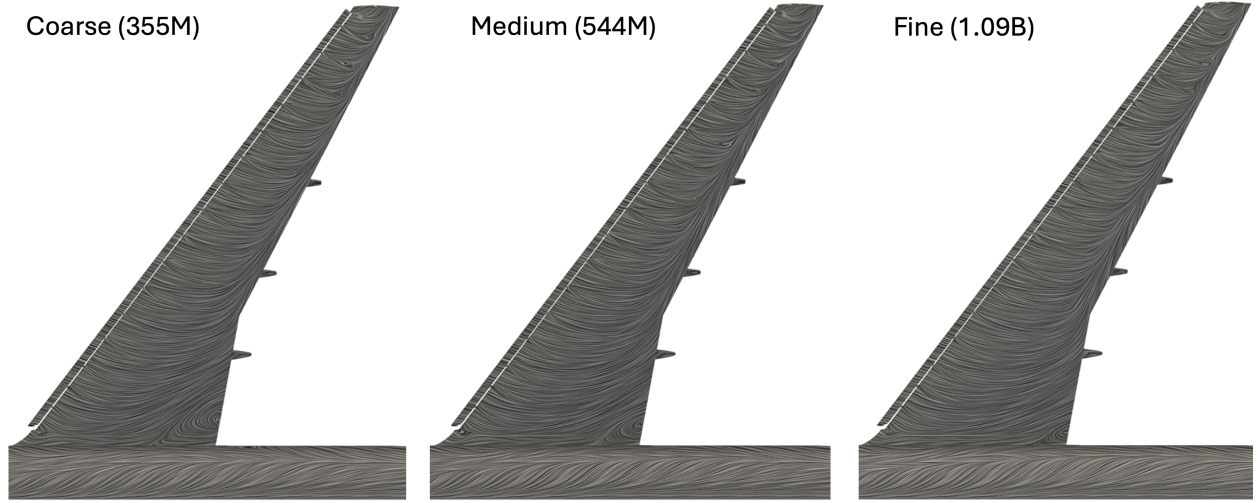


Fig. 9 Surface streamlines for Case 2.2 on the three grids at $\alpha = 23.8^\circ$.

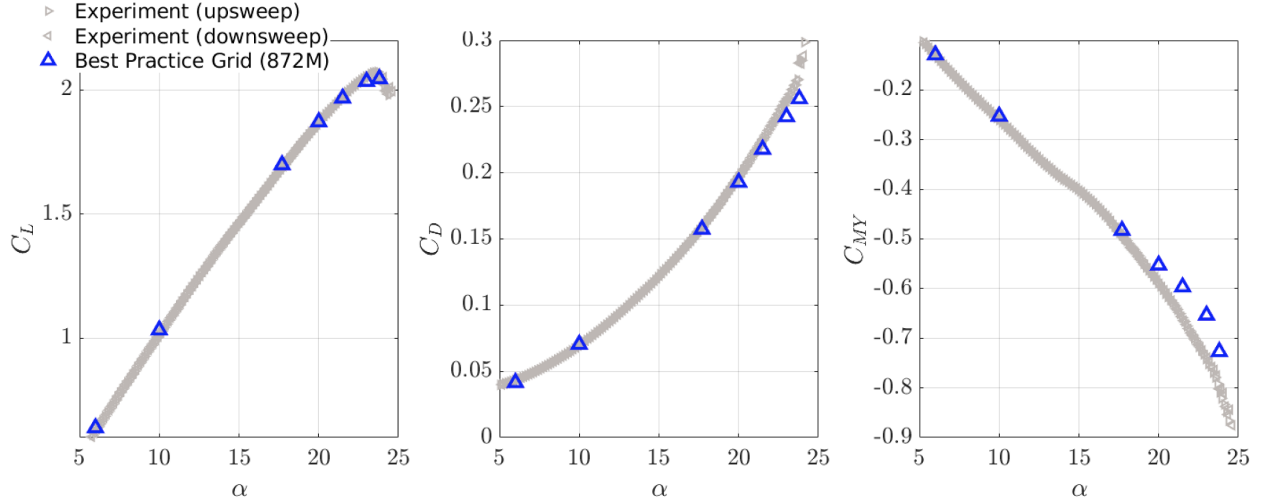


Fig. 10 Integrated forces and moments for the “best-practice” grid for Case 2.2.

by the WMLES on the “best-practice” grid is somewhat smaller than that observed in the experiment. Upon more careful assessment of the experiment data, we noticed that the experiment values at $\alpha = 23.8^\circ$ show quite a lot of variations with certain runs show a drop in lift compared to $\alpha = 23.0^\circ$, indicating a potentially bi-stable state with stall occurring at an angle of attack very close to $\alpha = 23.8^\circ$. As such, the over-predictions seen at station B are not particularly concerning and we emphasize that the overall agreement between WMLES and the experiment for this test case is in fact very good.

B. Case 2.3 Configuration

Next, we consider the test case with the flap extended along with the extended slat (Case 2.3). The primary effect of extending the slat is an offset increase in the lift coefficient at all angles of attack. Comparisons between integrated loads and pitching moment predicted by the three grid resolutions with the experiment are shown in Figure 14. Figures 15 through 19 compare the “best-practice” grid results with the ONERA WT experiment. Several interesting remarks can be made for the predictions of Case 2.3.

- 1) We observe a monotonic increase in lift coefficient at C_{Lmax} ($\alpha = 20.7^\circ$) with grid refinement; with the finest resolution grid showing a roughly 1.5% under-prediction in lift compared to the experiment. The increasing lift

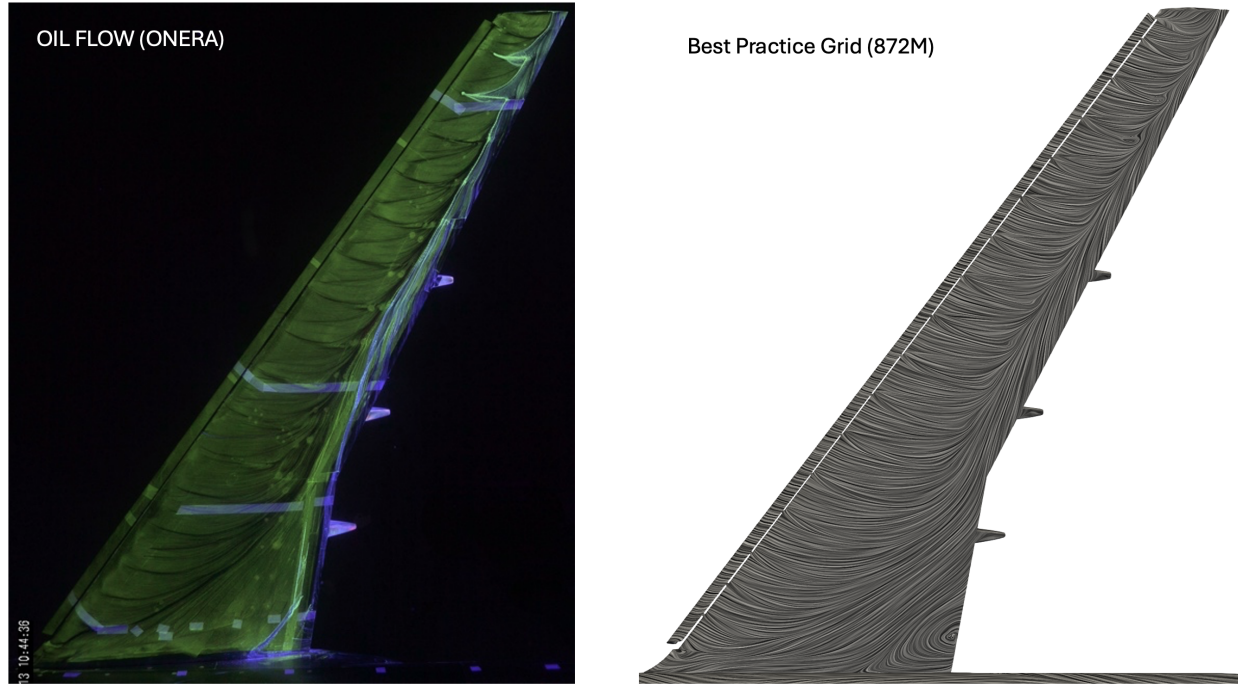


Fig. 11 Surface streamlines for Case 2.2 on the “best-practice” grid at $\alpha = 23.8^\circ$ compared with the ONERA WT experiment [21].

with refinement appears to result in an increasingly nose-down pitching moment approaching the experimental values near CL_{max} . This suggests that the increased lift is primarily occurring in outboard portions of the wing, slat, and the flaps.

- 2) The loads computed on the “best-practice” grid also show reasonably good agreement with the experiment with the lift at CL_{max} within 2-2.5% of the experiment.
- 3) Inclusion of extended flaps results in a substantially more complex flow-field at lower angles. At $\alpha = 6^\circ$, large region of flow separation is observed on the outboard flaps, and we observe that even with the 2.2 mm flap resolution on the “best-practice” grid, there are fewer than 1000 points spanning the flap-chord. This is insufficient resolution that what is typically used to capture smooth body separation on lifting surfaces such as 2D airfoils with WMLES. Although the integrated lift and moment at $\alpha = 6^\circ$ are in reasonable agreement with the experiment, a closer examination of the pressure coefficient (Figure 16) shows deficiencies of the simulation. C_p on the inboard flap shows a slight over-prediction while the outboard flap shows some under-prediction right next to the flap-gap (station D). This implies some error cancellation of lift resulting in an accurate overall lift coefficient.
- 4) The lower lift seen at CL_{max} ($\alpha = 20.7^\circ$) is likely due to under-prediction of outboard flap suction (Figure 17). This is an issue that has plagued all scale-resolving simulations for some time [9] and one possibility is that it is caused by the transitional nature of the flap boundary layers at high angles of attack for the subscale Reynolds numbers being considered. Some error cancellation is again observed for this case, with the inboard flap over-predicting suction near the wing root (see row A).
- 5) Apart from the issues with the outboard flap, the agreement in C_p at the stall angle ($\alpha = 23.8^\circ$) is quite promising (Figure 18) given the highly complex and unstable nature of the separated flow. Figure 19 shows the comparison between the surface streamlines for the “best-practice” grid and the experiment oil flow. Remarkable agreement is seen throughout the wing and the WMLES correctly predicts the outward cross-flow resulting from the swept wing along with the incipient trailing edge separation occurring throughout the outboard wing. The wedge-shaped outboard separation is correctly predicted; this is also seen in terms of excellent agreement in C_p at the row I station for both $\alpha = 20.7^\circ$ and $\alpha = 23.8^\circ$.

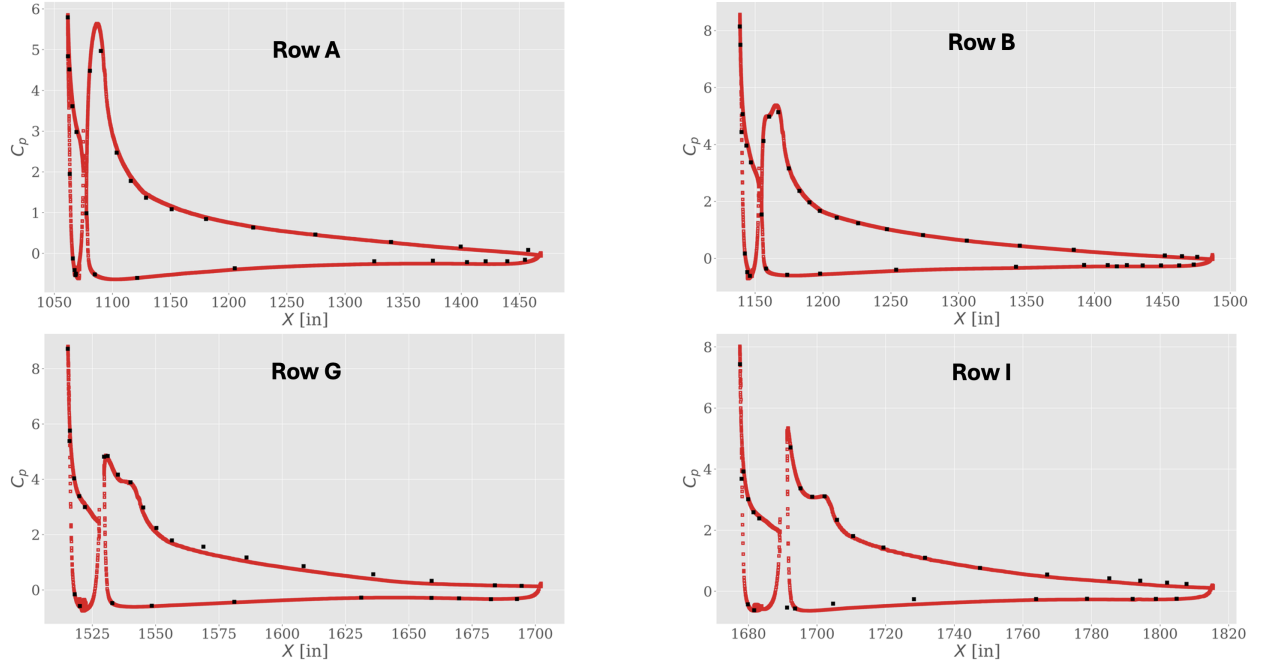


Fig. 12 Pressure coefficient for the “best-practice” grid simulation for $\alpha = 23.0^\circ$.

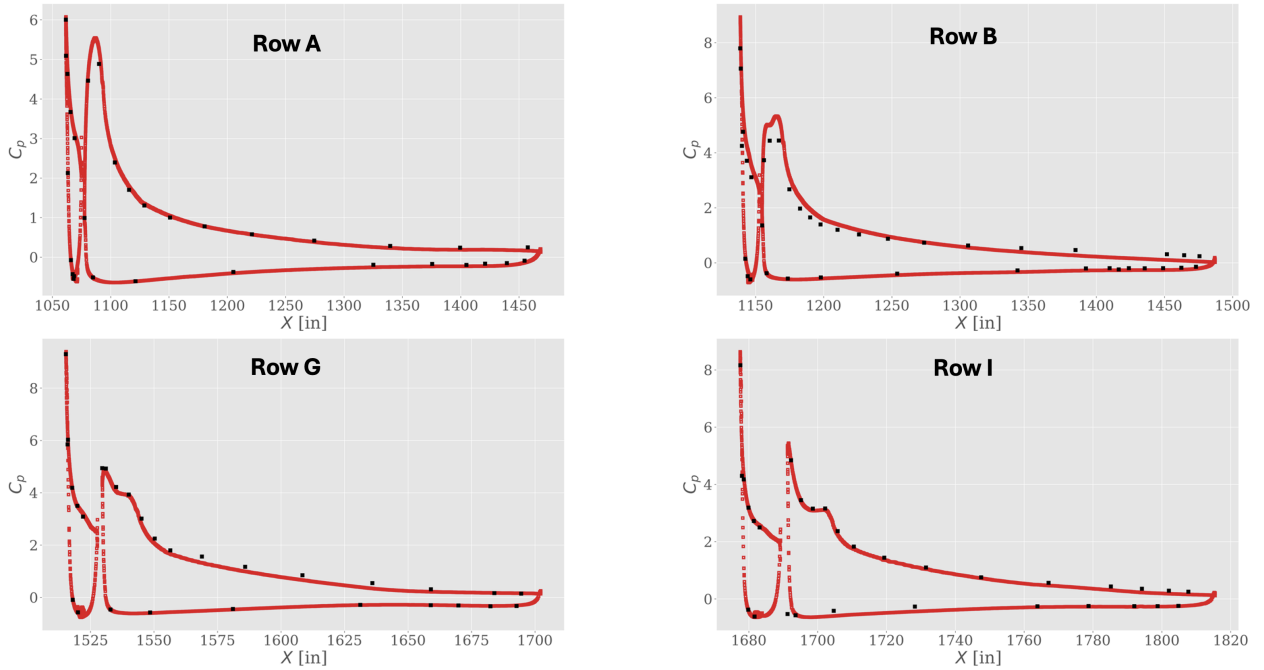


Fig. 13 Pressure coefficient for the “best-practice” grid simulation for $\alpha = 23.8^\circ$ (Case 2.2).

C. Case 2.4 Configuration

The most complex configuration which is based on Case 2.3 by adding the nacelle (with the pylon attached to the wing), along with a chine/vortex generator on the nacelle is studied. Figure 20 shows the integrated forces and the pitching moment for the three grids considered. Figures 21 through 25 consider loads, surface streamlines and the pressure coefficients for the “best-practice” grid.

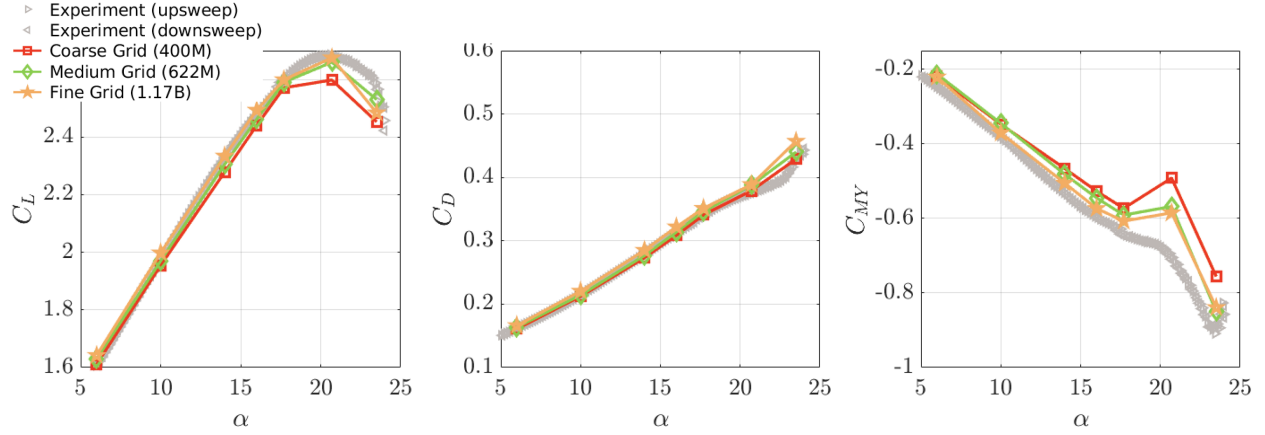


Fig. 14 Integrated forces and moments for the three grids for Case 2.3.

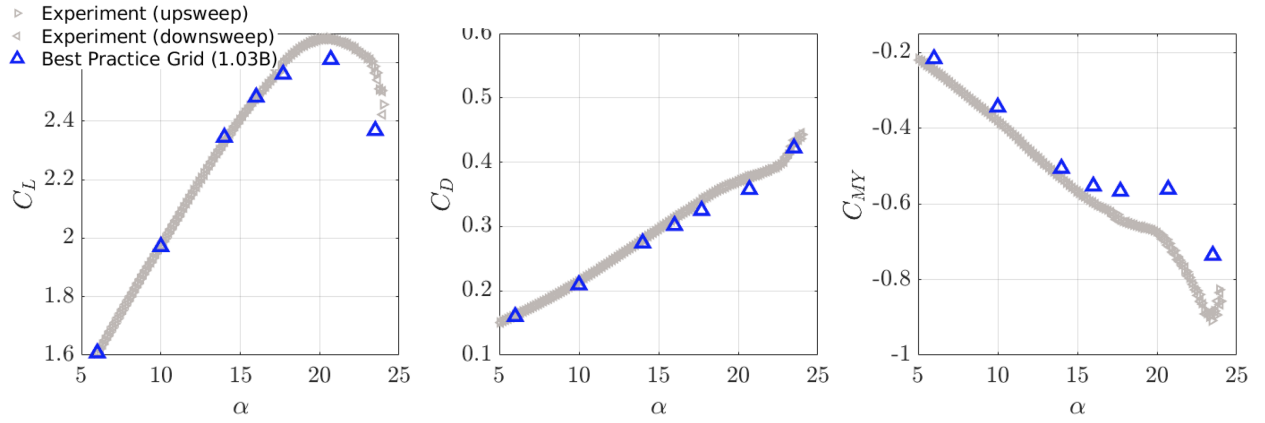


Fig. 15 Integrated forces and moments for the “best-practice” grid for Case 2.3.

- 1) A monotonic grid convergence towards the experiment data is observed with the finest grid showing approximately 1% error in lift coefficient at CL_{max} ($\alpha = 19.7^\circ$). These overall trends are largely consistent with those for Case 2.3 with slightly lower errors since the CL_{max} value is slightly lower for Case 2.4.
- 2) The “best-practice” grid also shows excellent agreement with the experimental data; a 1-2% error is observed in lift at CL_{max} with good agreement in lift at all angles of attack. The flap separation observed near the flap gap in the experiment for Case 2.4 is qualitatively replicated in the simulation (Figure 22).
- 3) At the stall-state ($\alpha = 23.6^\circ$), the side-of-body separation as well as the outboard wing-separation predicted on the best-practice grid appears to be in remarkable agreement with the oil-flow in experiment (Figure 23).
- 4) Pressure coefficient at $\alpha = 19.7^\circ$ shown in Figure 24 at various spanwise-stations can be used to understand the excess nose-up moment seen in the simulations at high angles. Lower suction peaks are seen at the outboard flaps (rows E and G) similar to the findings in Case 2.3. However, C_p seen in the simulations is in excellent agreement with the experiment in all other parts of the geometry.
- 5) The stall state at $\alpha = 23.6^\circ$ is predicted with reasonable accuracy by the “best-practice” grid considering the complexity of the highly unsteady separated flow. Apart from suction-peak under-prediction on the outboard flap, the C_p distribution on much of the remaining wing is quite accurate.
- 6) The mitigation of the outward cross flow seen in Case 2.3 due to presence of the chine vortex is correctly reproduced in the WMLES. The streamlines in the midboard region of the wing appear to form the correct angle with the main-element trailing edge when compared with the oil flow. While the streamlines for Case 2.3 appear to be essentially tangent to the trailing edge at the midboard wing at the stall condition, Case 2.4 has midboard surface streamlines that are substantially less “curved”.

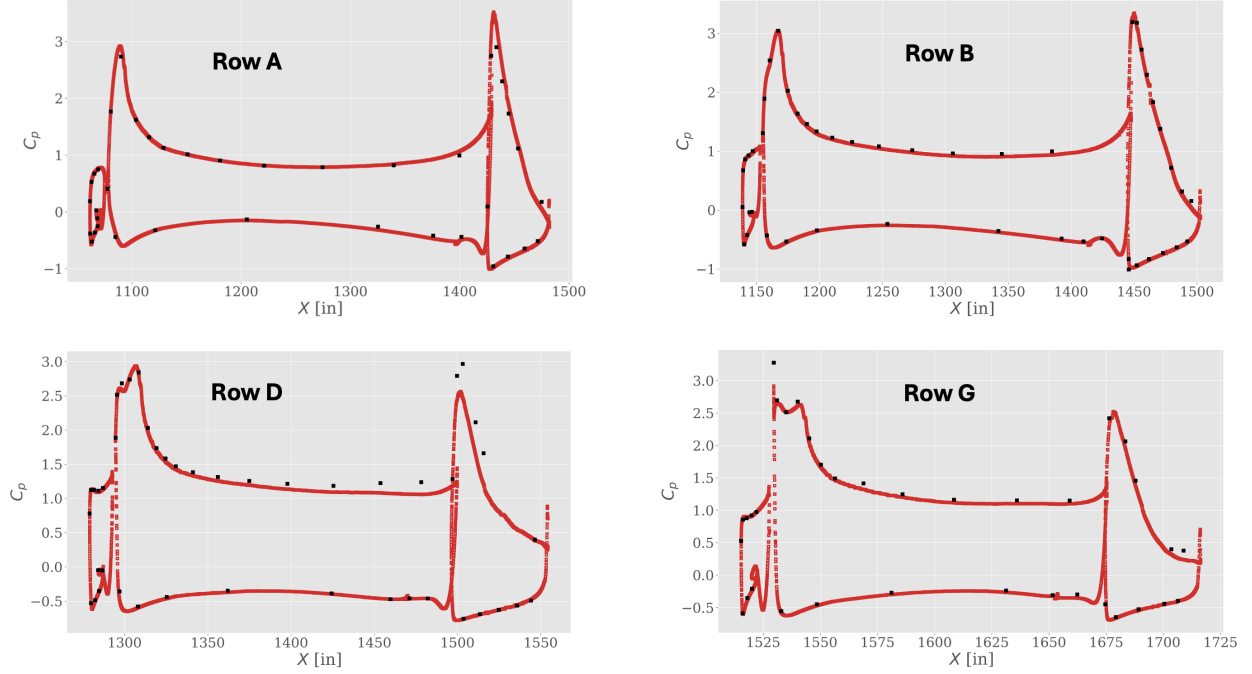


Fig. 16 Pressure coefficient at various spanwise stations for the “best-practice” grid for Case 2.3 at $\alpha = 6^\circ$.

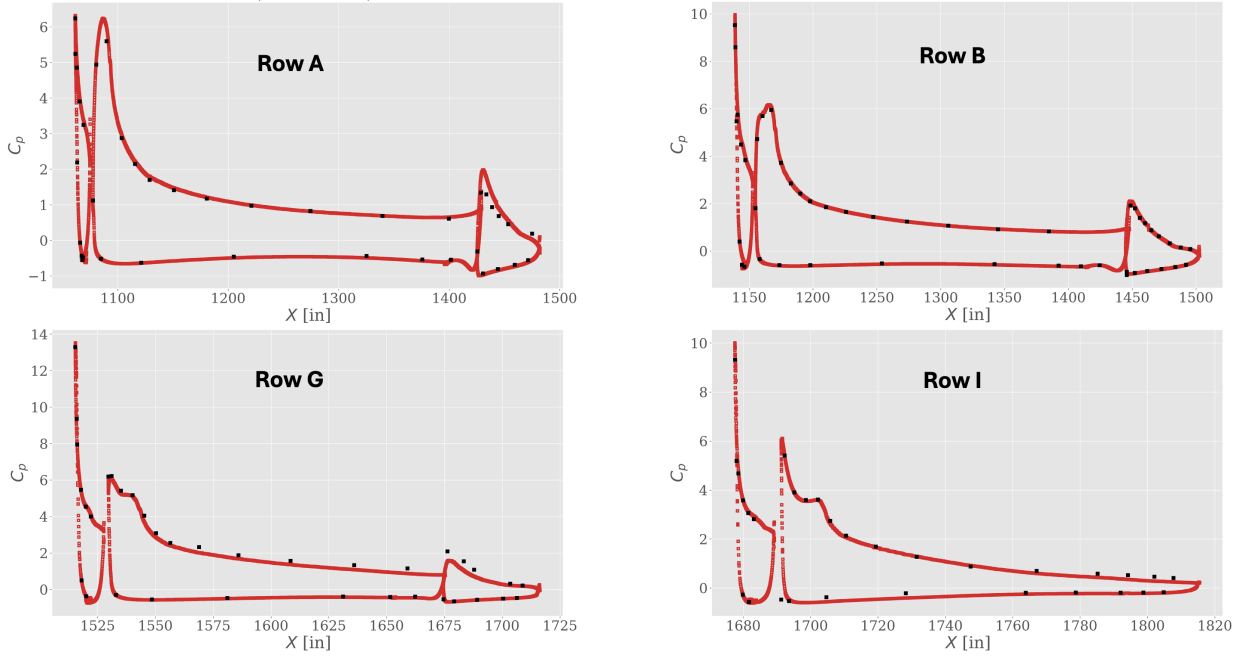


Fig. 17 Pressure coefficient at various spanwise stations for the “best-practice” grid for Case 2.3 at $\alpha = 20.7^\circ$.

D. Computational Cost of Simulations

All simulations discussed herein were performed on Amazon Web Services cloud platform. The computational efficiency and low memory usage of Volcano ScaLES mean that we could use a single Amazon EC2 g5.48xlarge instance which contains 8 NVIDIA A10g GPUs (each containing 24 GB GPU DDR5 RAM), along side a dual-socket 96 core AMD Rome-based CPU, for all simulations. Given the large number of simulations undertaken in this work, AWS ParallelCluster was used to create an ubuntu2004-based HPC cluster in the us-east-1 AWS region using the SLURM

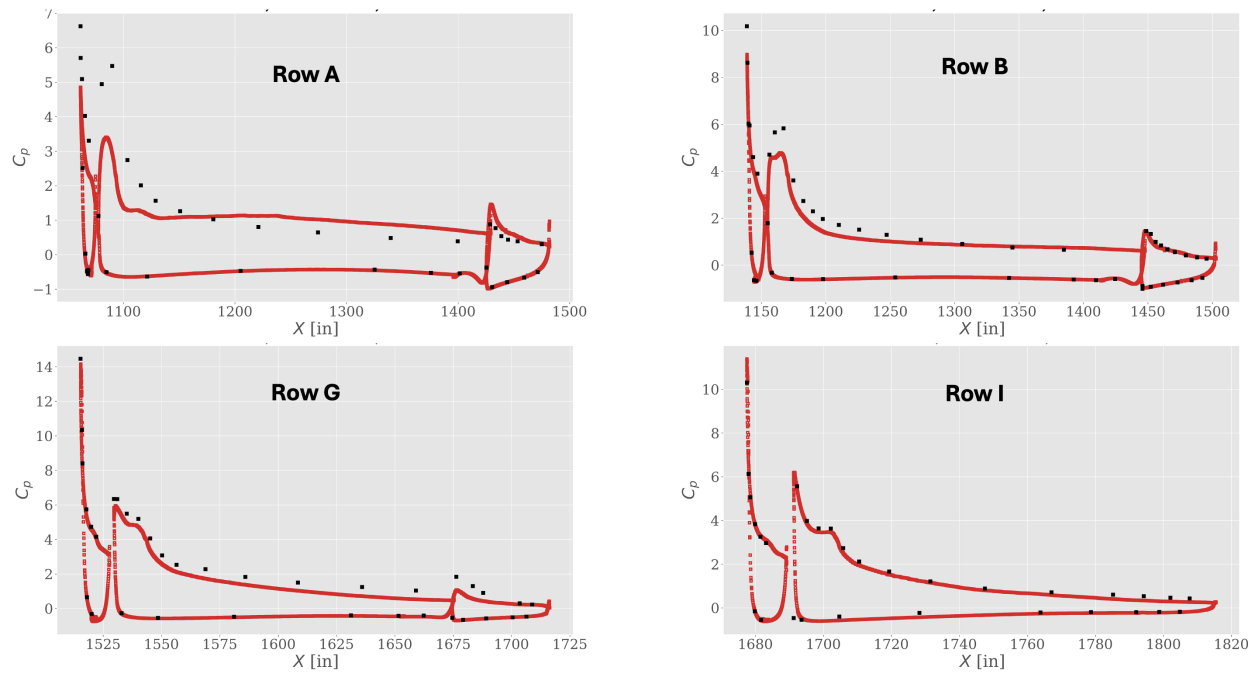


Fig. 18 Pressure coefficient at various spanwise stations for the “best-practice” grid for Case 2.3 at $\alpha = 23.8^\circ$.

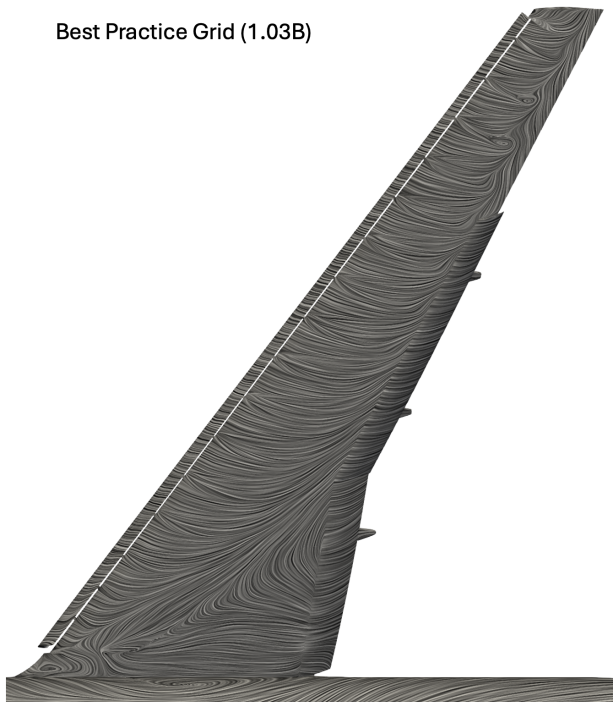
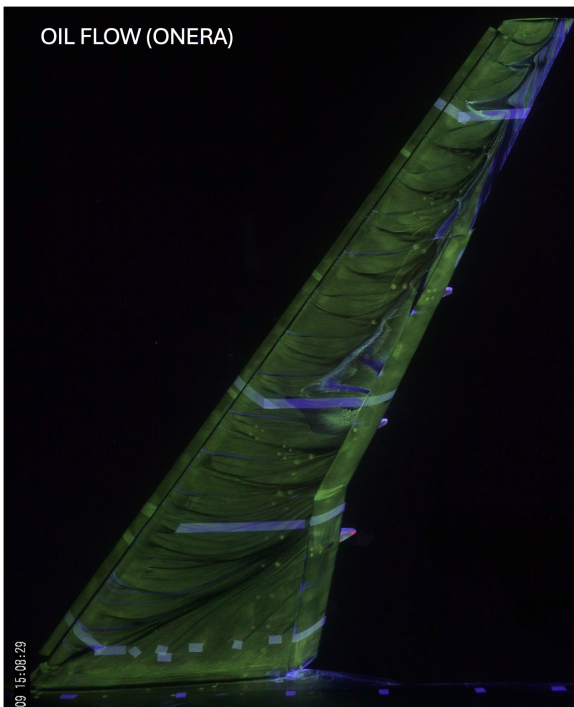


Fig. 19 Comparison of surface streamlines with Oil flow from the ONERA WT experiment [21] for Case 2.3 at $\alpha = 23.8^\circ$.

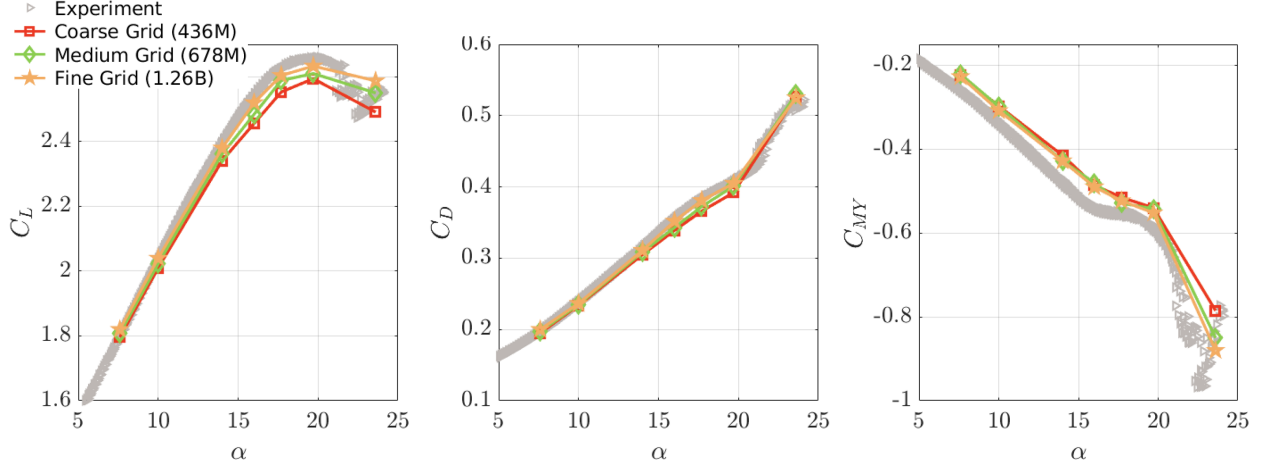


Fig. 20 Integrated forces and moments for the three grids for Case 2.4.

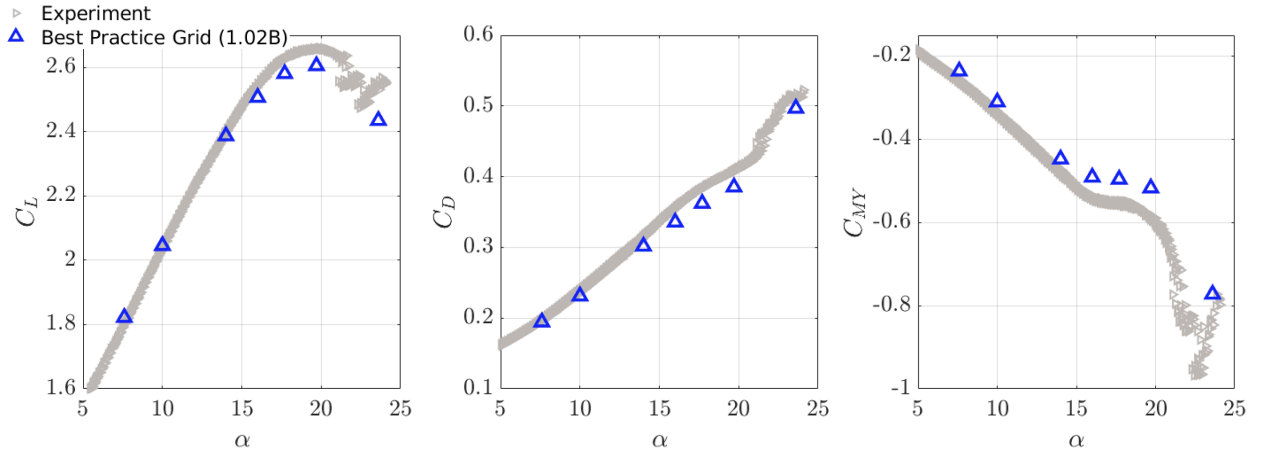


Fig. 21 Integrated forces and moments for “best-practice” grid for Case 2.4.

scheduler to dynamically provision instances as needed i.e not a fixed size cluster. A 160 TB Amazon Fsx for Lustre parallel file system was attached to the headnode and all compute nodes when launched. Table 2 summarizes the total computational cost of each simulation assuming \$7.98 per hour pricing[†]. Assuming 70 CTU’s of total flowtime required, this results in a total cost of approximately \$1100 for the finest mesh of Case 2.4. Whilst it is difficult to directly compare to others, in HLPW4 it was reported by multiple groups [12] that RANS simulations on approximately 300 million cells took 25,000 CPU core-hours to run until steady-state convergence for a comparable case. Assuming the use of an AMD Milan-based CPU hardware at \$0.017 per core-hour[‡] this translates to a cost of approximately \$450. This number naturally depends on the exact CPU hardware, but demonstrates that the cost of Volcano ScaLES on GPU hardware is the same order of magnitude as RANS methods on CPUs, which is arguably the industry standard at present. More recently released Nvidia L40s cards were also tested for fine grid in Case 2.4. These cards allow for a roughly two-fold reduction in turnaround time for approximately the same cost. Given the continued development of GPU technology, it is likely the runtime will continue to drop over future generations of HPC hardware, making WMLES even more approachable for the average engineer.

Furthermore, it is important to highlight the low-cost of grid generation. As an example, generating the fine grids using the Volcano grid generator for Case 2.4 used the exact same resource as the simulation (1 g5.48xlarge instance)

[†]Assuming 3 year saving plan in us-east-1 as of Dec 9th 2024 - <https://aws.amazon.com/savingsplans/compute-pricing/>

[‡]based upon Amazon EC2 hpc6a.48xlarge 3 year saving plan in us-east-2 as of Dec 9th 2024 - <https://aws.amazon.com/savingsplans/compute-pricing>

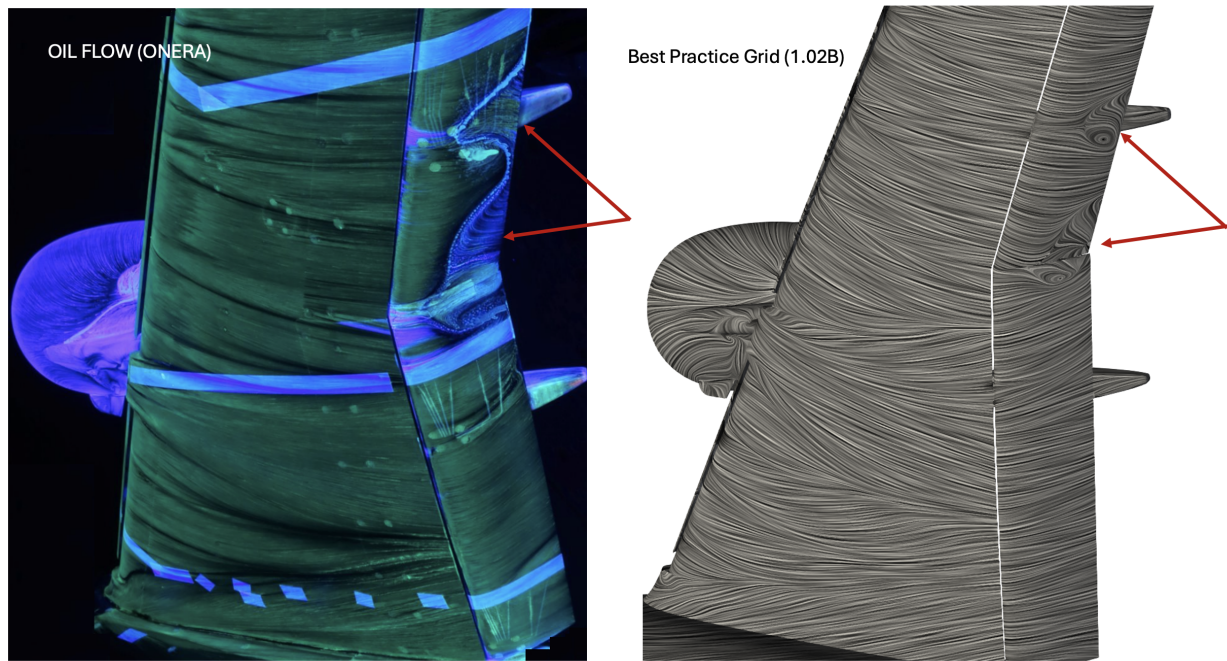


Fig. 22 Flap separation observed at CLmax ($\alpha = 19.7^\circ$) compared between the ONERA oil flow and WMLES on the “best-practice” grid (Case 2.4)

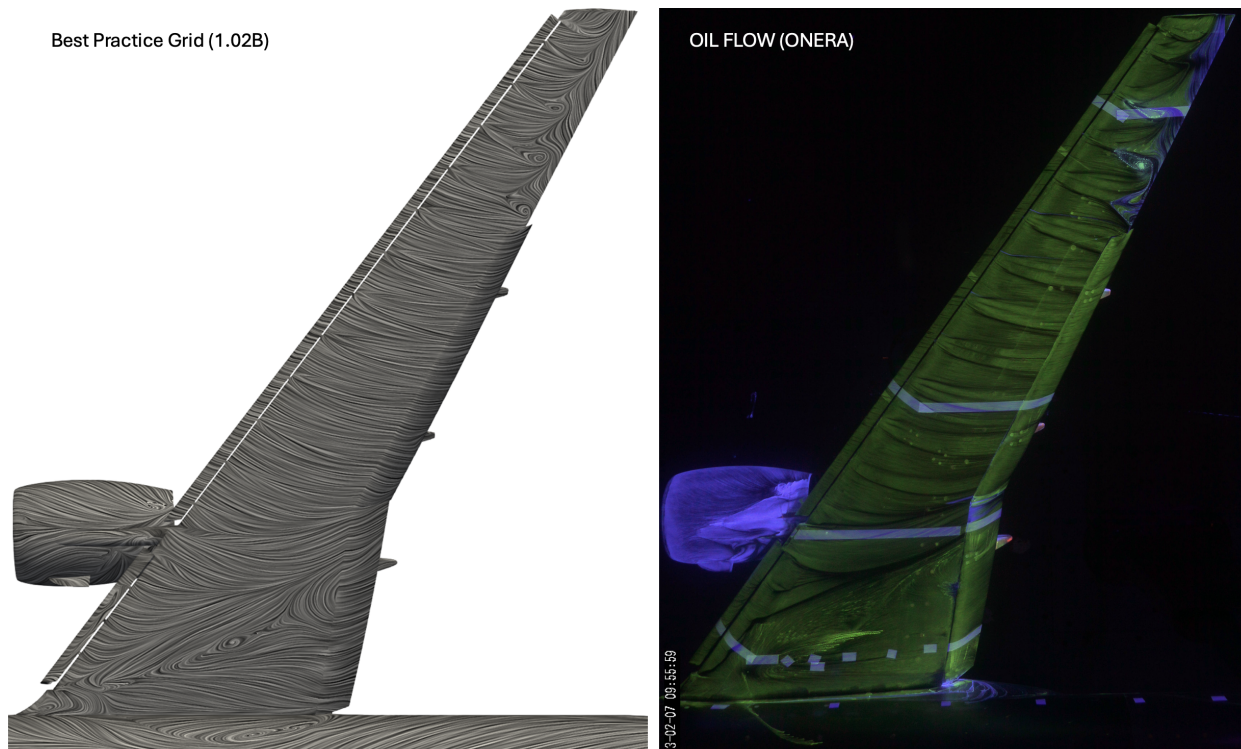


Fig. 23 Surface streamlines for Case 2.4 at $\alpha = 23.6^\circ$ on the “best-practice” grid.

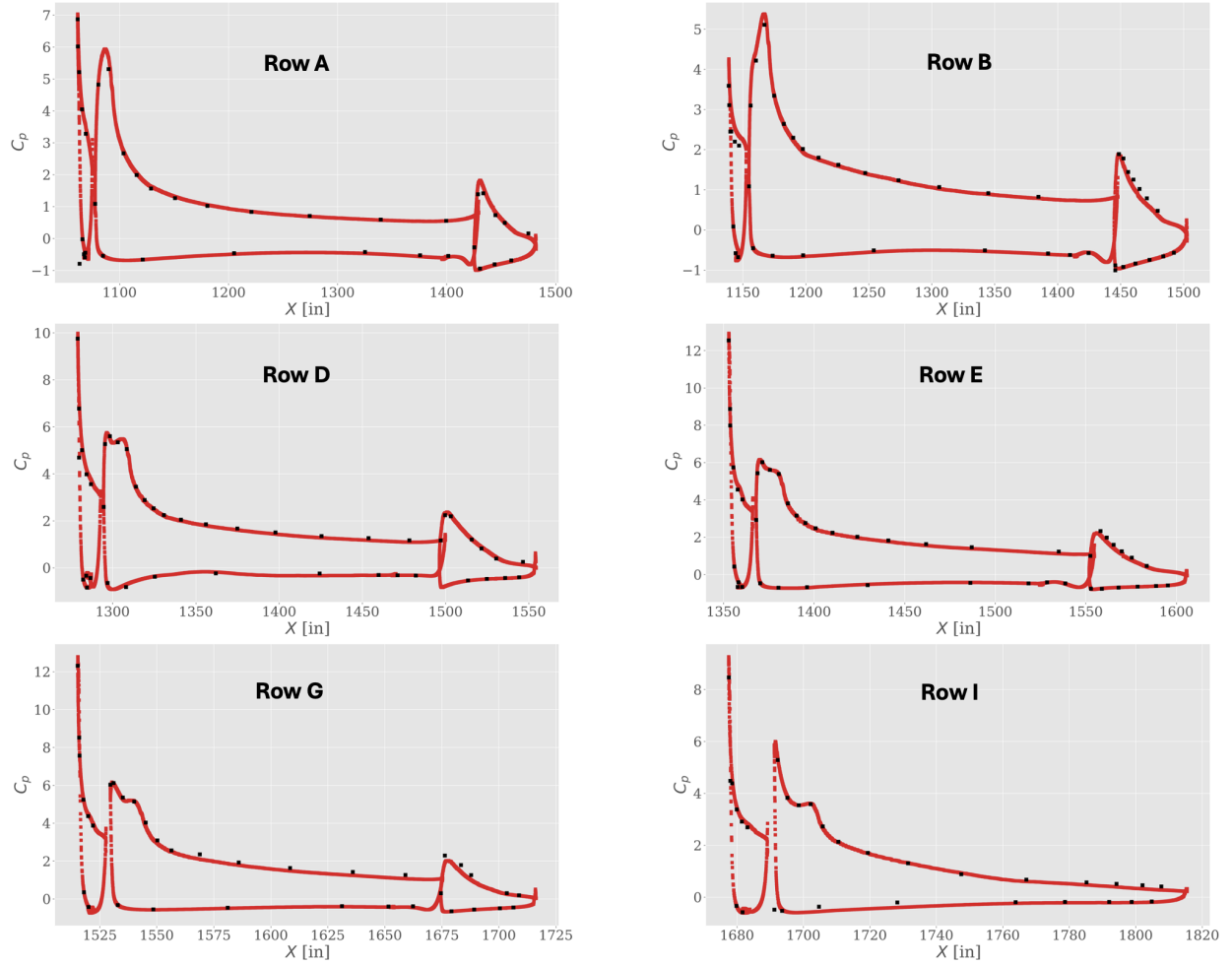


Fig. 24 Pressure coefficient for Case 2.4 on the “best-practice” grid at $\alpha = 19.7^\circ$.

Table 2 Computational expenditure for the WMLES of the three high-lift configurations using Amazon EC2 g5.48xlarge instances (8x Nvidia A10g) using 3 year saving plans on AWS in us-east-1 - <https://aws.amazon.com/savingsplans/compute-pricing/>

Case	Grid level	Wall time per CTU	Cost per CTU
Case 2.2	Coarse	0.41 hours	\$3.26
	Medium	0.81 hours	\$6.45
	Fine	1.56 hours	\$16.59
Case 2.3	Coarse	0.49 hours	\$3.89
	Medium	0.97 hours	\$7.72
	Fine	1.86 hours	\$14.82
Case 2.4	Coarse	0.54 hours	\$4.30
	Medium	1.04 hours	\$8.28
	Fine	2.01 hours	\$16.01

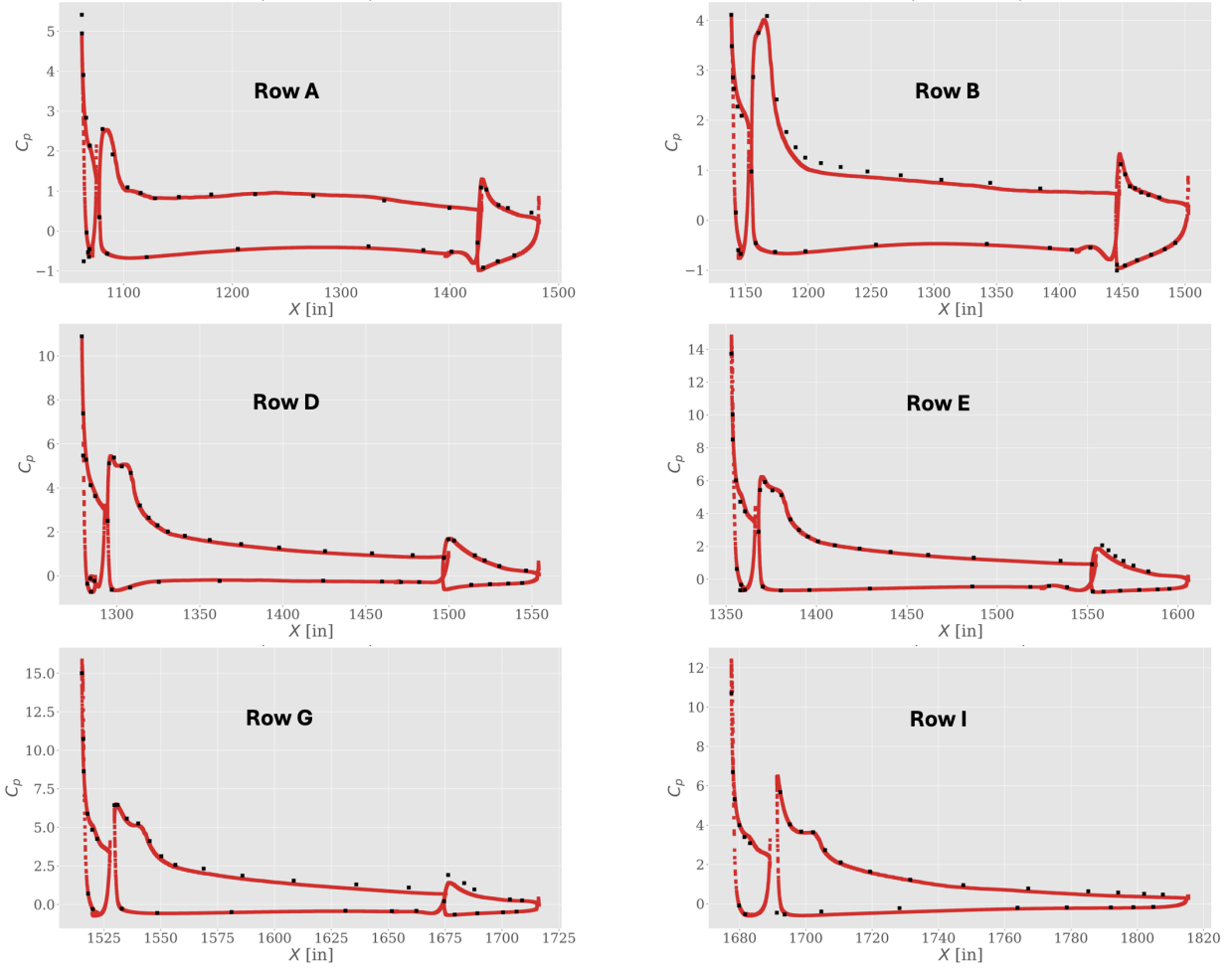


Fig. 25 Pressure coefficient for Case 2.4 on the “best-practice” grid at $\alpha = 23.6^\circ$.

and takes about 5 minutes of wall time to go from the CAD to the generated volume mesh. This short turnaround time makes it very easy to iteratively generate and optimize the grids shown in Section 2.

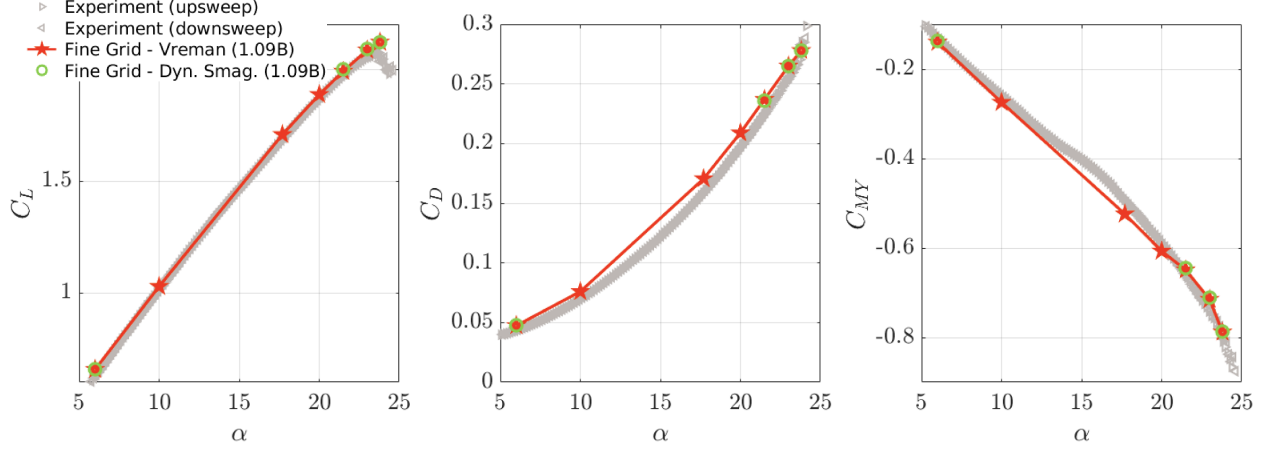


Fig. 26 Integrated forces and moments for Case 2.2 compared between Vreman model simulations and Dynamic Smagorinsky model simulations.

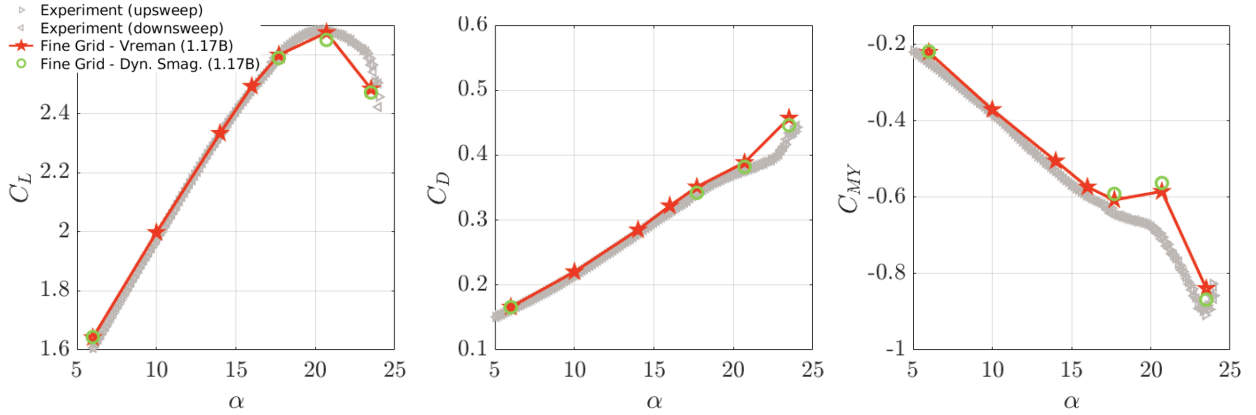


Fig. 27 Integrated forces and moments for Case 2.3 compared between Vreman model simulations and Dynamic Smagorinsky model simulations.

IV. Sensitivity to Subgrid-Scale Closure

Additional simulations using the dynamic Smagorinsky model were performed at selected angles of attack for all three test cases - Cases 2.2, 2.3 and 2.4 to understand both qualitative and quantitative differences in the predicted results. Figures 26, 27, and 28 show the integrated forces and pitching moments. The lack of any meaningful sensitivity to SGS model is evident in these plots; less than 1% change is observed in lift at CL_{max} for all three cases. The only noticeable change is perhaps in the pitching moments. Dynamic Smagorinsky model simulations show a more nose-up pitching moment compared to the simulations using the Vreman model. The instantaneous snapshot of Q -criterion and the surface skin-friction in Figure 29 for Case 2.4 at $\alpha = 23.6^\circ$ offers a very different perspective. Simulations with dynamic Smagorinsky model show finer-structures in the resolved boundary layers, as well as earlier onset of laminar-to-turbulence transition on the suction side of the slats. The latter is most likely responsible for the increase in nose-up pitching moment due to thicker slat boundary layers; the true state of the slat boundary layers seen in the experiment was unfortunately not characterized and as such it is not possible to know which one is more accurate. Figure 30 shows the time-history of the viscous drag seen on the nacelle and the slat; this largely confirms the claim that transition occurs earlier when the dynamic Smagorinsky model is used, resulting in larger skin-friction drag. Perhaps the most striking difference is seen on the nacelle lip for Case 2.4 at $\alpha = 23.6^\circ$ (Figure 31). Simulations with dynamic Smagorinsky model do not show any nacelle lip separation which is seen in the simulation performed using the Vreman model. No evidence of nacelle separation was seen in the experiments, and as such we expect the solution computed using the dynamic Smagorinsky model to be in closer agreement with the experiment. Finally, note that while the

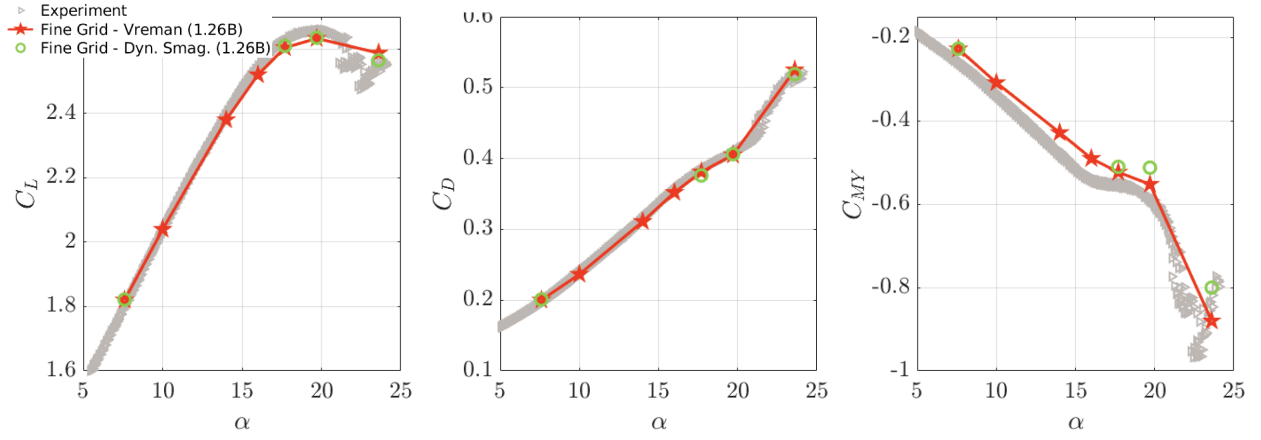


Fig. 28 Integrated forces and moments for Case 2.4 compared between Vreman model simulations and Dynamic Smagorinsky model simulations.

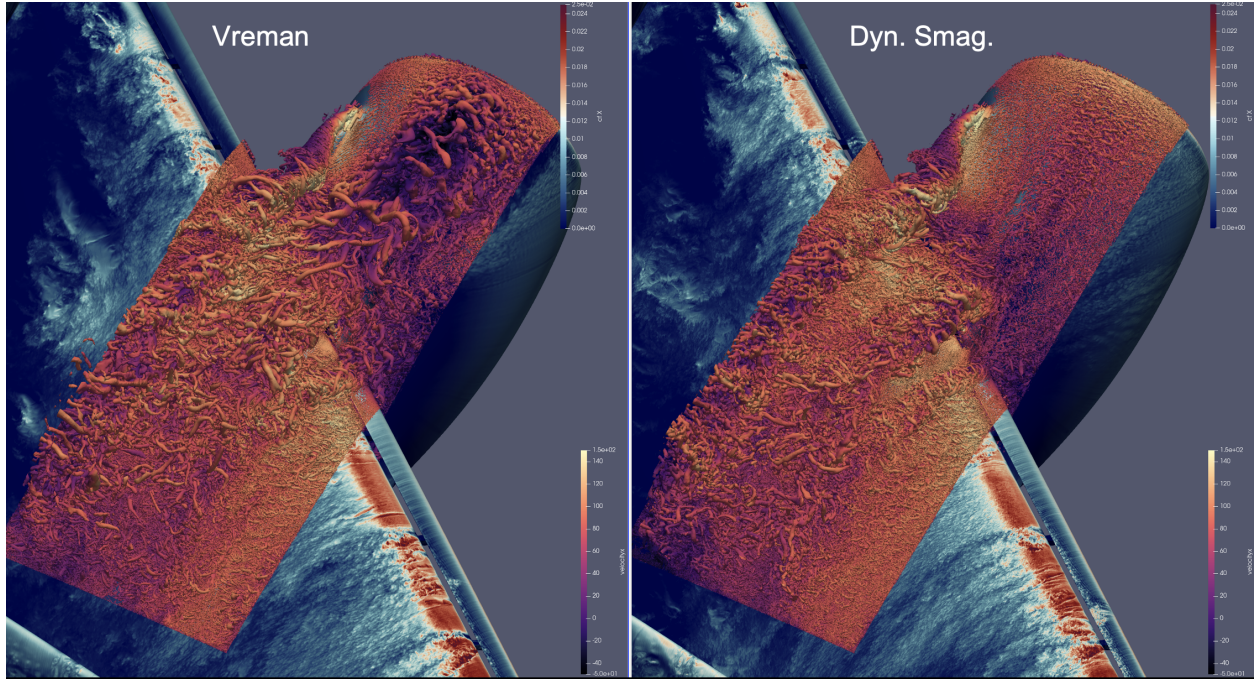


Fig. 29 Isosurface of Q -criterion and instantaneous skin friction shown for Case 2.4 at $\alpha = 23.6^\circ$.

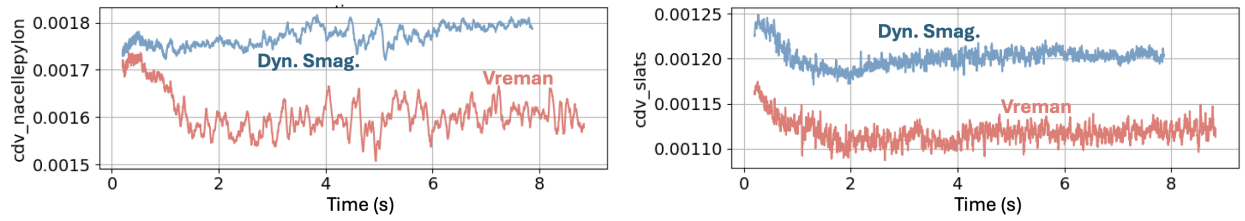


Fig. 30 Time history of skin-friction drag computed on the nacelle and the slats for Case 2.4 at $\alpha = 23.6^\circ$.



Fig. 31 Time-averaged surface streamlines showing sensitivity of subgrid-scale models at $\alpha = 23.6^\circ$ for Case 2.4.

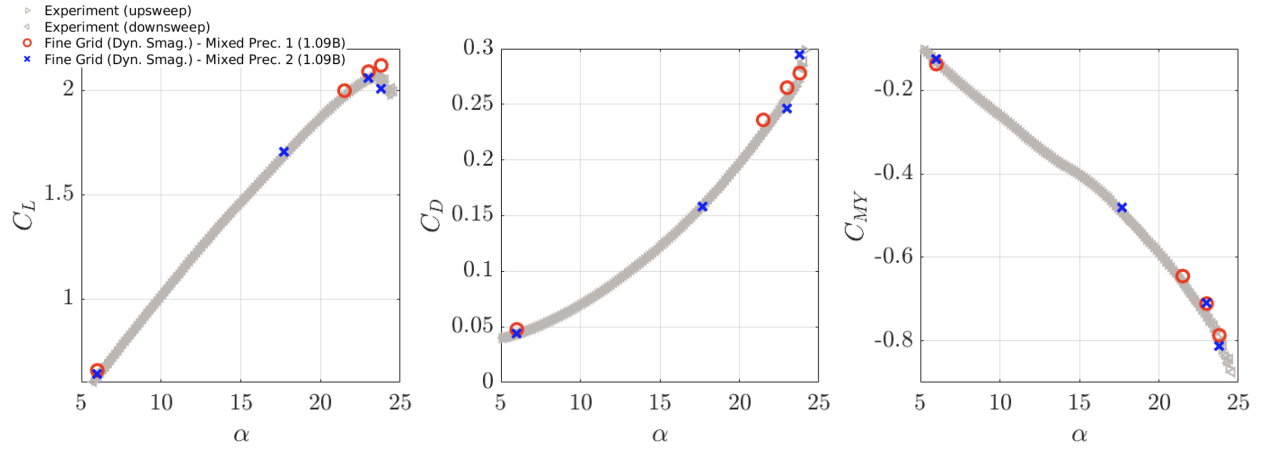


Fig. 32 Integrated forces and moments for Case 2.2 compared between mixed precision 1 and mixed precision 2 formulations.

computational cost of each time-step computed using the dynamic Smagorinsky model is approximately 15% higher, compared to using the Vreman model, the simulations using the former could be run at a larger CFL number, essentially negating any computational overhead compared to the Vreman model simulations for the relatively low-Mach problems considered here.

V. Effect of Numerical Precision Used

In this section we note the sensitivity observed to the choice of floating point precision used. Although the exact mixed precision algorithms available within Volcano ScaLES are not currently exposed to the user, we wish to compare essentially single-precision (denoted as mixed precision 1) simulations with those performed with the recommended setting in ScaLES that utilize a combination of double- and single-precision arithmetic with the GPU kernels (denoted as mixed precision 2). Figures 32 through 34 show the integrated forces and moments for the three test cases using the two different floating-point treatments, now performed using the dynamic Smagorinsky model on the fine resolution grid.

The effect of numerical precision is most prominently seen in the lift predicted for Case 2.2 near CL_{max} ($\alpha = 23.0^\circ - 23.8^\circ$). While the fine grid with mixed precision 1 over-predicts the values of CL_{max} , the use of mixed precision 2 results in a closer agreement with the experiment. The effect of precision is less pronounced in Cases 2.3 and 2.4 on CL_{max} values in general. While this incorrectly suggests that the mixed precision 1 is more accurate, a closer inspection of the solution field offers a better picture. Pressure coefficient on a tightly clamped axis is shown at two constant y planes in Figure 35 for Case 2.4 at $\alpha = 19.7^\circ$. The use of primarily single-precision arithmetic (with mixed precision 1) is seen in terms of small spurious pressure fluctuations away from the geometry. These artificial

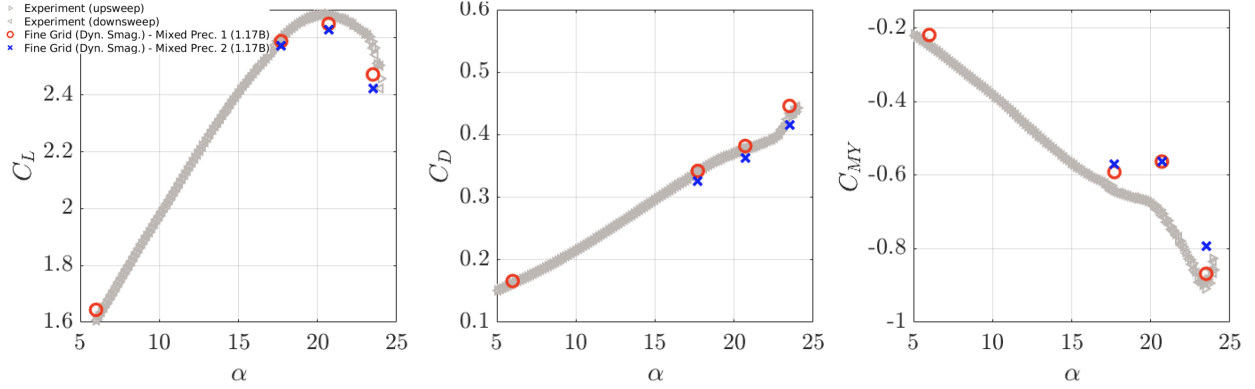


Fig. 33 Integrated forces and moments for Case 2.3 compared between mixed precision 1 and mixed precision 2 formulations.

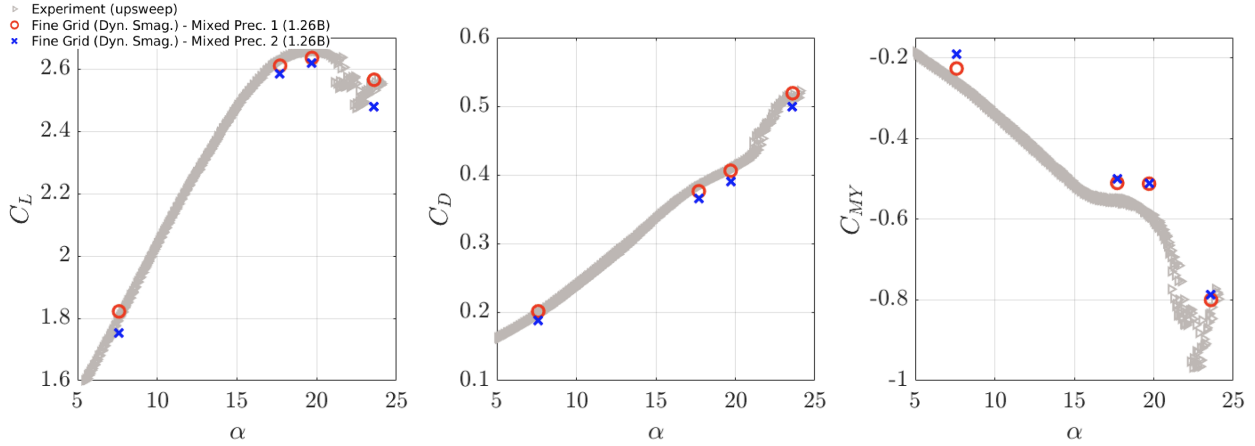


Fig. 34 Integrated forces and moments for Case 2.4 compared between mixed precision 1 and mixed precision 2 formulations.

perturbations are caused by inaccurate propagation of acoustic waves generated at the body; these perturbations are simply too small in amplitude to be tracked accurately using single-precision arithmetic (mixed precision 1). The more sophisticated mixed precision algorithm which combines FP64 operations with FP32 operations when appropriate does not suffer from this issue. Another consequence of these spurious pressure fluctuations is the change to the apparent “free-stream” angle of attack seen by the geometry as shown in Figure 36. These far-field modifications to the flow by under-resolved and contaminated acoustic motions result in changes to the near-body flow, altering the lift and drag on the geometry by as much as 1-2% at CL_{max} . Figure 37 shows the surface streamlines obtained for Case 2.2 at $\alpha = 23.0^\circ$. Note the differences in the side-of-body separation when the improved mixed precision 2 is used. The incipient separation observed is in perfect agreement with the experiment; verified by comparing the inboard pressure coefficient with the experiment. Similarly, for Case 2.4 at $\alpha = 19.7^\circ$, the contaminated mixed precision 1 simulation results in smaller wedge-separation regions and the switch to mixed precision 2 results in larger regions of separated flow which appears to be in closer agreement with the oil flow from the experiment.

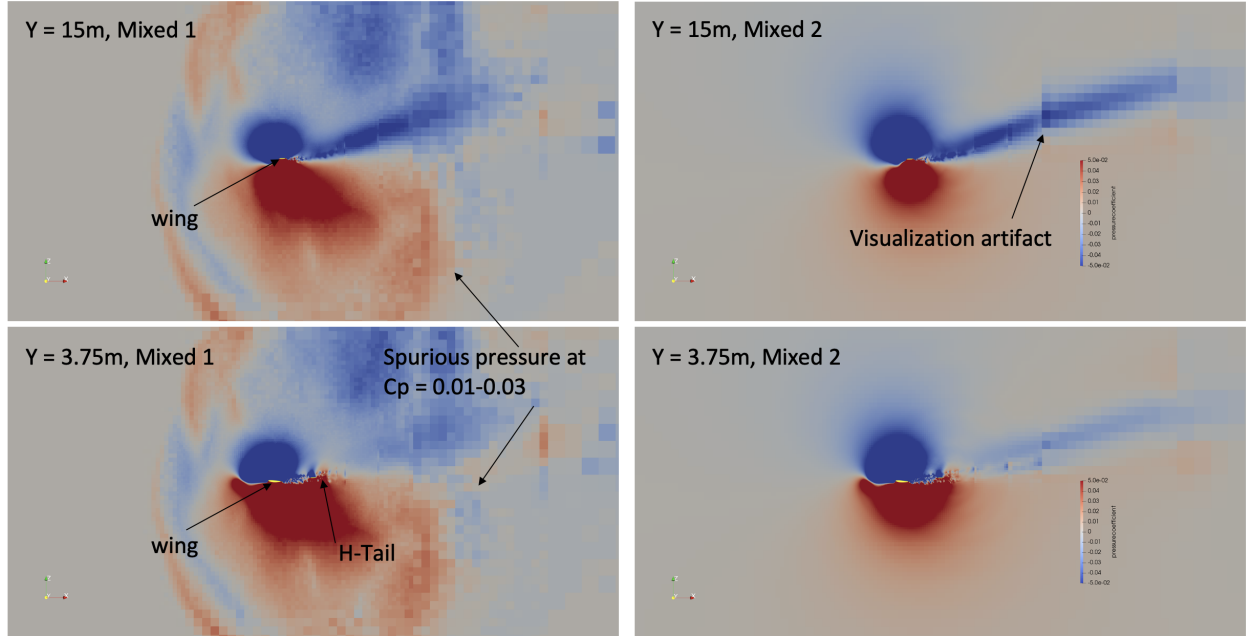


Fig. 35 Spurious far-field pressure coefficient seen for mixed precision 1 formulation compared to the mixed precision 2 formulation that avoids it for Case 2.4 at $\alpha = 19.7^\circ$. The colormap is scaled for $-0.05 < c_p < 0.05$.

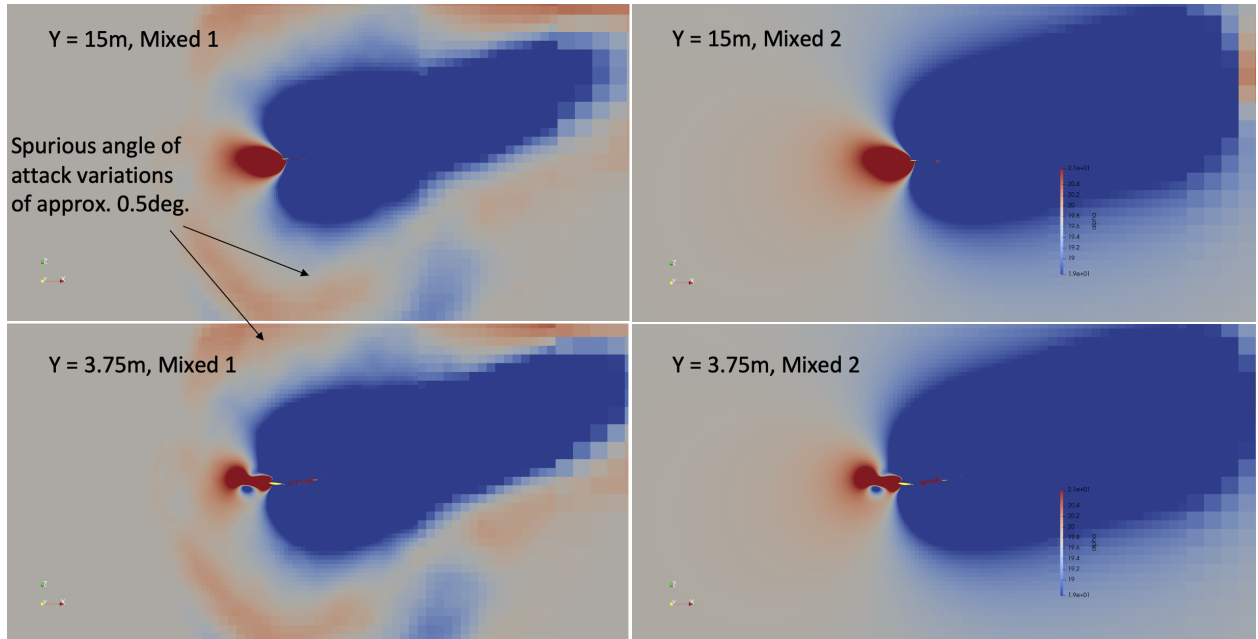


Fig. 36 Spurious apparent angle of attack seen for mixed precision 1 formulation compared to the mixed precision 2 formulation for Case 2.4 at $\alpha = 19.7^\circ$. The colormap is scaled for $19^\circ < \alpha < 20^\circ$.

VI. Reynolds Number Study (Cases 3.2, 3.3, and 3.4)

In this section, we consider the Cases 3.2, 3.3, and 3.4 that attempt to quantify the effect of Reynolds number on the aerodynamic loading for the high-lift CRM comprising of the nacelle (pylon and chine) with extended slats and flaps. Figures 39 through 42 show the integrated forces and moments for the three Reynolds numbers considered on four grid levels, coarse grid (256 million grid points, 7.2 mm of minimum spacing), medium grid (562 million grid points, 4.8

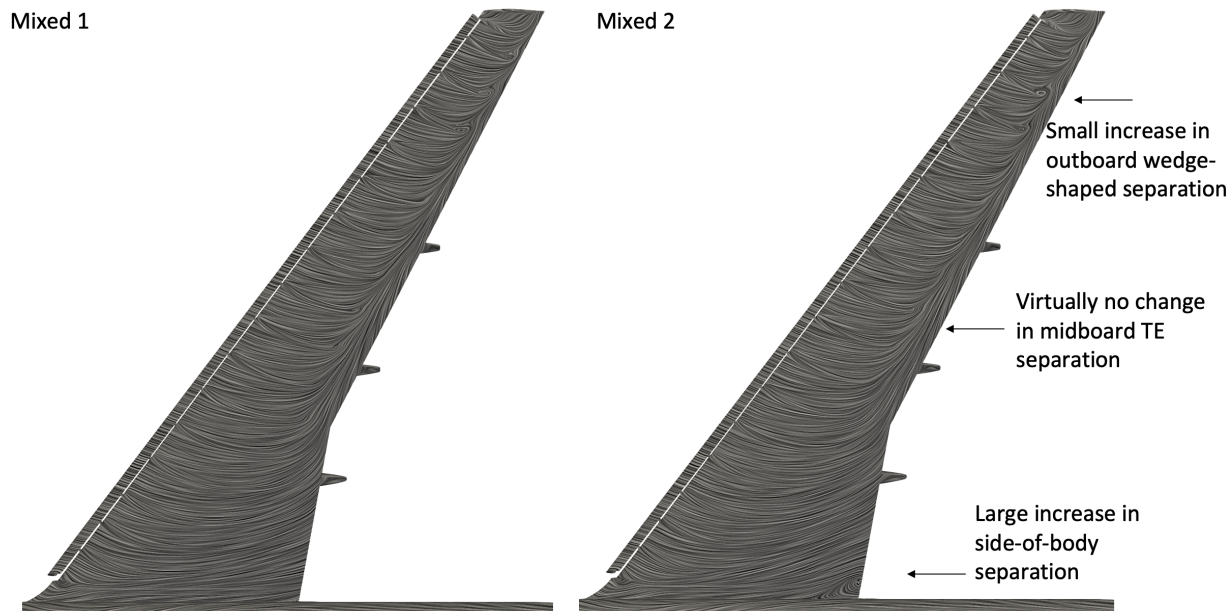


Fig. 37 Sensitivity to numerical precision seen in surface streamlines for Case 2.2 at $\alpha = 23.0^\circ$ on the fine grid.

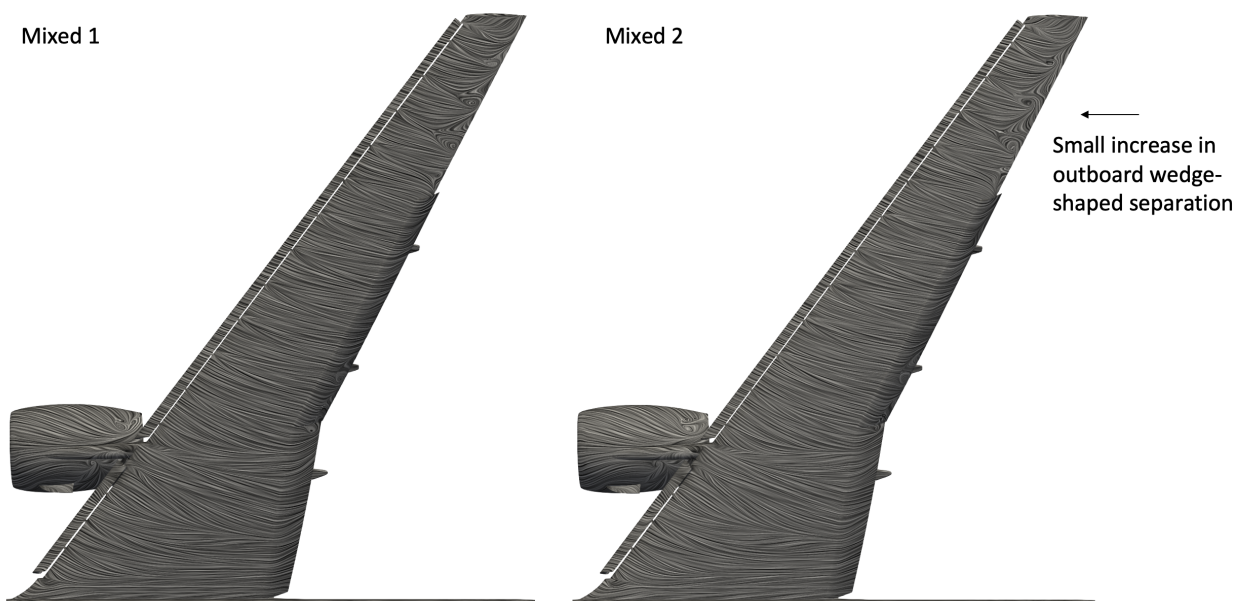


Fig. 38 Sensitivity to numerical precision seen in surface streamlines for Case 2.4 at $\alpha = 19.7^\circ$ on the fine grid.

mm of minimum spacing), fine grid (1.25 billion grid points, 3.2 mm of minimum spacing), and the “best-practice” grid (872 million grid points, 2.2 mm of minimum spacing). Figures 43 through 45 show the differences due to the increasing Reynolds number observed in the streamlines for the “best-practice” grid. Although the experimental data from the National Transonic Facility (NTF) was not available for comparison with simulations at the time of writing this paper, we can make several preliminary remarks about the simulations.

- 1) Reasonable grid convergence is observed for all three Reynolds numbers with a smaller difference between the fine and medium grids compared to the medium and coarse grids. Interestingly, while C_L appears to be monotonically converging with increasing resolution, the pitching moment shows non-monotonic behavior at high-angles, but monotonic (decreasing) behavior at low-angles. The non-monotonic trend in C_{MY} at high angles

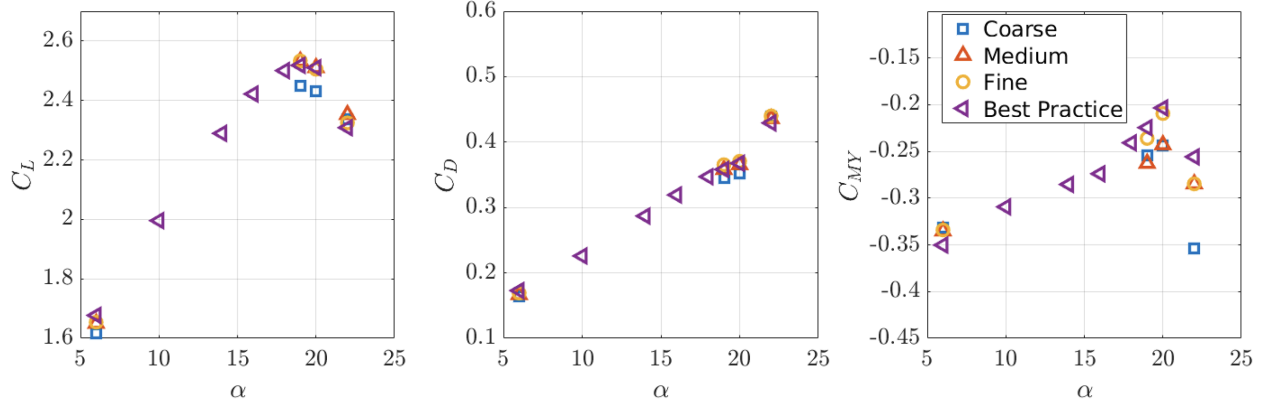


Fig. 39 Integrated forces and moments for the three grids along with the “Best Practice” grid for Case 3.2 ($\text{Re}_{\text{MAC}} = 5.49 \times 10^6$).

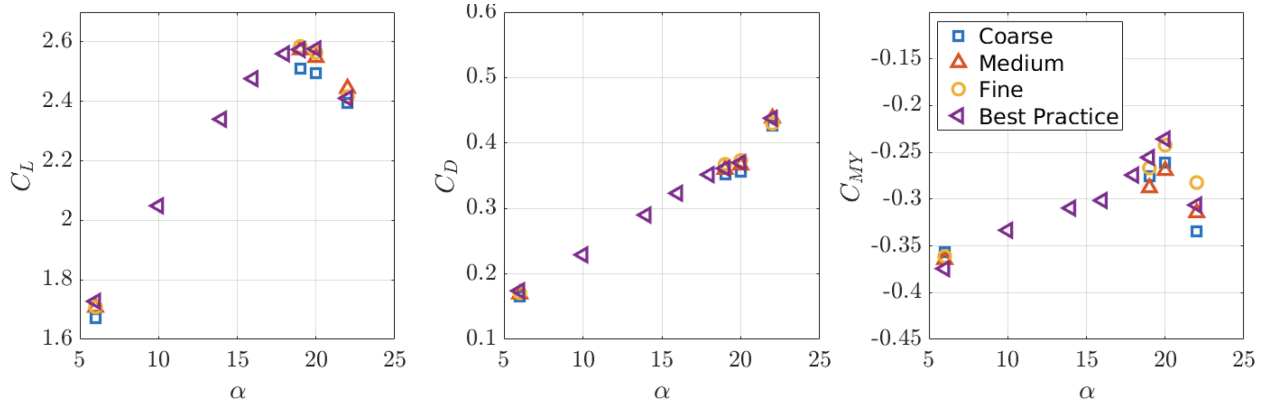


Fig. 40 Integrated forces and moments for the three grids along with the “best-practice” grid for Case 3.3 ($\text{Re}_{\text{MAC}} = 16 \times 10^6$).

is likely due to the transitional nature of the outboard slats at high angles of attack; with the finest resolution “best-practice” grid shown largely turbulent slat boundary layer near the slat trailing edge while the coarse grid showing not perceivable unsteady fluctuations in the slat boundary layer. This balance between inviscid (slat-curvature) driven loading and viscous (boundary layer thickness “deformation”) loading is most likely responsible for the non-monotonic pitching moment trends observed as the center-of-pressure shifts downstream with increasingly turbulent slat boundary layer.

- 2) Figure 42 shows the loads for all three Reynolds numbers obtained on the “best-practice” grid in one plot. It is clear that the lift sees a monotonic increase with Reynolds number at essentially all angles of attack. Similarly a more nose-down pitching moment is obtained with increasing Reynolds number, suggesting that more of the additional lift occurs on the outboard portions of the wing, slat, and the flaps than the inboard portions. This is consistent with overall lower chord Reynolds number on the outboard wing compared to the inboard wing due to taper.
- 3) The increase in lift from Cases 3.2 to 3.3 is much larger than the increase from 3.3 to 3.4. This suggests that the higher Reynolds number cases act closer to inviscid wall simulations (in the asymptotic limit) than the lower Reynolds number simulations.
- 4) Figure 43 considers the changes to the flap separation at $\alpha = 6^\circ$ with increasing Reynolds number. The separated flow region near the midboard flap fairing decreases with increasing Reynolds number, while the large trailing edge separation seen on the outboard flap is substantially reduced. This combined effect of thinner but attached (more equilibrium) boundary layers likely results in complex scalings for grid-point requirements with Reynolds number and are likely to not match with any of the theoretical scaling arguments suggested for attached boundary

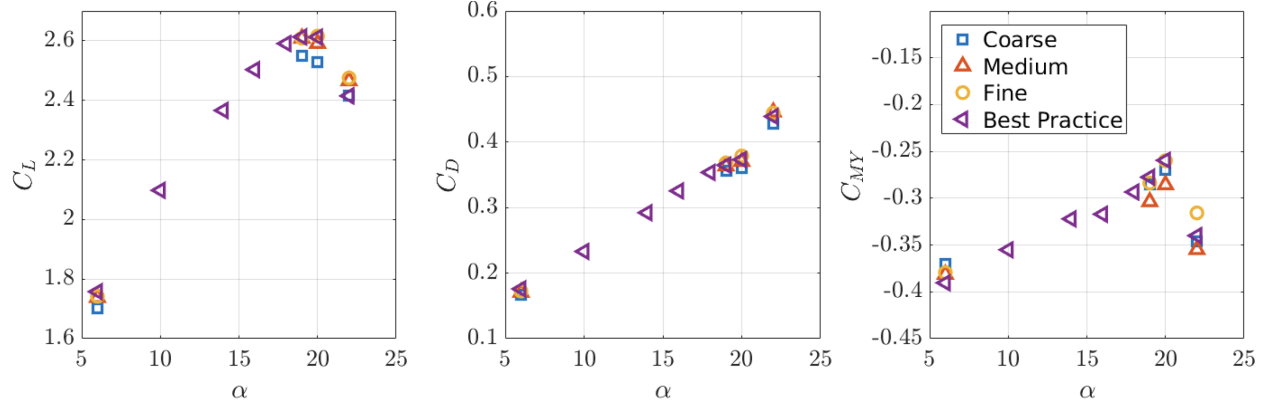


Fig. 41 Integrated forces and moments for the three grids along with the “best-practice” grid for Case 3.4 ($\text{Re}_{\text{MAC}} = 30 \times 10^6$).

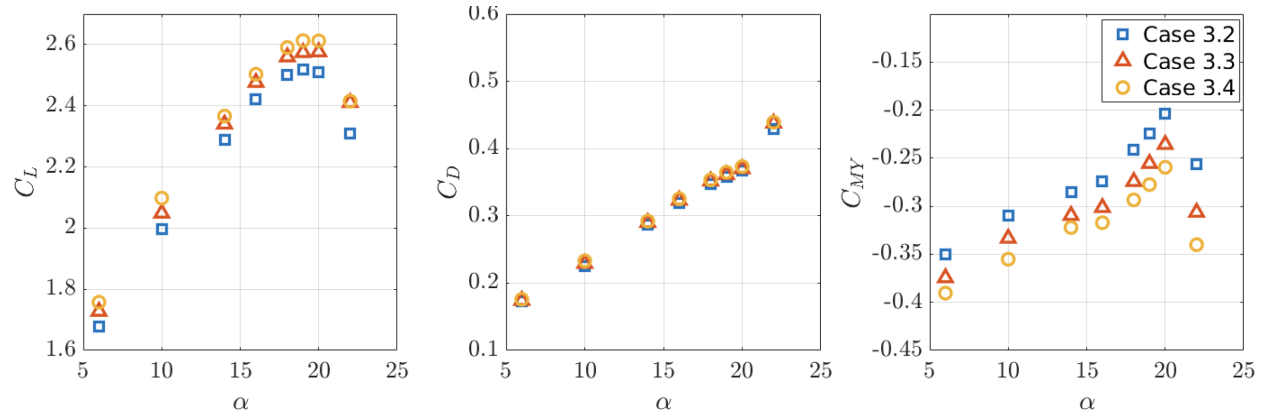


Fig. 42 Integrated forces and moments on the “best-practice” grid for shown for all three Reynolds numbers.

layers or shear layers.

- 5) Interestingly, while increasing Reynolds number raises the C_L at $\alpha = 20^\circ$ (presumed CL_{max}), it doesn’t appear to push the stall onset angle of attack any higher (all three Reynolds numbers show stall occurring at $\alpha = 22^\circ$). The surface streamlines shown in Figure 45 shows the surface streamlines at $\alpha = 22^\circ$ which exhibit essentially identical wing-root separation at all three Reynolds numbers. This suggests that the onset of stall might be dominated by the geometric/inviscid curvature effects (bluff-body like separation) as opposed to the turbulent state in the boundary layer (smooth-body like separation).
- 6) The outboard wedge-shaped patterns are however, sensitive to Reynolds number. Figure 44 shows the decrease in wedge-shaped separated flow regions at higher Reynolds numbers; this is consistent with the larger outboard lift with increasing Reynolds number hypothesized earlier.

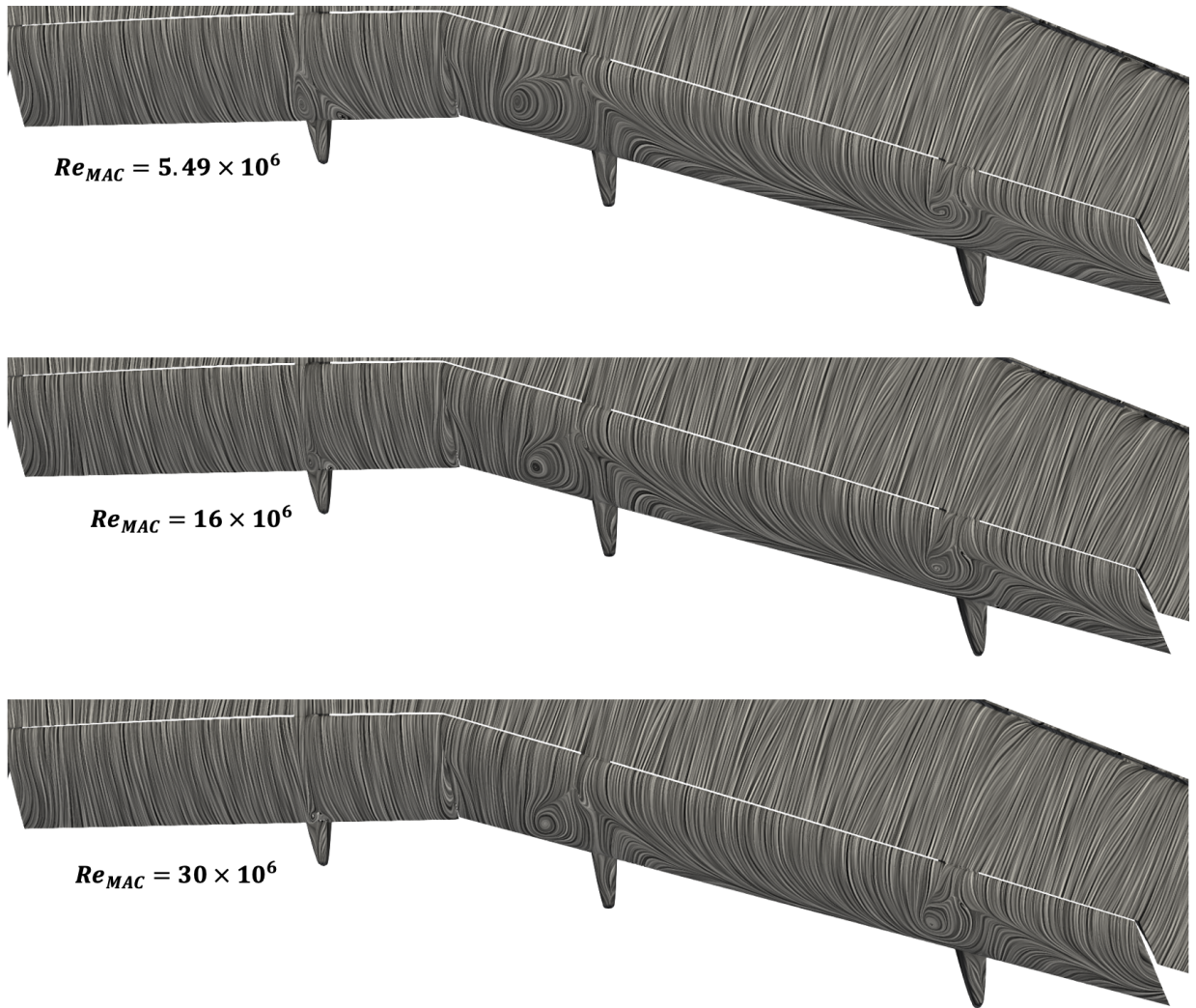


Fig. 43 Flap separation at $\alpha = 6^\circ$ compared for the three Reynolds numbers (Case 3).

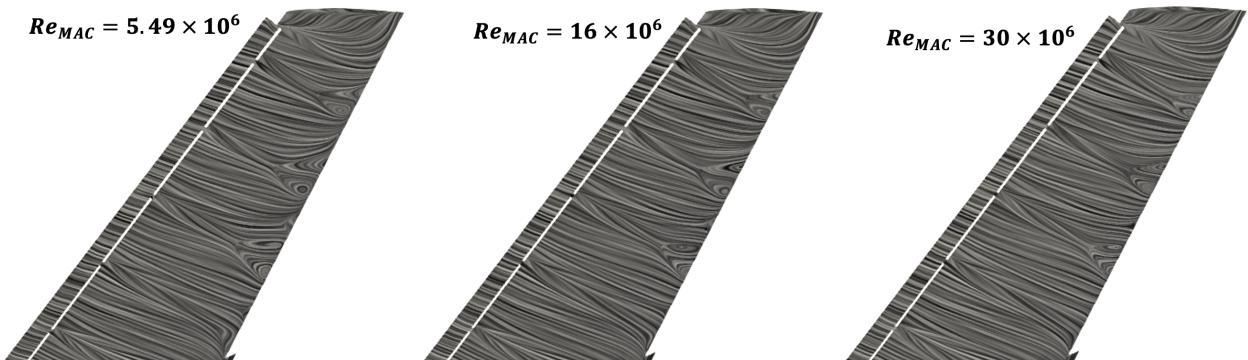


Fig. 44 Outboard surface streamlines comparing the CLmax flow for the three Reynolds numbers (Case 3).

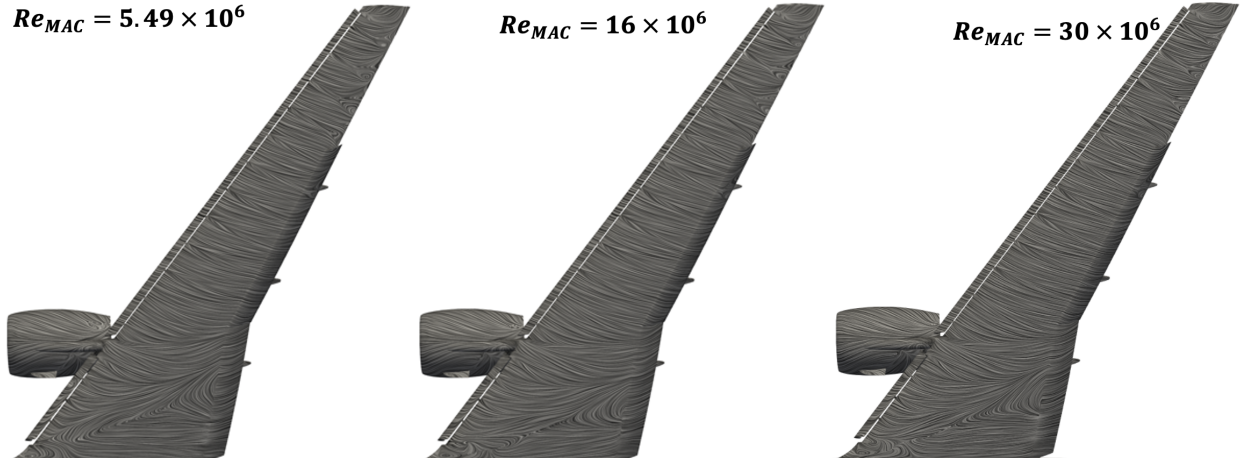


Fig. 45 Surface streamlines at $\alpha = 22^\circ$ comparing the three Reynolds numbers (Case 3).

VII. Conclusions

A comprehensive assessment of Volcano ScaLES was performed using the test cases defined in the fifth AIAA High-Lift Prediction Workshop. The short summary of findings presented in this paper represents a substantial body of high-fidelity simulations; more than 150 WMLES were performed on a variety of different grids for different geometries, at many angles of attack and three different Reynolds numbers. Most of these simulations used grids with more than a billion grid points. The goals of this work discussed in the introduction can now be re-examined.

- 1) A systematic grid sensitivity study using at least three grid levels was performed for all six test cases (Cases 2.2, 2.3, 2.4, 3.2, 3.3, and 3.4). While strict grid-convergence was not observed, the changes between fine and medium resolution grids was lower than that between coarse and medium resolution grids for all cases without exception. Furthermore, the lift predicted at CLmax showed less than 2% variation between the fine and medium resolution grids suggesting reasonable grid independence within tolerance levels approaching typical engineering requirements.
- 2) The “best-practice” designed grids showed lift at CLmax predicted with 2-3% of the experimental data when available (for Cases 2.2, 2.3, and 2.4). But more importantly, surface flow features showed remarkable agreement with experimental oil flow suggesting qualitatively accurate flow-phenomena predicted by LES.
- 3) Some small error cancellation was observed near CLmax and at low angles of attack for cases with flaps. ScaLES results showed consistent under-prediction of outboard flap suction peaks near CLmax along with a slight over-prediction of suction near the wing root. While this led to error cancellation in C_L , there was a slightly excessive nose-up pitching moment for most of the cases near CLmax. Uncertainties regarding slat transition could also be responsible for this excess nose-up pitching moment.
- 4) Sensitivity to SGS closures (Vreman and Dynamic Smagorinsky models) was rigorously studied on the set of finest resolution grids available. While the integrated forces and moments did not show appreciable differences, the dynamic Smagorinsky model was noted for its lower dissipation characteristics which led to earlier transition to turbulence in boundary layers. One notable consequence of this property was the lack of nacelle lip separation seen in Case 2.4 at $\alpha = 23.8^\circ$ with the dynamic Smagorinsky model, in agreement with the experimental data. As such dynamic Smagorinsky model was considered preferable over Vreman model for the “best-practice” simulations.
- 5) The importance of using mixed precision floating point arithmetic (over single precision) was emphasized by identifying the artificial contamination of the far-field flow by incorrectly propagated low-amplitude acoustic waves with excessive use of FP32 floating point arithmetic. These far-field differences caused some minor differences in the near-body solutions, especially in cases with incipient boundary layer separation.
- 6) Reynolds number sensitivity study (Case 3) showed monotonically increasing lift with Reynolds numbers. The increasing lift appeared to be consistent with reduced flap-separation at lower angles and reduced outboard wedge-shaped separation at high angles of attack leading to an increasing nose-down pitching moment with increasing Reynolds number. However, the flow-state at stall ($\alpha = 22^\circ$) appeared nearly identical for all three Reynolds numbers.

- 7) A key objective of this work was to assess the viability of using ScaLES in an industrial computation environment. The simulations discussed here were demonstrated to be a similar order of magnitude to computational expenses of traditional steady state RANS done using current CPU-based state-of-the-art commercial solvers even with grids with over 1 billion degrees of freedom. While all simulations discussed here used consumer grade GPU cards such as the Nvidia A10g (Amazon EC2 g5 instance), new architectures introduced in the past year offer even better performance. For instance, preliminary simulations using Nvidia L40s cards (Amazon EC2 g6e instances) show twice as fast turnaround times for the same dollar cost. With appropriate grid sequencing on coarse grids to flush out transience, a typical 1 billion point grid with 3.2 mm minimum spacing for Case 2.4 simulation, a statistically stationary state can be achieved at CLmax in under 24 hours of wall time and for under \$1100 using commercial cloud resources. Furthermore, a major enabler for industrial use is the rapid and iterative grid generation procedure that is used within the ScaLES ecosystem. Reducing human-labor time from weeks to a matter of minutes; the >1 Billion point grids used in this work took fewer than 5 minutes to generate. This rapid workflow allows for systematic grid convergence studies even in non-canonical real-world problems where flight or experimental data is not available a-priori.

VIII. Acknowledgements

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