

Pre-Experimental Aerodynamic Design Study for a High-Lift Wing FSI Benchmark Model Using the Lattice Boltzmann Method [†]

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Abstract

A numerical design study is carried out to support the setup of a wind tunnel experiment for the flap cover seal, which will serve as a benchmarking reference database for Fluid–Structure Interaction (FSI) in aeronautics. To this end, 3-D scale-resolving unsteady Large Eddy Simulation (LES) with the Lattice Boltzmann Method (LBM) is carried out using the simulation software ProLB. A new aerodynamic layout for the chosen F15LS (Large-Scale) high-lift wing model is established to fit the high-lift wing in the DLR-AWB tunnel. The design process involves variations in the leading-edge nose contour’s streamwise length and camber lines (inducing a negative S-shape) to reduce the leading-edge suction peak, thereby lowering the absolute lift while preserving the flap operating conditions. Initial simulations utilize a simplified periodic LES slice and a theory of the method of images to model wind tunnel jet flow deflection, culminating in a full-span 3-D WM-LES-LBM simulation of the entire wind tunnel installation, including free shear layers, to confirm the designed performance of the modified F15LS. This simulation serves to make informed decisions on model settings such as the boundary layer fence and model-nozzle distance. The successful experimental validation of critical performance characteristics, including angle-of-attack requirements and flow deflection, confirms the fidelity of the pre-test WM-LES-LBM evaluation.

Keywords: FSI Benchmark; WM-LES; LBM; aerodynamics; scale-resolving simulations

1. Introduction

This work was carried out within the EU project FALCON (Foreseeing the next generation of Aircraft: hybrid approach using Lattice Boltzmann, experiments and modeling to optimize fluid/structure interactions). The objective of the German Aerospace Center (DLR) in this project was to design and conduct an experiment on the flap cover seal to serve as a benchmarking reference database for fluid-structure interaction (FSI) in aeronautics. The wind tunnel (WT) under consideration is the DLR-AWB (Aeroakustischer Windkanal Braunschweig) open-jet tunnel.

The primary purpose of the flap cover seal is to close the gap between the flap cove and the flap when the flap is fully retracted. Figure 1 shows a numerical simulation depicting the flap cover seal concept, where the seal is displayed in dark blue. The flow field moves from right to left, and the contour colors represent the velocity field. The experiment concerns the dynamic deformation of a seal covering the connection between two elements



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(the flap and the main element) in a high-lift wing. This unsteady loading on the seal is caused by the turbulent flow developing around it when the flap is in close vicinity. Future work will address the seal's sustainability and noise reduction characteristics.

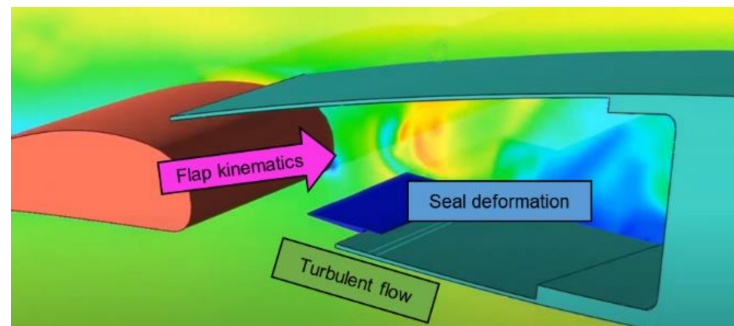


Figure 1. Flap cover seal concept described via an example numerical simulation [1].

This paper discusses the outcomes of a numerical design study conducted using wall-modeled Large Eddy Simulations based on the Lattice Boltzmann Method (WM-LES LBM) with the state-of-the-art LBM solver ProLB. This study was performed *a priori* to facilitate the planning and setup of the subsequent experimental configuration (rigid body simulations).

2. Lattice Boltzmann Solver: ProLB

ProLB [2] is an industrial LB solver that was developed within a consortium including CS GROUP, Renault, Airbus, Safran, Ecole Centrale de Lyon, and Aix-Marseille University. DLR is also a part of this consortium as a scientific contributor to the development of ProLB. It is a node-based solver that deploys a D3Q19 lattice. To ensure superior stability at higher Reynolds number, a Hybrid Recursive Regularised Bhatnagar–Gross–Krook (HRR-BGK) [3] collision scheme is used instead of BGK. A logarithmic wall function is used to model the dynamics of turbulence at the first off-wall cell with extra correcting terms for the adverse pressure gradient and curvature corrections. ProLB version 2.6.3 was used in this study.

3. DLR-F15LS

The high-lift wing configuration selected for this study is the DLR F15LS, where the suffix “LS” denotes Large-Scale. This wing features a modular design concept that provides high flexibility and component interchangeability, enabling the realization of various aerodynamic configurations. The model is scaled at 1:3.67 relative to the full-scale aircraft, featuring a clean chord length (c) of 1.2 m and a total wingspan of 7 m. This specific high-lift wing was chosen because it effectively facilitates optical access for particle image velocimetry (PIV) measurements and yields fluid-structure interaction (FSI) eigenfrequencies that align closely with real-world flight conditions.

Figure 2 (left) shows the arrangement of the DLR F15LS wing within the DNW-LLF open-jet facility. While this wing configuration offers operational simplicity, its original span imposed a geometric constraint for the DLR-AWB facility (see Figure 2 (center)), which features a smaller nozzle exit cross-section of 1.2 m $\times$ 0.8 m. To accommodate the wing within the AWB facility, the inherent modularity of the F15LS design was leveraged.

Specifically, only a designated portion of the original wing layout—highlighted by the red bounding box in Figure 2 (right)—was extracted and utilized for the AWB installation. This modified configuration consists exclusively of the trailing-edge section of the main element and the deployed flap, as illustrated in Figure 3. Because this extracted structural segment lacks an aerodynamic leading edge, the development and integration of a newly designed nose was required.

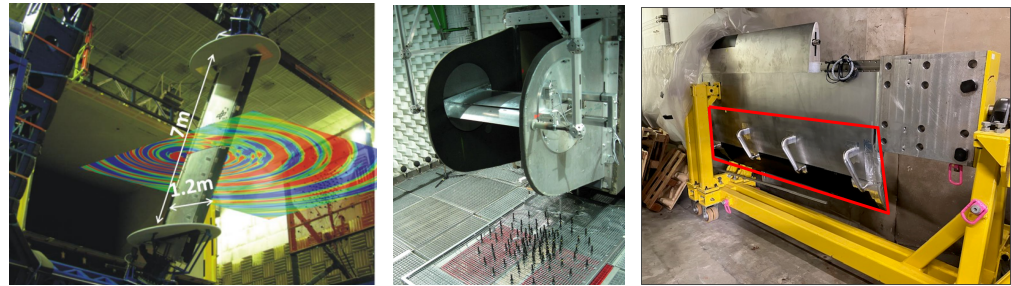


Figure 2. (Left) DLR-F15LS high-lift wing in the DNW-LLF facility (EU OPENAIR). (Center) DLR-AWB open jet facility, nozzle cross-section area 1.2 m $\times$ 0.8 m. (Right) Portion of the F15LS wing, in a storage space, from which the highlighted section was extracted.

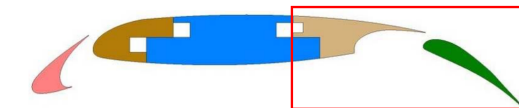


Figure 3. Cross-section of the modular wing [4]; different modular wing sections color coded.

4. F15LS Mod

The selected section of the F15LS did not include a leading edge (see Figure 4 (Left)), which required the design of a new nose. The preliminary nose design was elliptical (see Figure 4 (Right)). Hereafter, the modified F15LS is referred to as F15LS mod. The flap was deployed at an angle of $\delta_F = 8^\circ$, with a gap distance of 15.6 mm between the trailing edge of the wing and the flap, and an overlap of 102.8 mm. This flap setting represents the takeoff configuration. The resulting clean chord length was 0.63 m with a span of 2.0 m. The Reynolds number based on the clean chord length was 2.6×10^6 , and the Mach number was 0.18. The F15LS mod was investigated in this study at an angle of attack of 0° .



Figure 4. (Left) CAD representation of the extracted F15LS and (Right) F15LS mod with an elliptical nose.

The chosen computational domain consisted of a square box measuring $30c \times 30c$. Velocity inlet boundary conditions were defined at the left, bottom, and top sides of the box, while the right side was designated as a pressure outlet. Periodicity was applied in the spanwise direction, with a span width of $0.2c$. A wall-modeled boundary condition was enforced on the wing surface. A mesh refinement study was performed to identify the resolution limits required for the accurate development of the boundary layer. Table 1 summarizes the numerical parameters used in the simulation. Although the results presented here are obtained from a coarse mesh, they provide sufficient and valuable insights for guiding subsequent design changes.

Table 1. Numerical settings for the F15LS mod with an elliptical nose.

Parameter	Value
Finest grid size, Δ_f [m]	1×10^{-3}
Simulated time, [s]	0.57 s
Refinement levels	6
No. of grid points	10 million
Core hours 384 cores	3 hrs

Figure 5 shows the C_p distribution and instantaneous velocity magnitude plots for the F15LS mod. Based on the pressure coefficient (C_p) distribution and velocity contours, the following observations can be made: Significant flow acceleration occurs on the suction side of the main element, induced by the nose shape. Further downstream along the wing, flow separation develops on the suction side, starting at a non-dimensional distance of $x/c = 0.2$. Subsequently, this separated flow transitions into a fully turbulent boundary layer.

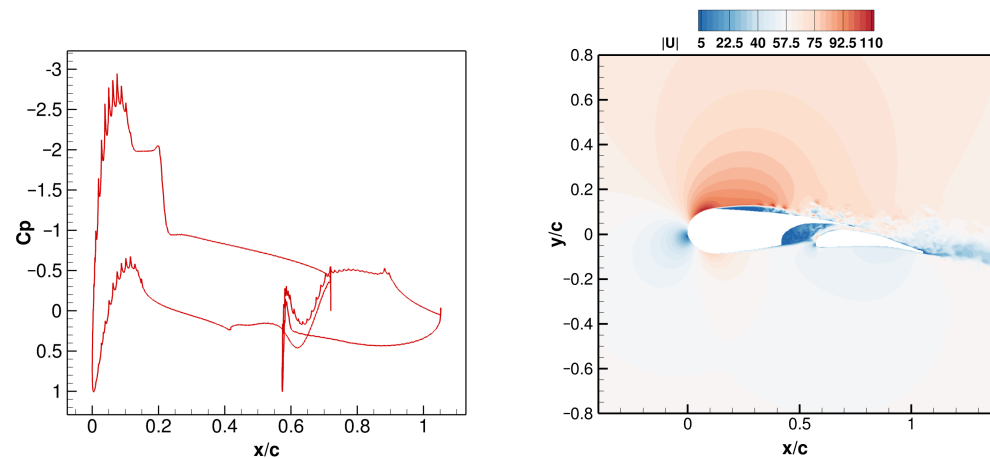


Figure 5. (Left) C_p distribution, (Right) Instantaneous velocity magnitude contour of F15LS mod.

F15LS Mod—Design Targets for Nose Modification

Based on the results obtained from the elliptical nose shape, several design targets for the new nose were established:

1. First, the overall setup of the model must maintain the flow deflection of the wind tunnel's open jet within an acceptable range. Due to the large spanwise and chordwise extension of the F15LS-mod high-lift wing model, combined with the relatively high lift coefficient of the selected takeoff configuration, a substantial absolute lift force is generated. This force inevitably induces a significant flow deflection of the AWB wind tunnel jet relative to the nozzle cross-section of $0.8 \text{ m} \times 1.2 \text{ m}$. If the absolute lift force is excessively high, there is a risk that the vertical displacement range of the movable collector will be insufficient to recapture the jet flow for open-return wind tunnel operation.
2. Second, the design must ensure proper mass flow through the flap cove of the wing when the flap is deployed. Achieving a realistic aerodynamic loading on the flap is crucial to accurately trigger the onset of coupled fluid–structure interaction (FSI) modes.

5. F15LS Mod—Nose Design Space

Based on the previously defined targets, the leading-edge nose design space was narrowed down to two key parameters: the streamwise length (E) and the camber line (f) of the leading-edge nose. Figure 6a shows a schematic of the design space, where X_0 denotes the center.

Several design variations were investigated to identify a suitable leading-edge nose; however, to justify the final choice of the parameters E and f , only a few key variants are discussed here. Figures 6b and 6c show the variations resulting from applying a positive and a negative camber, respectively. The geometric modifications applied to the leading-edge nose are highlighted in blue and green. Regarding the constraint on the absolute lift force, the results of the design parameter variation in f with a fixed $E = 1.8$ are presented below.

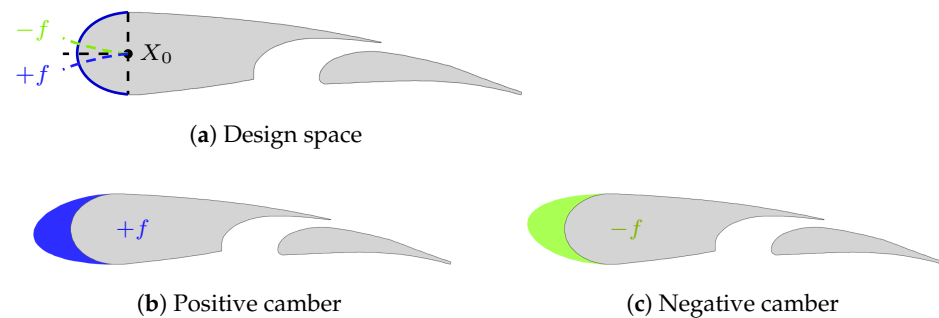


Figure 6. Design space for the leading edge nose and design variants for different f .

Figure 7 shows the aerodynamic impact of these camber variations. The objective was to reduce the lift generated by the leading edge of the wing without altering the aerodynamic loading on the flap.

Three camber variations were compared: zero, positive, and negative camber. From the C_p distribution plot (see Figure 7), it is evident that employing a negative camber line—effectively a reversed S-shape—reduces the lift induced on the leading edge. This is manifested by a minimal or zero ΔC_p between the suction and pressure sides of the leading edge. Crucially, the aerodynamic loading on the flap remains unaffected. Consequently, a negative camber line was selected for further development. As a side note, the localized discontinuities observed on both the pressure and suction sides of the leading edge can be smoothed out via spanwise averaging. With the negative camber line (f) selected, the next step in the design process was to determine the optimal streamwise extent (E) of the leading-edge nose.

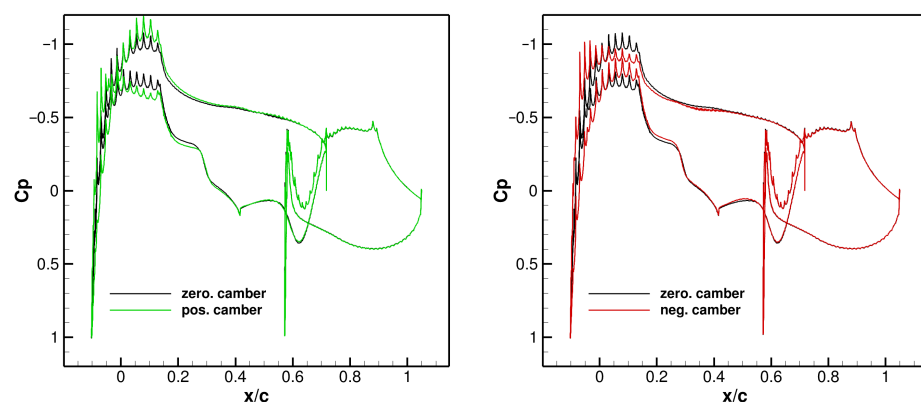


Figure 7. C_p distribution comparison—(Left) zero vs. positive camber, (Right) zero vs. negative camber.

Configurations with varying nose lengths and negative camber values underwent a sensitivity analysis to ensure attached flow on the pressure side of the main element, thereby guaranteeing proper flap loading. The results of one such parameter permutation are shown for an angle of attack (AoA) of -4.5° in Figure 8. For grid resolutions evaluated below an AoA of -4.5° on this coarse mesh, the flow was found to be susceptible to separation on the pressure side. Analyzing the results of the parameter variation, the combination of $f = -0.01$ mm and $E = 1.8$ was selected as the optimal candidate for further investigation, as it predicted the lowest lift coefficient while maintaining attached flow on the pressure side of the main element (ensuring proper loading on the flap). Figure 9 (Left) shows the C_p distribution of the newly designed nose. The resulting clean chord length was 0.702 m, with a corresponding Reynolds number of 2.9×10^6 . The isosurface of the Q -criterion, colored by velocity magnitude, is presented in Figure 9 (Right) to highlight

the resolved complex flow features. The next step is to determine the operational envelope, specifically the angle of attack (AoA) limits, of the F15LS mod.

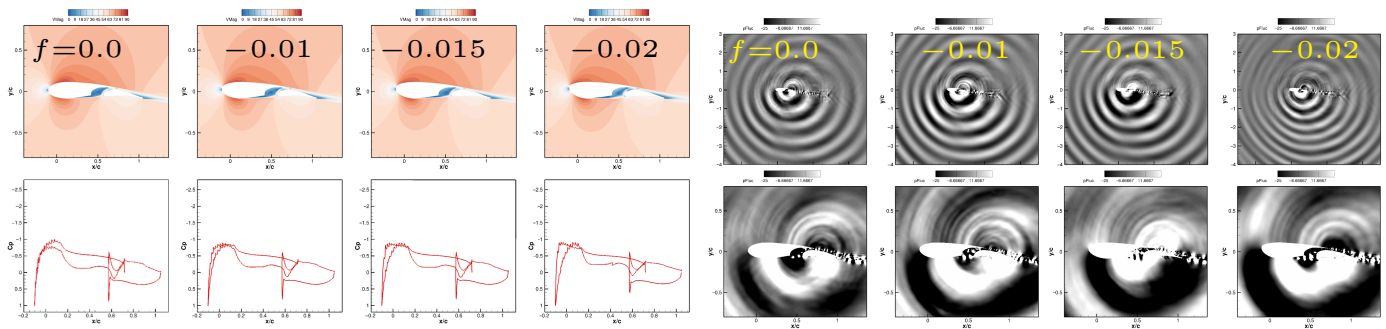


Figure 8. Results of the parameter variation in f and fixed $E = 1.8$. (Left) Velocity magnitude contour and C_p distribution plots. (Right) Sound pressure fluctuation contour plots –25 to 25 Pa.

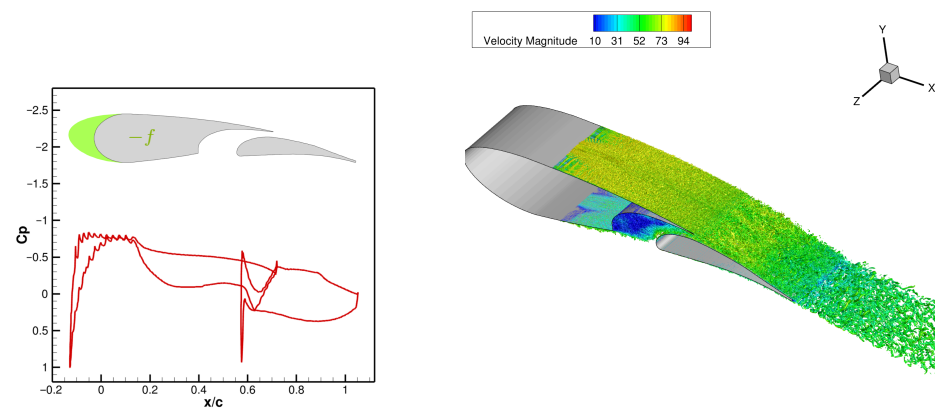


Figure 9. Chosen configuration for the F15LS mod. (Left) C_p distribution of the chosen nose. (Right) Q -criterion colored with velocity magnitude.

Operating Range of the F15LS Mod

To determine the operational angle of attack (AoA) range for the new aerodynamic layout of the F15LS mod within the AWB tunnel, a finer mesh was utilized to precisely resolve the surface forces.

The simulations conducted up to this point employed a 3-D WM-LES periodic slice in a free-field flow configuration. Figure 10 (left) displays the lift coefficient (C_L) polar as a function of AoA for different setups. Initially, the lift polar was computed using the free-field configuration, as indicated by the black curve in Figure 10 (left). It was observed that below an AoA of -6° , the flow tends to separate from the pressure side of the wing. Because this separation must be avoided to ensure nominal performance, -6° was established as the lower operational limit for the F15LS mod.

While the free-field configuration simulated an infinite-span wing via periodic boundary conditions, a high-lift wing measured in the AWB will encounter a wind tunnel jet flow deflection as a reaction to the lift force generated by the wing. Consequently, it is necessary to determine how to incorporate these wind tunnel jet deflection effects into a simplified, free-field computational framework.

To account for the wind tunnel jet deflection, a correction method based on the Method of Images—originating from potential flow theory—was applied (see Figure 10 (right)). For the numerical simulations, this concept was implemented by introducing a few modifications to the baseline free-field (infinite wing) configuration discussed in Section 4. The specific modifications were as follows:

- The domain height was adjusted to match the physical AWB nozzle height of 1.2 m.
- While the standard free-field configuration utilizes periodicity solely in the spanwise direction to simulate an infinite wing (analogous to a isolated model singularity), periodic boundary conditions were additionally enforced at the top and bottom domain boundaries to replicate the infinite array of image singularities.

The primary limitation of this simplified framework is that it neglects the localized shear-layer deformation at the boundaries of the open jet, which physically occurs due to the presence of the F15LS mod as an aerodynamic obstacle. However, this approach effectively provides a computationally efficient estimate of the jet deflection effect on the wing's surface forces, specifically the lift coefficient (C_L).

Once the lift force was generated, a distinct flow deflection onset was observed. This jet deflection was quantified to be approximately 8° – 9° based on the streamlines visualized in Figure 11. The red curve in Figure 10 (left) displays the resulting lift polar for the F15LS mod with the wind tunnel nozzle flow deflection effects incorporated. A substantial reduction in the slope of the lift curve is observed in comparison to the baseline free-field lift polar (black curve; see Figure 10 (left)).

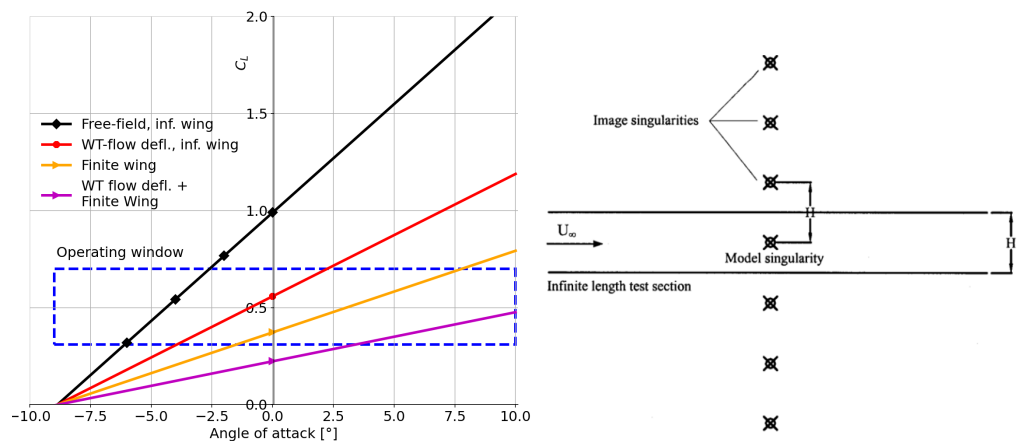


Figure 10. (Left) Lift polars, AoA vs. Lift (C_L), (Right) Concept for method of images [5].

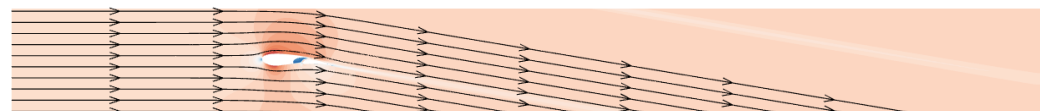


Figure 11. Time-averaged velocity magnitude contour, wind tunnel jet flow deflection simulation.

The wind tunnel configuration introduces an additional aerodynamic effect resulting from the finite wing span, which induces tip-vortex rollup at the lateral edges of the wing. This phenomenon causes a further reduction in lift generation at a given AoA. Utilizing analytical handbook formulations, the modified lift curve slope (orange color) accounting for this finite wing effect was computed from the baseline free-field polar (black curve). The total estimated lift polar for the wind tunnel scenario, derived via the free-field computational framework, is obtained by combining the inverse slopes of both the nozzle jet deflection and the finite wing effects (see the purple curve in Figure 10 (left)). Based on this combined correction, the operational AoA range was determined to be from $+3^\circ$ to $+15^\circ$.

6. F15LS Mod–Full 3-D Wind Tunnel Setup

As a final step in the numerical design study, 3-D wind tunnel simulations of the F15LS mod under full installation conditions were conducted to confirm the performance of the modified aerodynamic layout across the targeted angle of attack (AoA) range; this

served as a numerical proof of concept. The simulation resolved the full spanwise extent (2.1 m) of the model alongside the wind tunnel nozzle, explicitly accounting for the open jet free shear layers and the resulting jet deflection. The AoA for these installation simulations was set to 0° with a nozzle exit velocity of $U_\infty = 40$ m/s. Additionally, boundary layer fences were designed pre-experimentally to shield the wing from the nozzle shear layers (see Figure 12 (left)).

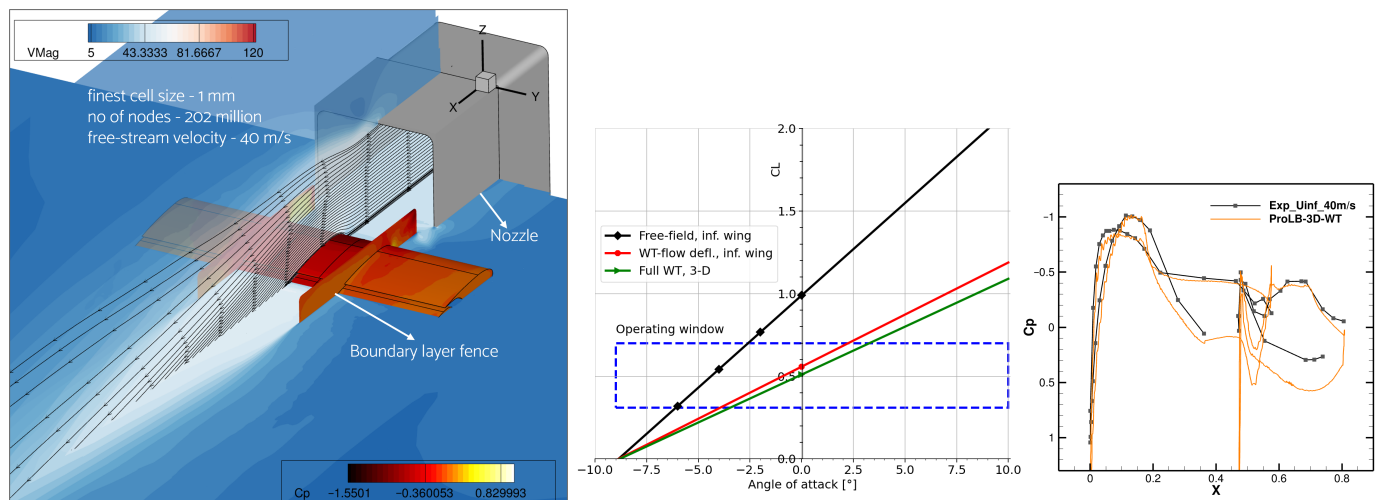


Figure 12. (Left) Outcome of a full 3D wind tunnel arrangement represented with velocity contours, streamlines and numerical settings, (Centre) Full WT 3-D Lift polar AoA vs. C_L , (Right) C_p distribution comparison between pre-test 3-D WT simulation and a posteriori measurements.

The contours depicted in Figure 12 (left) illustrate the results of the final wind tunnel configuration incorporating the boundary layer fences alongside the previously optimized design parameters. The jet deflection measured from the streamlines is approximately 8° – 9° , aligning closely with the values obtained from the simplified open-jet wind tunnel deflection simulations. Figure 12 (center) demonstrates that in the full installation simulation, the jet deflection effect exerts a dominant influence on the resulting lift curve slope, whereas the finite wing effect plays a negligible role. Based on these full installation results (green curve), the final operational window for the F15LS mod was established to be from -3° to $+3^\circ$.

Figure 12 (right) compares the pre-experimental numerical C_p distribution with the *a posteriori* experimentally measured C_p . Based on Figure 12 (right), the following aerodynamic characteristics are consistently observed in both the numerical predictions and experimental data: moderate suction peaks at the leading edge of the main element (indicating controlled lift levels) and fully attached flow on the pressure side of the main element, which guarantees the targeted loading on the flap. While preliminary, this comparison successfully demonstrates that the modified aerodynamic layout exhibits the exact physical behavior in the physical wind tunnel tests as predicted by the pre-test simulations.

The minor deviations observed on the pressure side of the main element and the flap are driven primarily by the mesh resolution constraints of the simulation. This proof-of-concept simulation served as a blind prediction to ensure the structural and aerodynamic viability of the F15LS mod prior to the physical measurement campaign.

7. Conclusions & Outlook

Three-dimensional, wall-modeled Large Eddy Simulations utilizing the Lattice Boltzmann Method (3-D WM-LES LBM) were carried out using ProLB to support the design of the flap cover seal experiment. Based on the prerequisites derived from these numerical

simulations and prior experiences, a new leading-edge nose for the F15LS mod high-lift wing was designed. Additionally, a new, computationally efficient approach to incorporate the effects of open-jet wind tunnel flow deflection onto the wing surface within a free-field framework was introduced, and its efficacy was verified against a full 3-D wind tunnel installation pre-test simulation. The newly optimized nose of the F15LS-mod wing was subsequently manufactured for the experimental measurement campaign.

The primary aerodynamic characteristics observed during the wind tunnel testing confirmed the pre-test numerical evaluation of critical performance metrics, including the required operational angle of attack envelope, proper aerodynamic loading of the flap, and the induced flow deflection. These results serve as a testament to the capability of WM-LES LBM framework to deliver accurate and reliable data for complex, highly unsteady aerodynamic flows.

As an outlook, future work will involve a systematic *a posteriori* validation of the ProLB results against the experimental database, accounting for the slightly modified flap settings that were ultimately selected and implemented during the physical measurement campaign.

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