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KRUEGER FLAP NOISE MITIGATION ON A SEMI-SPAN AIRCRAFT MODEL

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ABSTRACT

During the aircraft approach and landing phase, airframe noise is a predominant concern, with leading edge high-lift devices being a major contributor. Traditionally, classical slats are employed for this purpose. However, an alternative solution is the Krueger leading edge flap, a prerequisite for laminar wing technology - a promising innovation to enhance aircraft efficiency and reduce emissions. This device was experimentally investigated in the Airbus-led German INTONE project. Specifically designed for a 3D wing, it was tested in DNW's low-speed wind tunnel acoustic test section in Braunschweig.

The present study focuses on simulating flow and noise for two experimental configurations, aiming to validate these simulations against measurement data. Two high-lift designs are examined:

1. A conventional slat, and
2. A Krueger flap selected for its acoustic benefit.

Unsteady flow simulations around the 3D wing model utilize the lattice-Boltzmann method. Acoustic time pressure signals are derived from both direct flow simulation noise and Ffowcs-Williams and Hawkings surface integration. Favorable comparisons are observed between simulated results and experimental data, including static pressure measurements on the wing model and far-field microphone recordings.

Keywords: *Krueger flap noise, airframe noise, Lattice-Boltzmann method, CFD validation*

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1. INTRODUCTION

During the aircraft approach and landing phase, airframe noise is a predominant concern, with leading edge high-lift devices being a major contributor. Traditionally, classical slats are employed for this purpose. However, an alternative solution is the Krueger leading edge flap, a prerequisite for laminar wing technology - a promising innovation to enhance aircraft efficiency and reduce emissions. This device was experimentally investigated in the Airbus-led German INTONE project. Specifically designed for a 3D wing, it was tested in DNW's low-speed wind tunnel acoustic test section in Braunschweig. More details about the experimental set-up and analyses of measurements can be found in Ref. [1].

Numerical noise prediction for complex models, such as a semi-span aircraft with deployed high-lift systems, poses significant computational challenges. Within the INVENTOR project framework [2], Chalmers University of Technology and ONERA collaborated to explore suitable computational strategies. In this project, for saving the computational resources, a specific approach was to restrict the acoustic computations on a limited wing span where a dedicated mesh refinement is applied. Chalmers simulation results have been reported by Li *et al.* in Ref. [3]. The present work is a continuation of ONERA's computational strategies exploration on this configuration. Based on past experience, the mesh design has been improved in order to compute acoustics on the whole wing while maintaining a reasonable computational cost.

The present paper deals with the validation of simulation against measurement data for two selected experimental configurations, namely:

1. A conventional slat, named 'SLAT', and
2. A Krueger flap, selected for its acoustic benefit, named 'K19t'.

The paper is organized into two parts: simulation methods and setup (§2), followed by a comparison of numerical and experimental results, covering both aerodynamic and acoustic aspects (§3).

2. SIMULATIONS METHODS AND SET-UP

2.1 CFD approach

The flow simulation is achieved with the lattice-Boltzmann method (LBM) implemented in the ProLB solver [4]. A D3Q19 lattice is used to compute the distribution functions. As for the collision model, a Hybrid Recursive Regularized approach is used [5]. It includes some corrections to cancel high order (M^3) terms leading to a more robust code under M=0.7, while remaining athermal. As for the turbulence, a shear-improved Smagorinsky model [6] is used here. Solid surfaces are defined by means of immersed boundary conditions and the fluid boundary layer is resolved thanks to an advanced wall log-law which takes into account adverse pressure gradient [7] and curvature effects. A direct coupling approach is used to drastically reduce the spurious noise generated at grid borders where the resolution changes since the present LBM method makes use of octree grids [8].

2.2 Numerical set-up for LBM

The flow simulation aims reproducing the main features of the experimental set-up (Figure 1) and includes some simplifications. The peniche and the slat and Krueger flap tracks are not taken into account. The numerical set-up is identical between the two high-lift configurations, i.e. SLAT and K19t. Only the semi-span aircraft skin and its first wall layers of cells are consequently modified from one simulation to the other.

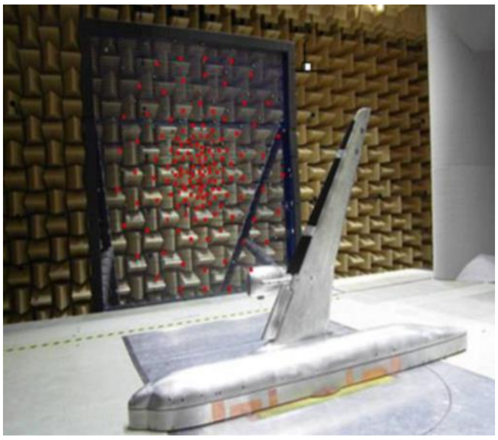

Figure 1. 3DFNGY model mounted in the ¾ open test section of DNW-NWB.

The fluid simulation domain is made of four different boundary conditions:

- a velocity condition at the inlet including the incidence angle
- a wall condition associated to a wall law on the semi-span aircraft skin
- a frictionless condition on the floor
- a pressure condition on all other walls including outlet

Absorbing layers are located in the far-field in order to damp waves and avoid their reflection in the fluid domain.
The minimum and maximum cell sizes are 60 µm and 61.44 mm respectively. Meshes are roughly composed of 1050 millions nodes which approximately corresponds to 350 millions equivalent fine nodes. The minimum time step is 1.00346E-7 s and the simulated physical time length is about 105 ms. The transient time before the convergence of the model forces is about 50 ms leading to about 55 ms of relevant time signal. An insight of the flow structure on the SLAT configuration is shown in Figure 2.

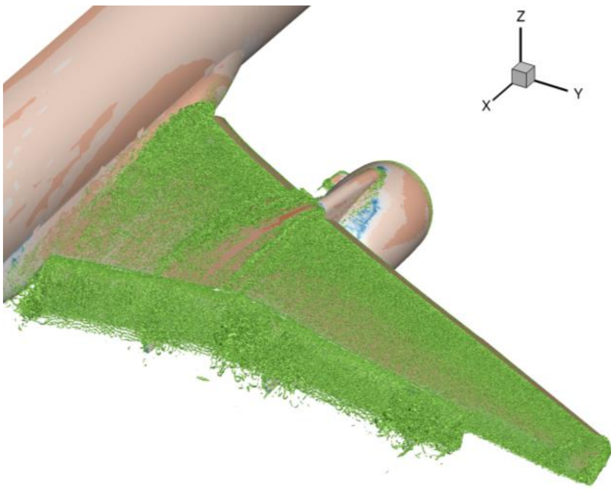

Figure 2. Instantaneous 3-D view of SLAT configuration flow with the iso-surface of *Q=5E7* criterion. Aircraft skin is colored with the friction coefficient.

Figure 3 compares the wall pressure coefficient distribution on the suction side of the wing between the SLAT and K19t configurations. The leading edge device induce a local modification of the pressure distribution. For instance, a higher suction peak is observed on the midboard and outboard part of the wing for the K19t configuration whereas a higher suction peak is observed in the inboard part of the wing for the SLAT configuration. On the opposite, the global pattern of the pressure distribution is very similar between both configurations.

2.3 CAA approach

A Ffowcs-Williams and Hawkings (FW-H) integration on the aircraft skin computes the far-field acoustic pressure time signal. For this purpose, wall pressure is collected at a sampling frequency of 311424 Hz during the last 50 ms of physical time. The fuselage part – whose CFD resolution is low – is excluded from the FW-H integration. The spectra analysis relies on the Welch method with 50% overlapping and a Hanning window.

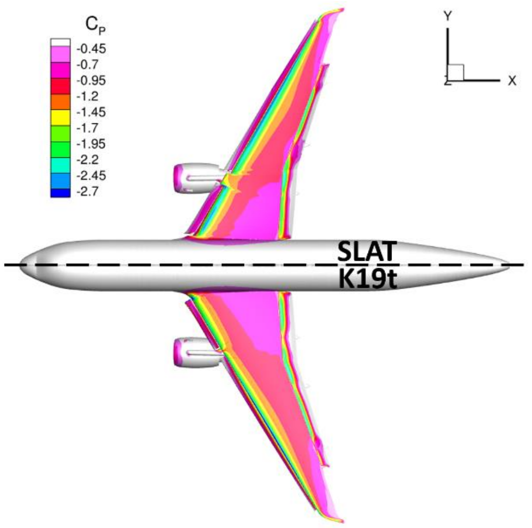

Figure 3. Comparison of the average wall pressure coefficient distribution on suction side between SLAT (top) and K19t (bottom) configurations.

3. NUMERICAL SIMULATION VALIDATION AGAINST MEASUREMENTS

3.1 Aerodynamic validation

The 3DFNGY model has been equipped with pressure static probes during the wind tunnel test. The numerical pressure distribution globally shows a favorable comparison with the measurements. For instance, Figure 4 shows this comparison for the SLAT configuration.

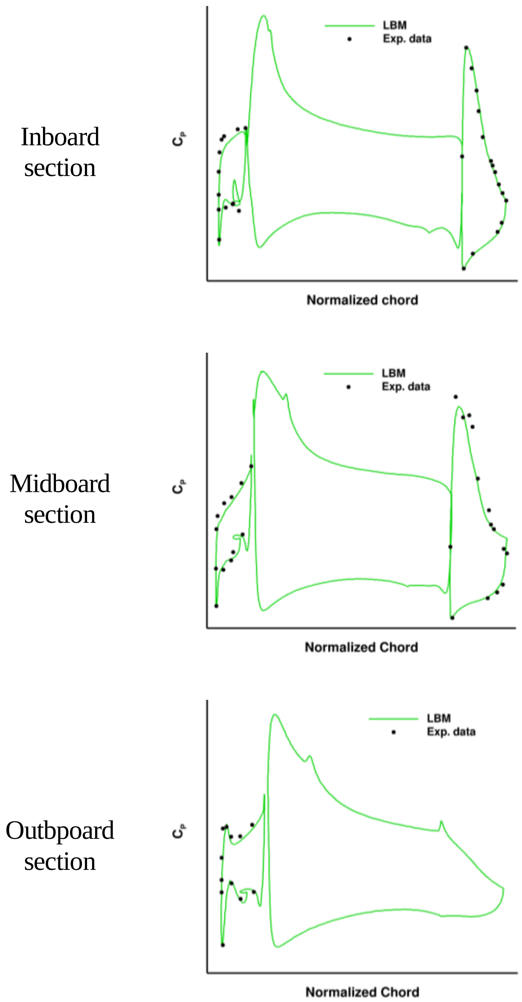

Figure 4. Static pressure comparison between measurements and LBM simulations on the SLAT configuration.

3.2 Acoustic validation

Figure 6 focuses on the Sound Pressure Levels (SPLs) of the central microphone of the acoustic array (see background of Figure 1). The experimental spectra are obtained after post processing of the acoustic array. A conventional beamforming technique is applied to the pressure time signals of the array microphones. Then the area around the wing is integrated from the resulting noise map to perform a backward noise propagation up to the central microphone of the array. The following experimental spectra are computed from this last backward propagation, aiming to a fair comparison with the numerical simulations by separating the noise sources of the model from any other spurious noise sources. LBM spectra are obtained after FW-H computation as described in §2.3.

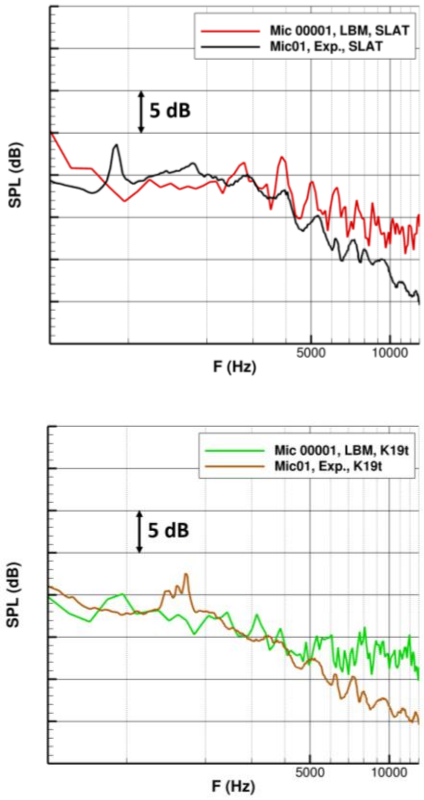

Figure 5. Sound Pressure Levels comparison between simulations and measurements. Top: SLAT configuration; bottom: K19t configuration.

LBM results shows a favorable comparison with the experimental results. Levels are in good agreement from 500 Hz to 5 kHz whereas LBM SPLs increasingly overestimate the noise levels as frequency increases above 5 kHz. In the SLAT configuration, the LBM spectrum reproduces the arch pattern remarkably well from 3 kHz to 8 kHz. Finally, Figure 6 compares the noise reduction provided by the Krueger flap with respect to the reference slat. The LBM results well retrieve the noise benefit observed during the wind tunnel tests. Indeed, from 1kHz to 3kHz, the noise reduction (computed or measured) roughly raises from 0-2 dB to 4.5-6 dB. Then, above 3 kHz, both noise reduction patterns show similar arches. In this frequency range (3-8 kHz), the experimental noise reduction varies between 2 dB and 4 dB. Numerically, because of the lower statistics of shorter time signals, the ΔSPLs varies more, i.e. between -5 dB and 1.5 dB. Nonetheless, a gross smoothing among these frequencies should highlight a similar noise reduction with a slight increase by about 1 dB.

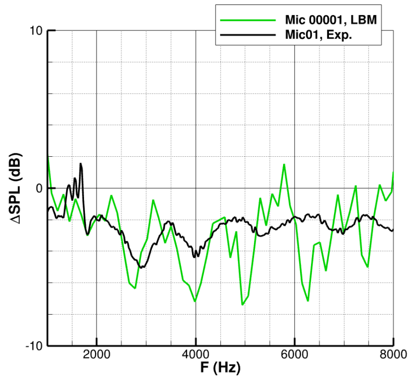

Figure 6. Sound Pressure Levels discrepancies between K19t and SLAT configurations.

4. CONCLUSION

Lattice-Boltzmann Method (LBM) simulations successfully replicated unsteady flow and noise sources for a semi-span aircraft model equipped with either a classical slat or a Krueger flap with acoustic benefit. The results showed good agreement with measured static wall pressures on the wing and far-field Sound Pressure Levels on the acoustic array. In particular, the noise benefit brought by the Krueger flap is well retrieved between 1 kHz and 8 kHz. However, high-frequency overestimation in LBM SPLs suggests potential spurious noise sources or weaknesses in the computational setup. Future work will focus on improving the simulation setup.

5. ACKNOWLEDGMENTS

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