Prospects of Low-Noise-By-Design Approach for Airframe Components using the Lattice Boltzmann Method

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Introduction

Direct Noise Computation (DNC) of high-lift wing sections using the wall-modeled LES (WM-LES) Lattice Boltzmann Method (LBM) is the focus of this work. Simulations were carried out with LBM solver ProLB [1]. When considering high-lift device noise, slat track's have been identified as the catalyst in exaggerating the slat noise and eventually the overall HLD noise. Slat track is a protruding structural element of the mechanism responsible for deploying and retracting the slat. In this work, starting from the baseline DLR-F16 unswept high-lift wing section, individual effects of subsequent addition of sweep and slat track was studied. Slat track investigated in this study was used in several other projects at DLR. Outcome of adding sweep to the baseline DLR-F16 was a reduction in the absolute noise levels over the entire resolved frequency range (up to 11 kHz) and a reduction in the maximum noise level. This can be attributed to the fact that both baseline and swept arrangements will see a different normal velocity component. Addition of slat track increases the absolute nose levels by +5 dB over the entire frequency range.

As a part of the European Union project INVENTOR, novel Noise Reduction Technologies (NRT's) were investigated for the slat track noise. Active NRT - in the form of an air-curtain and passive NRT - in the form of a porous glove around the track were realized. Effectiveness of each of these NRT's will be discussed in the later sections of the paper in terms of both flow and acoustic response. This paper summarizes the results published in [5].

This paper is organized as follows: i) description of ProLB solver ii) Test-case description and numerical settings iii) Results of the NRT's applied iv) Conclusion and Outlook

Lattice Boltzmann Solver - ProLB

ProLB [1] is an industrial and research LB solver that is developed within a scientific collaboration including CS GROUP, Renault, Airbus, Ecole Centrale de Lyon, Aix-Marseille University and in special partnership with CERFACS. It is a node based solver that deploys a D3Q19 lattice. Details about the collision scheme along with the conceptual details about how wall modelling in LBM differs in comparison to the continuum based solvers is discussed in Soni *et al.* [6].

Test case description

DLR-F16 unswept high-lift wing cross-section is shown in figure 1. This was used as a baseline case for this study. Experimental database for the DLR-F16 has been published ed in the Benchmark for Airframe Noise Computation (BANC-category6) workshop [2]. It has a clean chord length (c) of 0.3 m and an unswept span of 0.8 m (in the wind-tunnel).

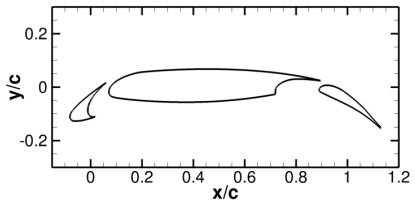

Figure 1: DLR-F16 high-lift wing c/s.

Figure 2 shows a comparison between the slat track on DLR-A320 aircraft, 2a), and the slat track chosen for the numerical simulations, 2b). When the slat is deployed, as shown in figure 2a), an opening on the leading edge of the wing is visible - referred to as cut-out- which is a prominent noise source and at the other end of the track a door panel is attached to the slat-cusp, purpose of which is to seal the cut-out. For the track investigated the cut-out is sealed, with a plate see figure 2b), as it is a prominent noise source and the door panel is also neglected.

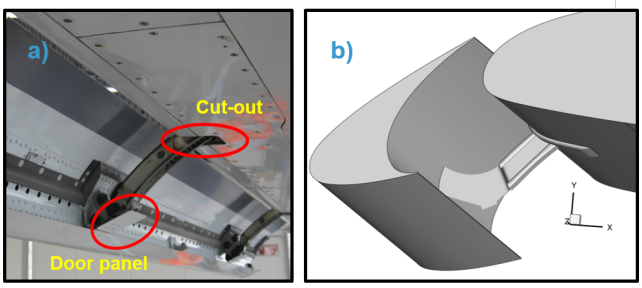

Figure 2: DLR-A320 "D-ATRA" slat track vs. simulated slat track.

Simulation strategy and numerical settings

Computational domain chosen was a square box of dimension 30c x 30c. Sponge zones are a part of these dimensions i.e. 3c. Velocity inlet and pressure outlet b.c's were enforced in far-field. Wall model b.c. was applied on the high-lift wing section. LES slice of a limited spanwise extent i.e. 20%c is realized using the periodic boundaries. In this study we did not introduce a geometrical sweep but instead the velocity vectors are rotated, see top view in figure 3, for the unswept wing section arranged at a angle of attack i.e. 6.15°. Sweep angle realized was $\phi = 30°$. The computations were carried out for free-field uniform flow conditions with U_∞= 61.53 m/s, shown with black arrow. Speed of sound a_0=343.20 m/s, and the

Reynolds number of 1.23 million with Mach number of 0.18 was used. Numerical settings used are specified in the Table 1.

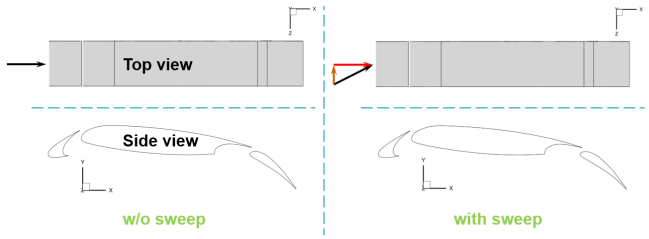

Figure 3: Introduction of sweep.

Parameter	Value
Finest grid size, Δ_f [m]	1.25e-04
Time step, [s]	2.1e-07
Total time, [s]	0.31
Refinement levels	9
No. of grid points	88 million

Table 1: Numerical settings.

Effect of slat track

Presence of track in the slat cove results in the following changes in flow: velocity magnitude increase near the slat trailing edge and an increased turbulent kinetic energy (TKE) in the slat gap region. Upon comparing its acoustic response with the clean slat configuration, an absolute noise level increase of +5 dB over the entire resolved frequency range was observed, for details see Soni *et al.* [5].

Active noise reduction technology: Concept and variants

As mentioned in the previous section, presence of a slat track in the slat cove increases the overall HLD noise. In an attempt to mitigate the noise introduced by the track, we have investigated an active noise reduction measure which creates an air-curtain around the track by steadily blowing bleed air from the track. Idea here is to avoid the direct contact of the oncoming cross-flow with the track. To achieve that, it is thought upon to locally create a stagnation point i.e. in-front of the track by steadily blowing air opposite to the oncoming cross-flow. This will force the cross-flow to go around the track resulting in generation of an air-curtain around the track. Looking at the Y-Z plane from behind, see figure 4a), the flow developed around the track with steady blowing can be seen in figure 4b).

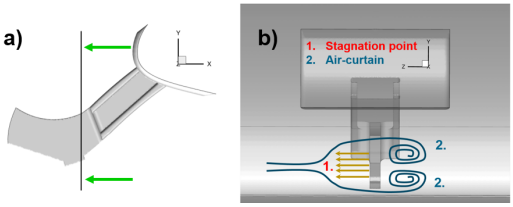

Figure 4: Air-curtain concept using steady blowing.

In this work, we have investigated two different blowing strategies: streamwise (X-axis)- and spanwise (Z-axis) flow direction. For the streamwise concept, the air is steadily blown along the +ve X-axis i.e. parallel to the track. Steady flow of air opposing the incoming cross-flow, along +ve Z-axis, is realized for the spanwise blowing concept, see figure 5b) & c). While investigating such active noise reduction strategies, additional efforts have to be applied to avoid any additional flow acceleration in the slat gap. To realize a steady air blowing in ProLB, a flow rate b.c. was used. Based on some very preliminary tests in the DLR-AWB open jet tunnel, a flow speed of 60 m/s was chosen for steady blowing.

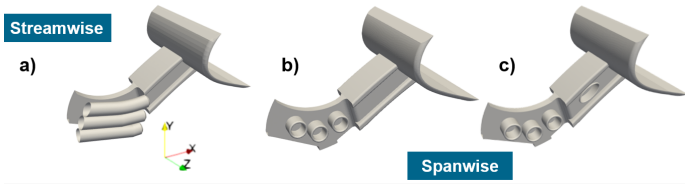

Figure 5: Streamwise and spanwise blowing variants.

Streamwise blowing

Initial attempt at creating an air-curtain was to blow along the streamwise (X-axis) direction and create a stagnation point, for the oncoming cross-flow, in front of the I-shaped track region. This will result in the faster oncoming flow to either slow down or go around the track i.e. the direct contact with the fast oncoming flow is avoided. Figure 5a) shows the arrangement of three nozzles protruding from the slat cove and placed alongside the track with a purpose of creating air-curtain. Other aspect of such an arrangement was to shield a portion of the track attached to the slat from oncoming cross flow. At each nozzle, a flow rate b.c. was applied in ProLB. Specific mass flow rate of 73.5 kg/s/m2, based on the velocity of 60 m/s with the flow direction defined as normal to the nozzle exit plane.

To assess the effectiveness of streamwise blowing, based on the initial hypothesis that a flow stagnation point will be created in front of the track, streamlines are used to depict how the flow coming out of each nozzle evolves. Figure 6 shows the streamlines colored with the velocity magnitude for each nozzle. Since the oncoming cross-flow is very fast, the streamwise directed flow is forced to go along with the cross-flow and hence rendering creation of air-curtain using streamwise blowing strategy to be difficult. Physics based corrections are applied on the

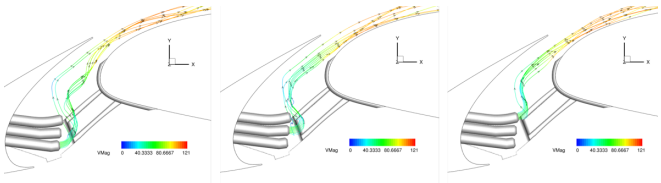

Figure 6: Streamlines colored with velocity magnitude.

resolved pressure spectra shown in this paper to account for: first - the full 3-D propagation in far-field, second - for the wind tunnel span i.e. 0.8m for DLR-AWB, third - to remove the "cut-on" type of jumps in the spectra introduced by periodicity. Refer to Soni *et al.* [3] [4] for the details on physics based corrections. F16 w/o and w

streamwise blowing is sketched in figure 7. Subtle gains - in terms of the reduced noise levels - along with the loss - increase in the noise levels - are observed over some frequencies. The maximum noise level is slightly increased for the blowing case i.e. at 4 kHz compare to the w/o blowing case. Increasing the flow velocity coming out of the nozzle, one can still attempt to realize the air-curtain. But it is highly likely that the self-noise of nozzle's might also come into play.

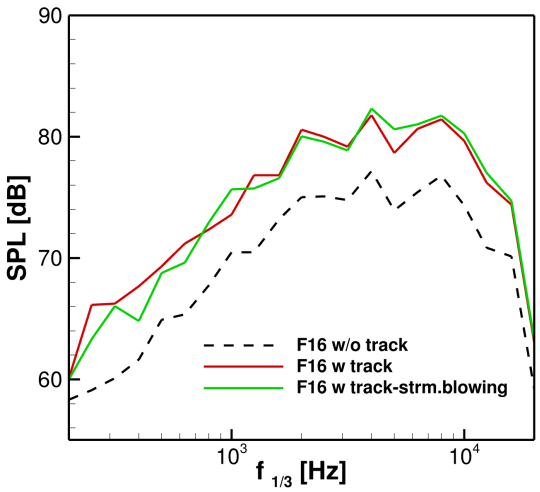

Figure 7: DLR-F16 without and with streamwise blowing, 1/3-octave band.

Spanwise blowing

Since the cross-flow carries a lot more momentum it renders the idea of creating air-curtain by streamwise blowing difficult. Next attempt was to use spanwise blowing direction (along +ve Z-axis) to create a stagnation point in front of the track & inside the recirculating bubble. Three nozzles are arranged on the portion of the track which will be exposed mostly to the re-circulating cove flow. Figure 5b) shows the spanwise steady blowing arrangement. At each nozzle exit, a mass flow rate of $5.1\text{x}10^{-4}$ kg/s is defined with the nozzle diameter of $2.98\text{x}10^{-3}$ m and a flow velocity of 60 m/s. As an outcome of spanwise blowing, additional flow acceleration on the suction side of only the main element was observed for the spanwise blowing case, see Soni *et al.* [5].

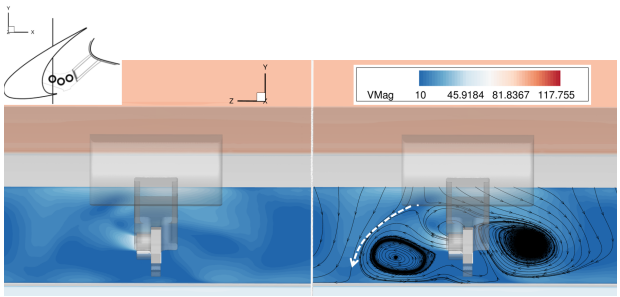

Figure 8: Velocity magnitude Y-Z plane, spanwise blowing.

Examining the effectiveness of this noise reduction measure, starting from figure 8 which shows shows the velocity magnitude contour in Y-Z plane for nozzle1. Position of the local stagnation point in the flow is visualised with the streamlines (Y, Z velocity component). Stagnation point is deflected upwards and is not in the front of the nozzles, shown with white dotted line, thus partially creating an air-curtain around the track as seen by a recirculation region in the front and other behind the track. With spanwise blowing a partial creation of local stagnation point in the flow was only achieved.

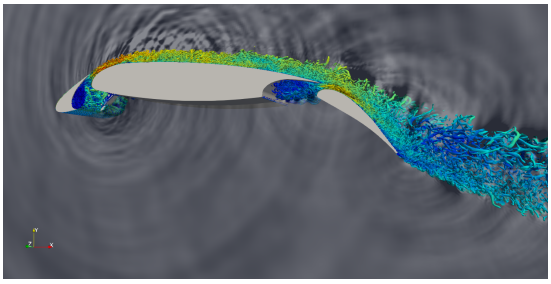

Figure 9: Iso-surfaces of Q-criterion colored with velocity magnitude and resolved sound pressure fluctuations.

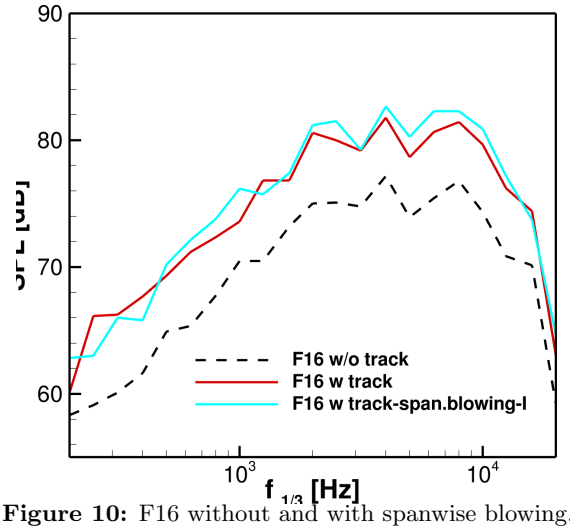

Figure 10: F16 without and with spanwise blowing.

Resolved unsteadiness in the complex flow that evolves around the F16 high-lift wing section with slat-track, spanwise blowing and the resolved sound pressure fluctuations in the far-field are shown in figure 9. Acoustic response of the spanwise blowing is depicted in the figure 10. Comparison of the 1/3-octave band pressure spectra between the w/o and w spanwise blowing reveal higher noise levels over several frequencies for the spanwise blowing case and also increased maximum noise level.

Passive noise reduction

In the previous sections attempts to create air-curtain by using the steady blowing and its effectiveness were discussed. Variations applied showed that trying to control the flow locally does have a partial success to reorient the flow, but the oncoming cross-flow carries a lot more velocity to push the stagnation point away from the nozzles and thus causing the measure to be less effective. Instead of trying to actively control the flow, we will showcase how a passive noise reduction measure fared in terms of reducing the overall high-lift noise when a track is present in the cove. Passive measure was realized in the form of a porous glove around the track, see figure 11.

Porous b.c. was applied on the glove in ProLB. For this

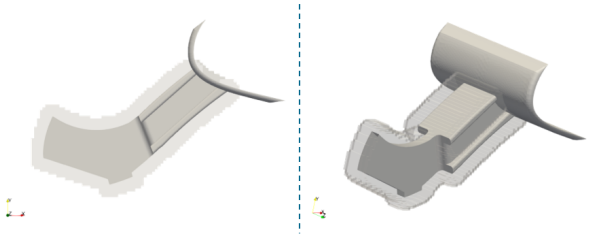

Figure 11: Porous glove around the slat track.

case, a homogenous porous material was realised using the viscous resistance (Rx = Ry = Rz=1490 (1/s)) based on the darcy constant k = 10^{-8} m^2. The glove had an equal offset of 2.5 mm from the surface of the slat-track in all directions.

On the discussion of effectiveness for this measure, a reduction in flow velocities in the vicinity of the track and near the slat trailing edge was observed. Also a significant reduction of TKE in the slat gap was a highlight. In terms of the acoustic response, figure 12 shows the comparison of the far-field acoustic pressure spectra between the F16 w/o and with porous b.c. applied . A reduction in the absolute noise levels over the entire frequency range from 2 - 6 dB is achieved with the use of porous material.

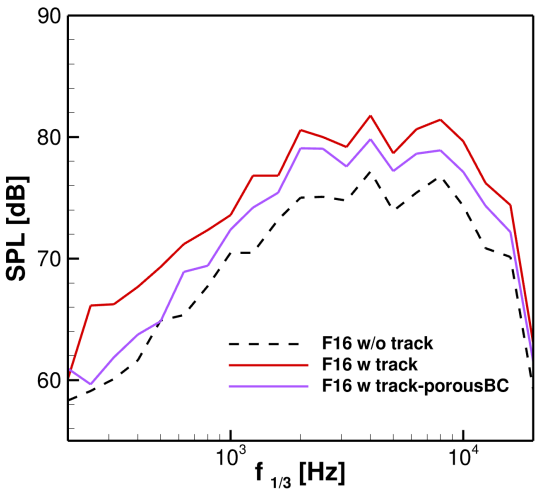

Figure 12: F16 without and with porous b.c..

Conclusions and Outlook

In this work the Direct Noise Computation (DNC) of high-lift wing sections with the WM-LES LBM approach was carried forward. In order to mitigate the noise increase introduced by slat track, we pursued both an active and a passive noise reduction measure. Using a steady blowing of bleed air it was attempted to generate an air-curtain around the track via creating a stagnation point in front of it. Two different steady blowing strategies were investigated: streamwise- and spanwise direction. Outcome of this investigation was a partial flow control in the vicinity of the track. As the track is exposed to the flow coming from multitude of directions, locally controlling flow on one side would result in the flow on other side to behave differently. This behaviour was often the increase of TKE in slat cove (spanwise blowing), gap flow velocity increase (streamwise blowing). Such local flow control measures have to be used with caution or it ends up easily increasing the overall high-lift noise. Important takeaways from the active noise control was: to apply such techniques to control the flow around the I-shaped region, such measures were rendered ineffective in the cove flow, and flow rate b.c. functioned robustly within ProLB.

Outcome of using a porous glove around the track was a reduction in the flow velocity around the track, a reduced TKE in the close vicinity of the track and also the slat gap. Result of such an abatement was an overall reduction in the absolute noise levels by 2-6 dB. This outcome serves as a proof of concept that porous material are an effective choice to reduce the noise associated with the track. In future, effective application of porous materials to reduce track noise will be worked upon.

Acknowledgments

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