Experimental study of noise generation due to flow through perforated plates

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Introduction

The current study aims on the investigation of fan noise due to boundary layer ingestion (BLI). It is part of a DLR internal project AGATA3S [1], which deals with a new aircraft concept based on embedding the engines in the fuselage, close to the vertical stabilizer, as shown in Fig. 1. With this approach, the boundary layer on the fuselage is sucked into the aero engines. Fig. 1 shows the flow velocity profiles on the fuselage, where red color stands for high flow velocity and dark blue for zero velocity. It is known that aero engines generate higher acoustic emissions depending on the inflow profile and turbulence impinging on the fan [2].

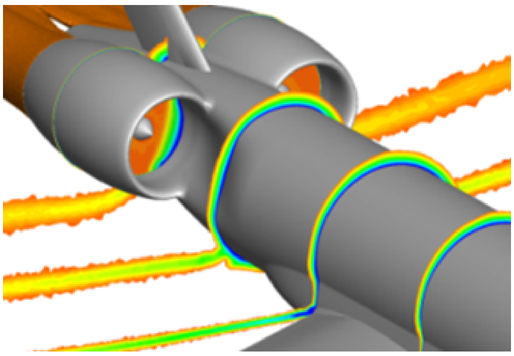


Figure 1: BLI due to embedding of aero engine. Extracted from Tapken [1].

For the experimental study, a representative inhomogeneous inflow profile had to be created. The approach was to insert perforated plates upstream in the flow [3]. Preliminary tests were conducted in a DLR fan test facility with such perforated plates and they reveled to be loud. However, the main question that arises is: does the sound generated at the perforated plate itself mask the fan noise generation? Indeed the used plates were designed to create a desired aerodynamic profile, but attention was not given to the their acoustic performance. If the perforated plates are noisier than the fan itself, it is not feasible to use such devices to create a BLI profile.

Therefore, this study investigates flow noise generation due to flow through perforated plates. The assessment was made in a compressor flow test facility, where flow velocities up to Mach number $M = 0.35$ can be reached, where the Mach number is the ratio of the flow velocity divided by the sound speed. In the following sections, the tested plates and the test facility are described. This is followed by a presentation of the acoustic results. The paper ends with a brief conclusion and an outlook on future work.

Test samples

Two types of plates were tested: "L" and "P" plates. "L" plates are standard stamped plates available off-the-shelf, "P" plates were custom made by high precision milling and are 9.8 mm thick, much thicker than the approximately 1 mm "L" plates. Table 1 lists the most relevant dimensions of each plate and Fig. 2 shows photographs of the plates. P2 has a complex geometry where half of it is made with square holes and half with round holes. The squares and round holes do not have constant size, nor the distance among them. For this reason, on Table 1 is shown an average number of the squares side length and the distance among each other, as well as the average hole diameter plus average spacing, respectively.

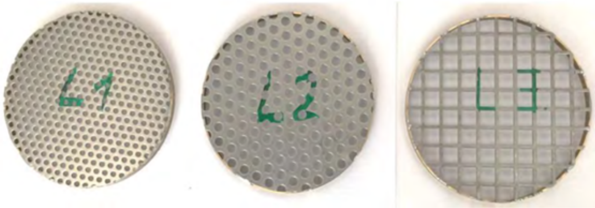
Table 1: Dimensions of the tested samples.

Name	Hole dist. (mm)	Hole diam. (mm)	Plate thick. (mm)	Open area (%)
L1	2.65	2.65	1.0	32.6
L2	2.80	4.65	1.2	35.3
L3	1.73	7.70	0.7	59.5
P1	1.0	9.15	9.8	60
P2	2.5/0.6	18/9.5	9.8	68.5
P3	1.4	8.65	9.8	55.4

Experimental setup

The high flow speed wind tunnel test facility used for the measurements is situated at the DLR department of engine acoustics in Berlin [4]. It has been used for tests with flow velocities up to around $M = 0.35$, without obstructions in the channel. The test rig, as shown in Fig. 3a, consists of a settling chamber supplied by a centrifugal compressor connected to a motor and a cylindrical test section. The settling chamber has screens and flow manipulators to reduce turbulence, connected to an approximately 2.3 meters long, 100 mm diameter duct. Plate samples under investigation are placed close to the first third of this length, as seen in Fig. 3a.

For acoustic measurements, two rings comprising 3 wall flush mounted microphones each are used. One

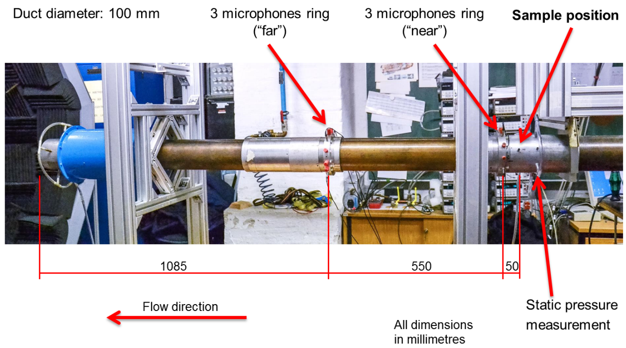


(a) In order left to the right: L1, L2 and L3

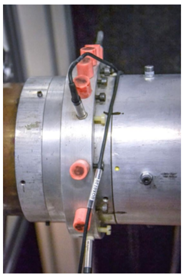
(b) In order left to the right: P1, P2 and P3

Figure 2: Plates tested in the current study.

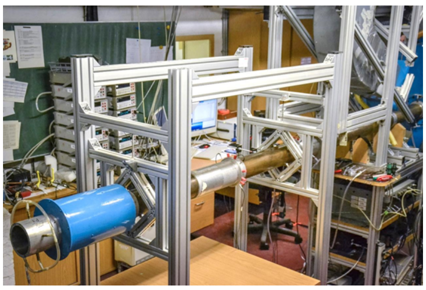
ring is approx. 50 mm downstream from the sample. The microphones in this ring are called "near" microphones. The other ring is set 0.6 m downstream of the sample and holds the "far" microphones. The long duct was used downstream the sample to avoid influences from the outlet jet on the measurements.



(a) Side view of the test setup.



(b) Microphone ring.



(c) Test bed overview.

Figure 3: "High flow speed wind tunnel" test facility.

Methodology

Tests were performed with all samples with Mach number ranging from 0.05 to 0.25 in 0.05 steps. Microphone data was acquired simultaneously with 100 kHz sampling frequency over 30 s. The power spectral density (PSD) was estimated for each microphone using Welch method, with Hanning window and 50% overlap. The PSDs of 3 microphones in one ring were averaged. Only the "near" ring microphones were used. The PSD plots are referred to 20 μPa.

Results

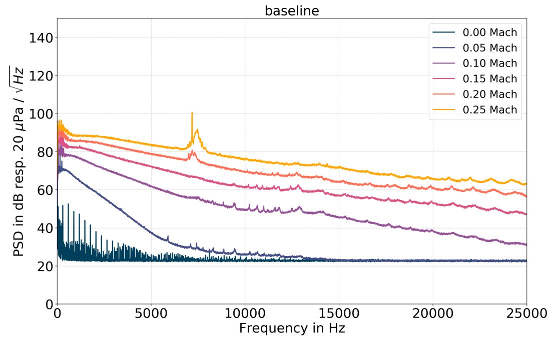


Figure 4: PSD levels for baseline, i.e., no plate inserted in the channel.

Power spectral density (PSD) of the microphones are presented in Fig. 4, for the baseline configuration, in Fig. 5 for "L" plates and in Fig. 6 for "P" plates. For plates L1 and L2 the maximum flow speed achieved was only $M = 0.15$. This is due to their high blockage area. The spectral shape is similar for all three "L" plates. Tones are excited for frequencies up to ≈ 7 kHz which is known to be cut-on related frequencies to the duct diameter of 100 mm. For mid and high frequencies, tones observed are likely due to noise generation on the plates itself. In Fig. 5 top, L1 spectrum showed a strong noise source for $M = 0.05$ for frequencies around 20 kHz. This might be due to some strong flow resonance and/or correlated to the holes size. This was not observed for the other plates and other flow velocities. It is also worth mentioning the strong tone for plate L1 at ≈ 7.5 kHz, which is higher than 140 dB.

"P" plates also showed similar performance for frequencies up to ≈ 5 kHz, when compared to "L" plates. However, the overall shapes of the spectrum differs. Especially for frequencies above 15 kHz, the spectrum does not have a negative slope anymore and sound pressure levels stay constant. On the other hand, many tones are observed for all "P" plates. For some plates spectral tone broadening occurs. A strong tone at $f \approx 5.5$ kHz for P1 and $f \approx 4.5$ kHz P3 with level of about 120 dB might be caused by flow resonance with respect to the hole diameter.

The top plot in Fig. 7 shows the integrated PSD as a function of Mach number. Another way to represent this result is by plotting the SPL versus the Mach number of the individual small jets, as shown on bottom plot. It was estimated from the free stream Mach number easily by $M_{JET} = M/OA$, where M is the

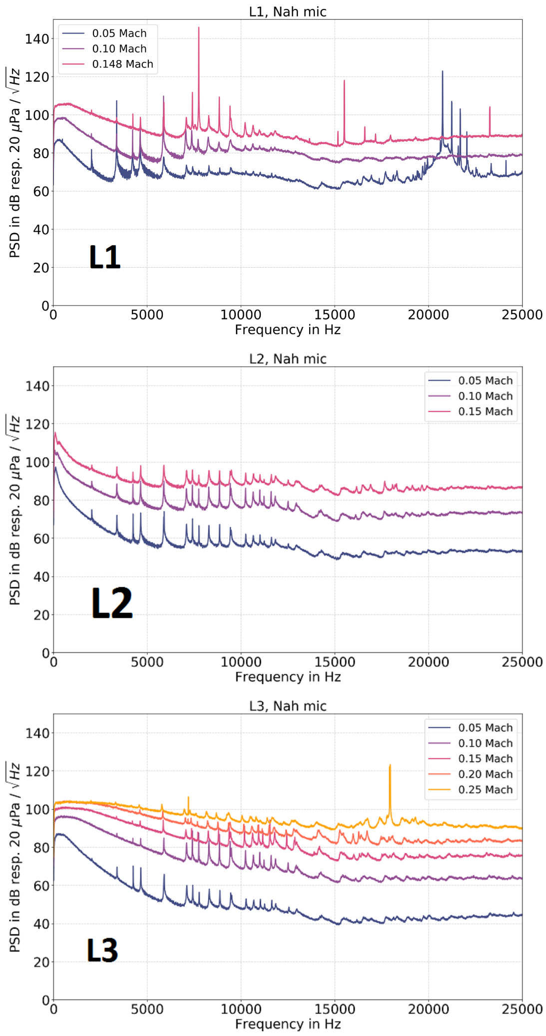


Figure 5: SPL levels of "L" plates.

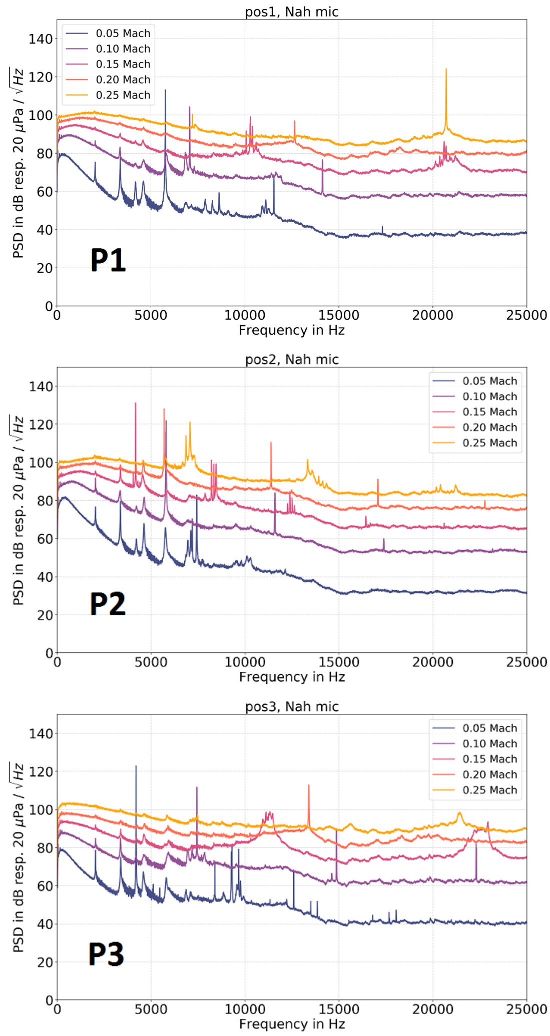


Figure 6: SPL levels of "P" plates.

free stream Mach number and OA is the test sample open area. In these plots however, one must have in mind that strong tones might mask the broadband noise, i.e., strong overall SPL does not necessarily mean the plate is in general worse than another one with lower overall SPL, because this might be due to only a single strong tone. It is possible to see the outstanding behavior of L1, which does not agree with any other plate. In fact, L3 and P2 have similar behavior which we suspect it is due to the square holes. On the other hand, for $M_{JET} > 0.15$, P1, P3 and L2 have all quite similar noise characteristics, as all spectra collapses, and therefore, noise mechanisms scaled to the jet flow velocity might be similar.

Special attention should be given to P2, as this plate has two different hole geometries (squares and circles) and varying sizes in order to simulate a boundary layer profile. For this reason, the PSD levels of P2 were plotted against the Strouhal number based on the trailing edge thickness. In this case, the average wall thickness of the square holes: $St = f \cdot d_{TE}/U_{JET}$, where f is the frequency in Hz, d_{TE} the trailing edge thickness and U_{JET} the aver-

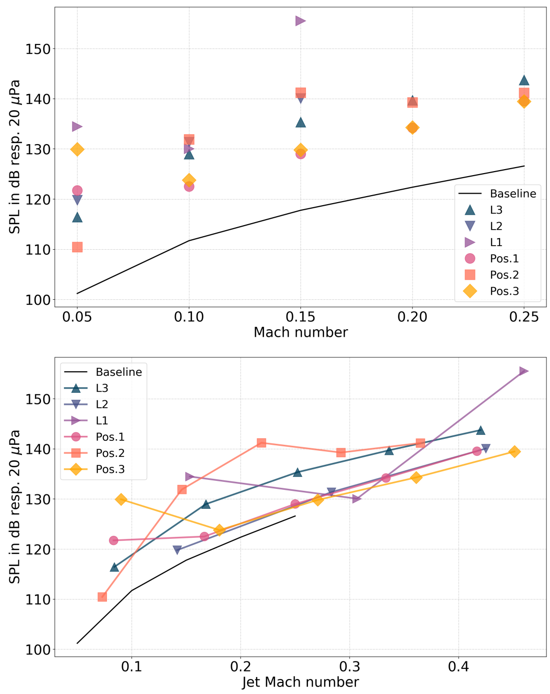


Figure 7: Overall SPL level vs Mach number (top plot) and average jet Mach number (bottom plot).

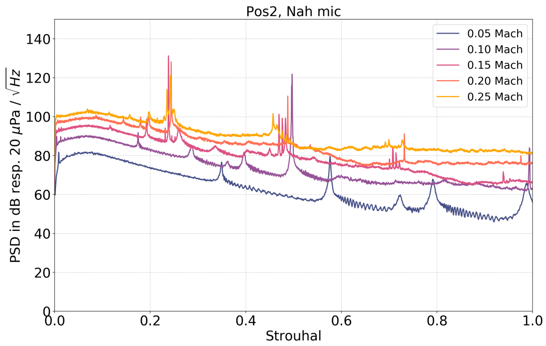


Figure 8: PSD levels for plate P2 versus Strouhal (Trailing edge thickness as reference).

age flow velocity of the individual jets. This result is shown in Fig. 8. There are several tones concentrated at St ≈ 0.25. According to Grosveld [6] this might be blunt trailing edge noise. In this case, blunt trailing edge means thick wall for the square holes which is followed by flow separation. This structure leads to shedding of coherent vortexes generating strong tones. In fact it is not straight forward to interpret these results and correlate to its geometry as this plate has a complex geometry, i.e., all holes have slightly different sizes and distance among them is also not constant.

Finally, Laffay [5] stated that a large number of small holes leads to lower overall SPL when compared to a small number of large holes, both with same open area (OA), and in the low to medium frequency band of the spectrum. Even though this is a good hint for our study, it is in fact difficult to trace this behavior, because none pair of plates have same OA allowing an easier comparison.

Conclusion and future work

Flow induced noise by perforated plates was assessed in this study. Attention was given for identifying the main noise source mechanisms of each plate. It was observed in this study, that square holes seems to perform, in average, worse, when compared to round holes with equivalent open area. This poor performance is also related to generation of tonal noise components. Plates L3 and P2, both with square holes, seem to have similar noise generation mechanisms when looking to their overall SPL noise versus jet Mach number (average flow velocity of the individual jets). On the other hand, the SPL plot versus Strouhal number based on the trailing edge thickness of plate P2 showed few tones concentrated at St ≈ 0.25. According to Grosveld [6] this might be due to blunt trailing edges, i.e., the thick sides the square holes causing vortex shedding. For plate P2, some tones are pure for low velocities and becomes broader for higher velocities. For both sources of noise: blunt trailing edge and jet noise, the flow characteristics in terms of laminar or turbulent is also playing an important rule.

For future work it is planned to search for guidelines (scaling laws, etc.) enabling low noise design. It is also necessary to conduct a more systematic experimental study because many parameters are changed among plates (OA, hole diameter, etc.). Due to the observed negative impact of laminar flow on the noise generation, it is planned to investigate the effect of a fine wire mesh placed just upstream of the perforated plates in order to change the inflow conditions. In terms of plate design, a next design improvement would be to round the leading-edges of the holes, especially for P2 (avoid sharp edges), reduce plate thickness (for the "P" plates) and use different holes pattern/distribution in order to reduce coherence, for example, using circles with different diameter or ellipses. We might also consider using porous materials (such as metal foams) instead of solid aluminium.

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