Experimental study of noise generation due to flow through perforated plates

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Introduction

The objective of a present project is the investigation of the impact of boundary layer ingestion (BLI) on the aerodynamics, aeroelasticity, structural mechanics and acoustics of the aero engine fan [1]. Currently, in the course of preparing tests at a large-scale fan test facility, a task consists in the specification of a means to emulate representative inlet flow fields. The BLI flow fields are derived from numerical simulations of an aircraft with the engines embedded in the rear fuselage (cp. Figure1). It is known from aerodynamic investigations that perforated plates with non-uniform hole distribution are suitable to create prescribed inhomogeneous flow profiles [2]. But, with regard to the assessment of the sound field created at the fan by the interaction with the BLI, the question is: Does the flow-induced noise of a perforated plate itself mask the fan acoustics?

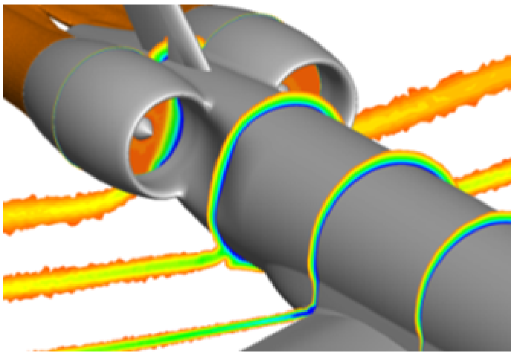


Figure 1: Boundary layer ingestion due to embedding of aero engine (CFD flow field visualization, extracted from Tapken [1]).

For a preliminary assessment the noise generation of six available plate samples was investigated in a high-speed flow duct. Three plates are cutouts chosen from a large perforated plate with non-uniform hole distribution, which recently was used in a compressor test campaign for creation of inhomogeneous inflow. They are compared against three plates with regular distribution of holes. In addition to the appraisal of the overall noise level and the tonal and broadband characteristics, attempts are made to identify dependencies on leading parameters.

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.

(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.

Test samples

The two sets of investigated plates are shown in Figure 2. The "L" plates are standard stamped plates available off-the-shelf. The "P" plates are cutouts of the large plate that was used in the compressor tests. The "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. 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.

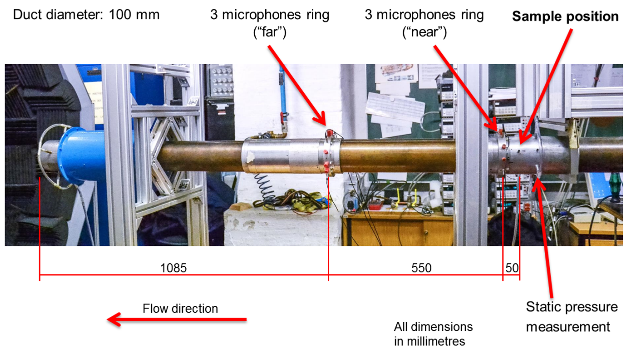
Table 1: Dimensions of the tested samples.

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

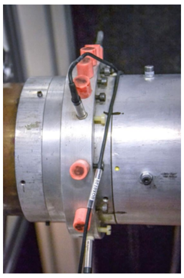
Experimental setup

The high flow speed wind tunnel test facility used for the measurements is situated at the DLR department of engine acoustics in Berlin [3]. The test rig 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. Outlet ducts with variable diameter can be installed. For the noise tests a duct of 100 mm diameter and approximately 2.3 meters length was connected. Without mountings inside the duct Mach numbers up to $M = 0.35$ can be adjusted. Plate samples under investigation are placed in the first third of the outlet, as seen in Fig. 3.

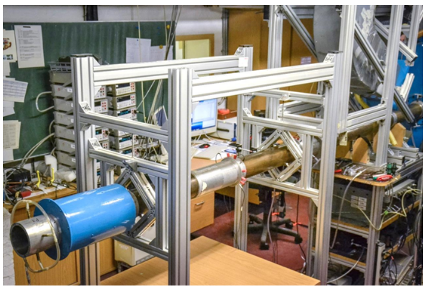
For the acoustic measurements, two rings each comprising 3 wall flush mounted 1/4" microphones each were used. One ring was approximately 50 mm downstream from the sample. The microphones in this ring close to the acoustic sources are called "near" microphones. The other ring is set 600 mm downstream 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. The impact of sound waves reflected at the outlet were reduced by a muffler.



(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.

Preliminary results

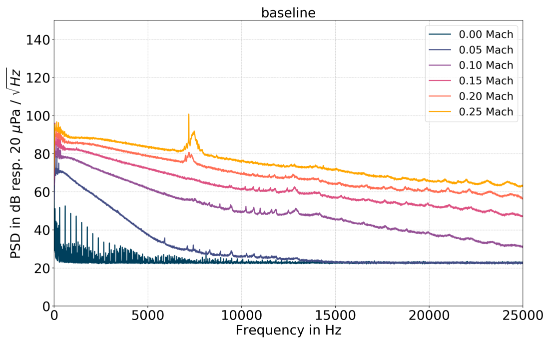


Figure 4: Average PSD spectrum measured by near microphone array for baseline case without plate.

Power spectral density (PSD) spectra averaged over all microphone signals of the near array 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 large blockage area. In the first glance the spectral shapes look similar for all three "L" plates. Tones are excited in the low to medium frequency range at frequencies related to the cut-on of duct modes. For mid and high frequencies, observed tones are likely due to sources independent of duct resonances. Striking is that the L1 plate shows much stronger multi-tone excitation at all measured flow velocities and a broad hump around 20 kHz for $M = 0.05$. At $M \approx 0.15$ the level of the strong tone near to 7.5 kHz even exceeds 140 dB.

Regarding the broadband noise generation at same incoming flow speed, plate L3 is in the order of 10 dB quieter in the mid and high frequency range than L1 and L2 due to the nearly double hole area and thus almost half jet speed. Comparing the broadband levels of plate L1 and L2 in the low frequency range at $M = 0.1$ and $M = 0.15$ one might find the trend that L1 is less noisy. This would be in line with investigations of Laffay et al [4], who in a systematic test series for perforated plates installed at duct exit found that a large number of small holes create less noise than small number of large holes (for constant overall open area). They relate their findings to two source regions, namely (i) multiple micro-jets formed by the individual holes causing primarily high frequency noise and (ii) a larger jet resulting as merger of the micro-jets and causing mainly low frequency noise.

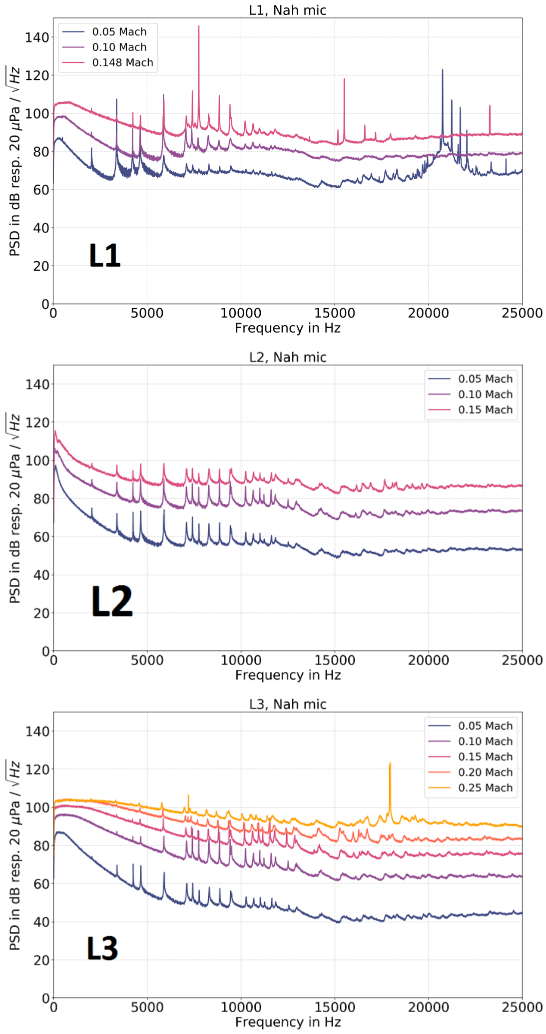


Figure 5: Average PSD spectra measured by near microphone array for “L” plates.

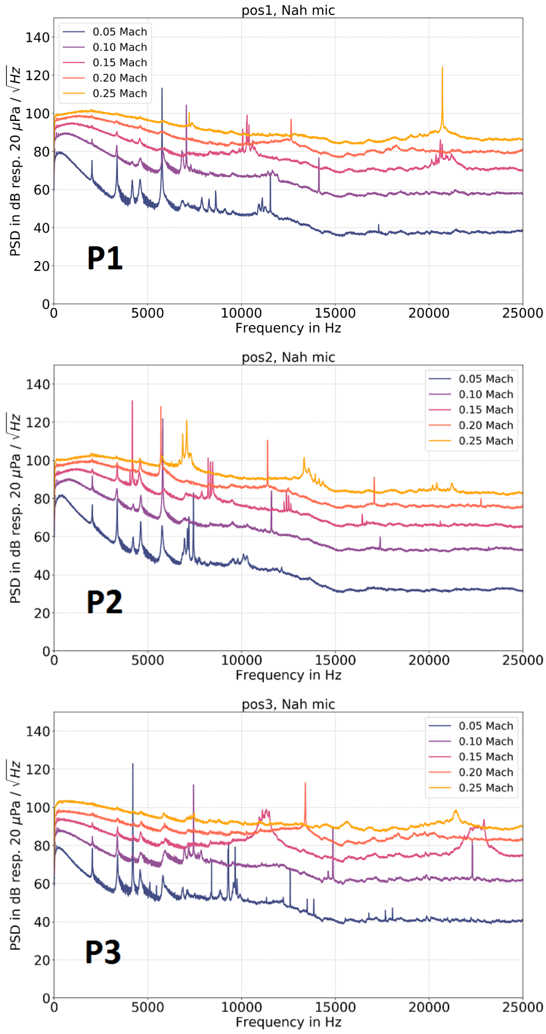


Figure 6: Average PSD spectra measured by near microphone array for “P” plates.

The “P” plates show similar performance for frequencies up to approximately 5 kHz, when compared to “L” plates. However, the spectral shapes above 5 kHz differ significantly. In all cases individual strong tonal components appear, some in the order of 120 dB. Further, humps can be observed with shape and center frequency varying with Mach number partly in a systematic way.

In order to reveal potential dependencies on characteristic parameters a Strouhal number analysis was implemented. Special attention is given to plate P2, since the border of the square holes feature pronounced bars that might be associated with blunt trailing edge noise, as e.g. was described by Grosveld [5]. Thus the Strouhal number is calculated as $St = f \cdot d_{TE}/U_{JET}$, where f is the frequency in Hz, d_{TE} the trailing edge thickness and U_{JET} the average flow velocity of the individual jets. The resulting Strouhal diagram is shown in Fig. 7. There are several strong tones concentrated at St ≈ 0.25. According to Grosveld they might be associated with shedding of coherent vortexes originating

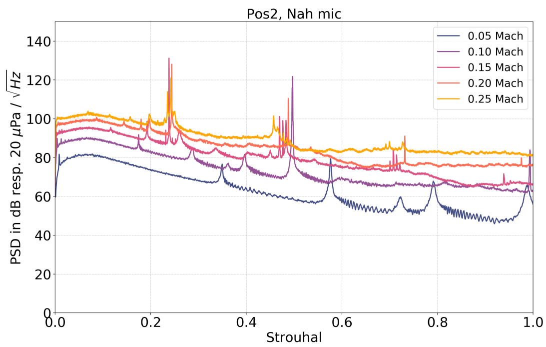


Figure 7: PSD spectra for plate P2 versus Strouhal number related to bar thickness and jet velocity.

at the bars. Further noticeable is the alignment of the broadband noise levels up to St ≈ 0.3. Here another scaling can be found, i.e. doubling the Mach number of the incoming flow leads to roughly 10 dB level increase.

A more general overview is given in Figure 8. The top diagram shows the integrated PSD as a func-

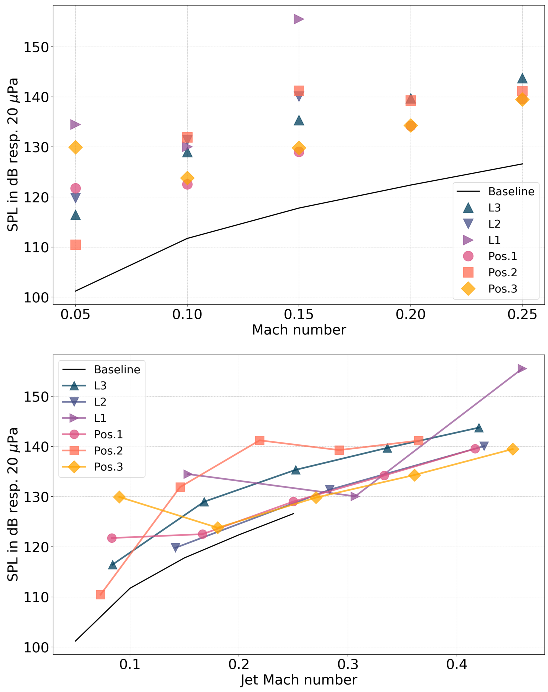


Figure 8: Overall SPL level vs Mach number (top plot) and average jet Mach number (bottom plot).

tion of the duct incoming Mach number. In the bottom diagram the integrated PSD is plotted versus the Mach number of the individual small jets. It was estimated from the duct incoming Mach number M by $M_{JET} = M/OA$, with OA being the test sample open area. In these plots however, one must have in mind that in some cases strong tones might dominate the overall SPL. This leads e.g. to the outstanding behavior of L1, which does not agree with any other plate. L3 and P2 in this observation show similar trend, which is suspected to be due to the square holes. On the other hand, P1, P3 and L2 having almost the same open area show similar overall noise level for $M_{JET} > 0.15$, as all spectra collapse. But looking at the individual spectra suggests that this observation can not be related to a single source mechanism.

Conclusion and future work

Flow induced noise generation of perforated plates was studied with the background of an application to fan acoustic tests. A first assessment of available plates revealed tonal and broadband noise of levels that in extrapolation to the fan experiment pose a severe risk to mask the fan noise to be analyzed (appraisal not shown in the paper). However, the current results suggest potential low noise plate design approaches. For a given overall open area the use of a large number of small holes seems to be favorable, since this might shift the emphasis of the noise generation to the multiple small jets associated with higher frequencies. To lower the excitation of tones potentially caused by shedding of coherent vortices the avoidance of thick bars respectively large mutual hole distances appears advisable.

In order to find out whether perforated plates can be designed such that the noise generation is acceptable for the envisaged fan test application, the search for scaling laws and guidelines has to be continued. In this regard a more systematic experimental study would be advantageous, in which only one design parameter is varied at a time. Further interesting would be investigations of different hole patterns or of added flow control means that for example reduce coherent flow structures or disturb vortex shedding.

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