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EXPERIMENTAL CHARACTERISATION OF PERFORATED PLATES IN A DUCT WITH FLOW IN NON-LINEAR REGIME

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Reducing the noise in a duct in the presence of a flow turns out to be a current industrial problem in many engineering applications, such as aircraft engine nacelles, ventilation systems and exhaust pipes. This study aims to analyze nonlinear behavior of absorbent materials used on the duct walls. This research is conducted experimentally through the use of an acoustic wind tunnel (Caïman wind-tunnel of the *Centre Acoustique du LMFA, Ecole Centrale de Lyon*). As an initial approach, the study is limited to a plane wave analysis. The two-source method is used to characterize the transmission loss of the liners. Different configurations are investigated at different flow regimes up to a Mach number of 0.3. Regarding the treated wall case, a perforated metal liner is considered. A sample with the same geometrical properties of the liner is initially tested on a Kundt tube, in order to characterize the absorption coefficient and the impedance. The perforated liner is thereafter tested in the wind tunnel for a transmission loss analysis with and without flow, first in linear and then in nonlinear regime. A comparison of the TL obtained experimentally with the one determined by calculation using a multi-modal approach, and a numerical time-domain code, based on finite-difference techniques, are presented.

Keywords: Perforated plates, acoustic liner, aeroacoustic non-linear behaviours

1. Introduction

The study of perforated plate liners used for noise reduction is of particular relevance in various industrial applications. At high acoustic levels, as highlighted in [1, 2, 3], the liner presents non-linear behaviour, with properties no longer depending merely on the excitation frequency but also on the excitation sound level. In industrial applications such as ventilation systems and nacelles of aircraft engines, the acoustic liner is subject to an air flow, directly affecting the liner's behaviour.

The aim of this study is to experimentally observe the non-linear behaviour of a perforated plate liner in a flow duct and to model it from an analytical point of view. This paper first presents a characterisation of the liner material, in the form of a perforated plate (PP), tested in a Kundt tube at different SPL values. This characterisation shows how the behaviour of perforated plates is non-linear even at levels where sound propagation remains a linear process. An analytical impedance model based on the model presented by Laly et al. [4] is implemented to validate the non-linear study of the perforated plate. Subsequently, experiments are conducted in an acoustic wind tunnel in order to test the acoustic performance of a perforated plate liner at grazing incidence at several excitation levels. A semi-analytical model based on a multimodal approach [5] is used for the prediction of the transmission loss (TL) within the flow duct and a comparison of the transmission loss is with the experimental results is conducted.

2. Acoustic characterisation of a perforated plate in an impedance tube

2.1 Experimental characterisation

The first section of the study presents the experimental characterisation of a perforated plate inside an impedance tube. A conventional two-microphone impedance tube Brüel & Kjær Type 4206 is used. The considered perforated plate, shown in Fig.1, has a diameter D of 33 mm, 3 perforations presenting a perforation diameter d of 2 mm and a distance between two adjacent holes i of 1.5mm. The thickness h of the plate is equal to 1 mm. The plate is made of galvanised steel and the cutting and drilling of the holes is carried out using a laser cutting technique, guaranteeing a high degree of precision in terms of size and surface smoothing of the cut. Considering the assembly inside the tube an air gap behind the plate measuring 30 mm is created. The perforation rate of the plate ϕ is of the order of 1.43%.

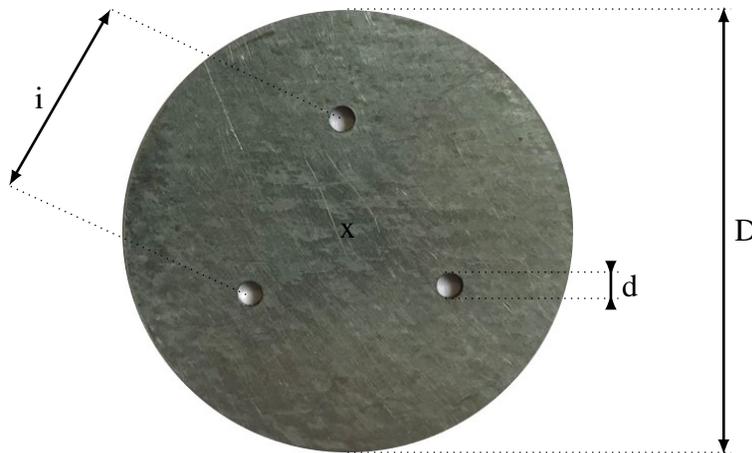


Figure 1: Picture of the perforated plate

Measurements were conducted using a broadband excitation filtered with a lower cutoff frequency of 100Hz and an upper cutoff frequency of 7000 Hz. Acquisition was implemented using two flush-mounted ¼" B&K type 4187 microphones, a B&K type 2718 amplifier, two B&K type 2670 preamplifiers, a type 2690 conditioning amplifier and a National Instrument 9250 front-end acquisition card. The post-processing of the time signals was handled using Matlab software. The method used to determine the acoustic properties of the plate is the two-microphone method [6], whereby the distance between the plate and the closest microphone is 35 mm and the distance between the two microphones is 20 mm. Based on the measurements, a value was deduced for the incident sound pressure level inside the tube and for the rms velocity v_{rms} at the perforation. The evolution of the plate's behaviour was studied starting from

a linear regime of 77 dB and then moving towards a non-linear range, more precisely at 107 dB, 117 dB, 127 dB and 130 dB.

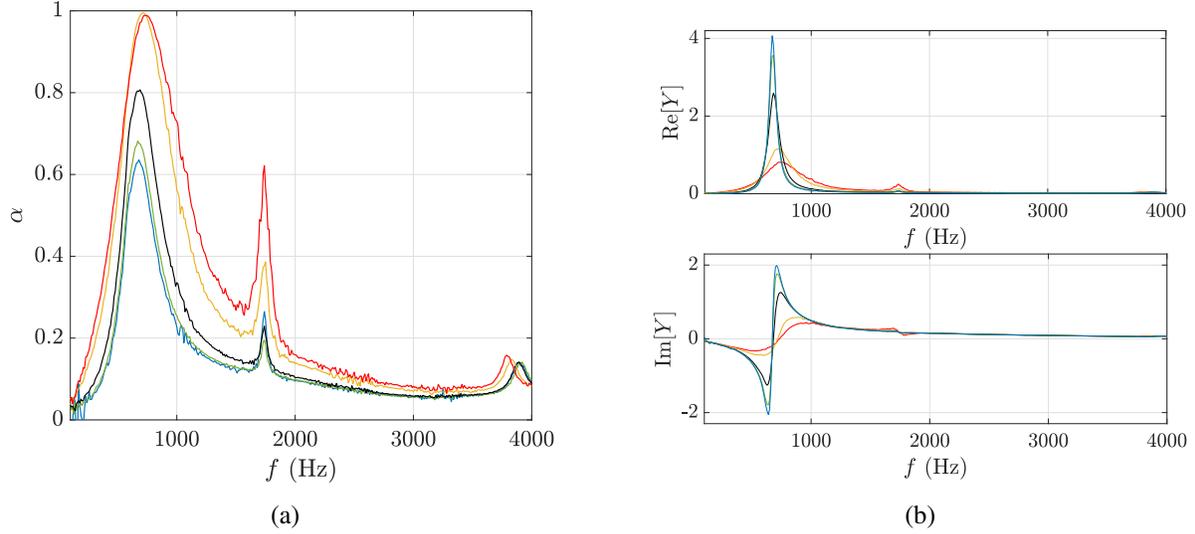


Figure 2: Experimental evolution of the absorption coefficient α (a) and the admittance Y (b) at different SPL levels: — 77 dB, — 107 dB, — 117 dB, — 127 dB, — 130 dB

The results show the evolution of the plate's absorption coefficient α (Fig. 2a) and admittance Y (Fig. 2b). It can be seen, in agreement with several studies conducted on similar plates [3], that the absorption peak has a tendency to increase in frequency and widen up to a value close to 130 dB and then begin a decrease with a relative shift to higher frequencies. As far as the admittance is concerned, it can be seen that both the real and imaginary parts tend to flatten as the SPL increases. In particular, the peak of the real part tends to decrease as the SPL increase at the same frequency up to 120 dB, beyond which a shift of the peak to higher frequencies is noted. This behaviour is consistent with the trend of the absorption curve, which is tightly interconnected to the admittance value.

2.2 Analytical impedance model

The analytical model presented by Laly et al.[4] for perforated plates in the non-linear regime appears to be valid and accurate for microperforated plates (perforation diameter less than 0.5 mm) and for perforation rates in the range of 1% to 5%. Even though the perforation rate is contained in the model's application range, the plate realised in this study turns out not to be microperforated. For this reason it was necessary to correct certain parameters of Laly's model in order to fit the plate acoustic properties. With reference to the study conducted by Laly, the parameter ψ is fixed at 5/3, while the discharge coefficient C_D is fixed at 0.6 and the non-linear coefficient β is fixed at 0.56. The flow resistivity σ is increased by a factor 7 compared to Laly's model:

$$\sigma = \frac{56\eta}{\phi r^2} \quad (1)$$

where r is the perforation radius and η the air dynamic viscosity of $1.84 \times 10^{-5} \text{ kg m}^{-1} \text{ s}^{-1}$. This modification would aim to model viscous effects in the macroperforations [7, 8], which are negligible for the microperforations.

The tortuosity $\alpha_{\infty\text{NL}}$ is defined by

$$\alpha_{\infty\text{NL}} = 0.85 + \frac{1.7\varepsilon}{h} \left(1 + \frac{\lambda}{\phi c_0} \sqrt{2} v_{\text{rms}} \right)^{-1} \quad (2)$$

in which an empirical coefficient λ set at 0.07 is introduced and where ε is the correction length related to ϕ and to the perforation radius r .

The modification of these parameters within the proposed model was dictated by the unique conditions of the setup and the plate, which need to be taken into account in order to optimally model the experimental results obtained. Figure 3 compares the absorption and admittance results obtained experimentally for three SPL levels (linear case at 77 dB, non-linear case at 117 dB and 127 dB) with the results obtained from the analytical model. It can be noted that the model allows the maximum and width of the absorption peak at the desired frequency to be accurately found. For values close to 1800 Hz, a secondary peak is evident, with a corresponding drop in coherence observed during the measurements, which is not taken into account in the analytical model.

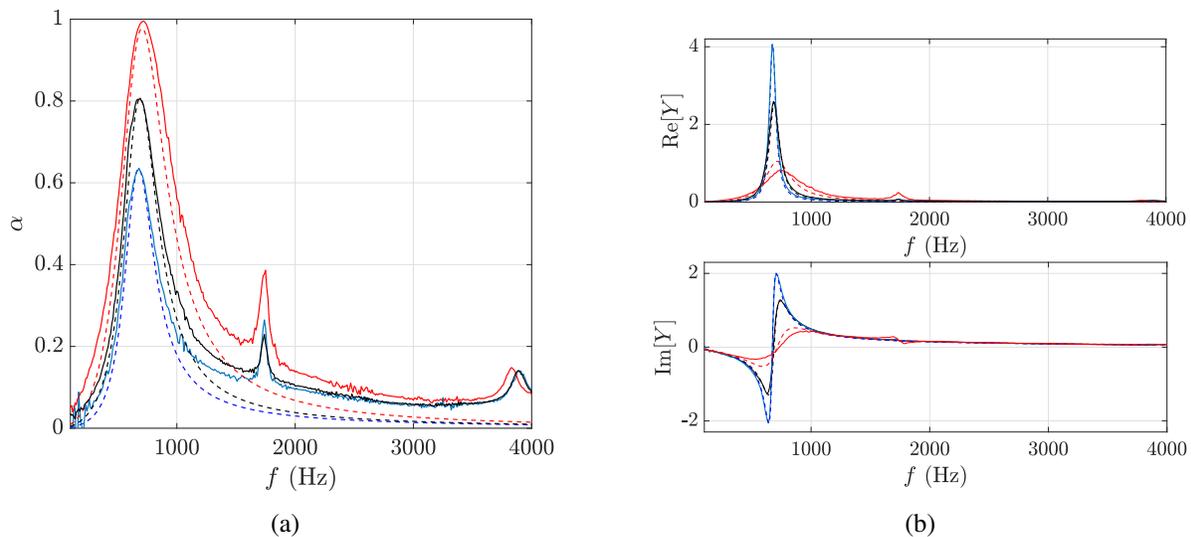


Figure 3: Comparison of experimental (solid line) and analytical (dashed line) trends of the the absorption coefficient α (a) and the admittance Y (b) at — 77 dB, — 117 dB and — 127 dB

3. Acoustic characterisation of a perforated liner in a wind tunnel

3.1 Measurements in an acoustic wind tunnel

The second part of the study presents the experimental characterisation of the acoustic performance of a perforated plate liner within a flow duct. The duct, depicted in Fig. 4a, is the Caïman open wind-tunnel of the *Centre Acoustique du LMFA, Ecole Centrale de Lyon*. The maximum fan power is 30.4 kW, generating a maximum mass flow rate of 1.1 kg/s for a maximum Mach number M of 0.4. The internal section of the duct measures 70 mm \times 111 mm. Referring to Figure 4b, the installation presents a flow-generating fan (1), a convergent (2), two silencers upstream and downstream of the acoustic treatment (3), two acoustic source allocation compartments, respectively upstream (4D) and downstream (4U), a rigid section (5) a treated section in which the perforated liner is placed (6) and an external silencer (7). The acoustic sources each consist of an array of 4 compression chambers, which can be excited

simultaneously or separately. Four GRAS 46DE-FV 1/8" CCP microphones, two upstream and two downstream of the treatment, were used for acoustic measurements. The duct discharges directly into an open environment.

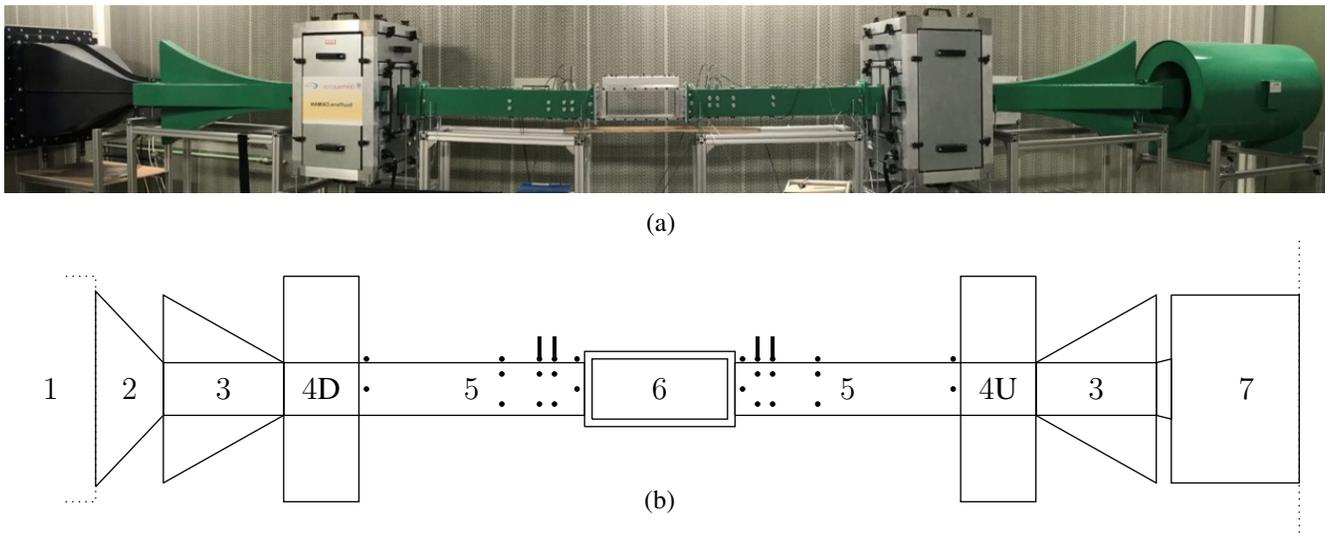


Figure 4: Photo of the Caiman wind tunnel (a) and schematic representation of the duct (b)

A perforated plate liner is considered. The properties of the perforated plate are similar to the one described in section 2.1. The dimensions of the liner are $300 \text{ mm} \times 60 \text{ mm}$. A 30 mm high 3D-printed honeycomb structure was positioned behind the plate to simulate an air gap. At the other end of the honeycomb, a plate acts as a rigid termination and structural support for the assembly. The liner is thus presented as a series of individual resonators, with each perforation having its own closed cavity in front of it. The liner was then assembled inside a dedicated compartment. The tightness of the assembly was ensured as far as possible through the use of rubber joints. Before conducting the experimental campaign, the duct was characterised from a fluid-dynamic, thermal and acoustic point of view.

An harmonic excitation between 200 Hz and 1400 Hz by steps of 100 Hz and by a 10 Hz step refinement between 600 Hz and 1100 Hz was employed. A two-source location method based on the scattering matrix [9] was implemented to process the measurements. The parameter chosen to study the acoustic performance of the liner is the transmission loss (TL). Figure 5a shows the evolution of the TL at different excitation levels. The levels correspond to different gains of the power amplifier. The SPL value corresponds to a frequency average value of the SPL measured at a microphone in the downstream rigid section of the duct and should be considered as an indicative value. The TL shows a similar evolution with the frequency for the different SPL values. In particular, the peak of TL is at the same frequency. However, the peak value tends to decrease with an increase of the SPL. The non-linear acoustic behaviour of the liner, in accordance with the results presented in section 2.1, affects the performance of the liner, already leading to a decrease in TL without flow.

Results are now presented for the cases with flow. Maintaining the same setup conditions of the case $M = 0$ and $\text{SPL} = 114 \text{ dB}$, flows corresponding to $M = 0.05$ and $M = 0.1$ were introduced. The corresponding TL are presented in Fig. 5b. It can be observed that the maximum of the TL drops and shifts to higher frequencies as the Mach number increases.

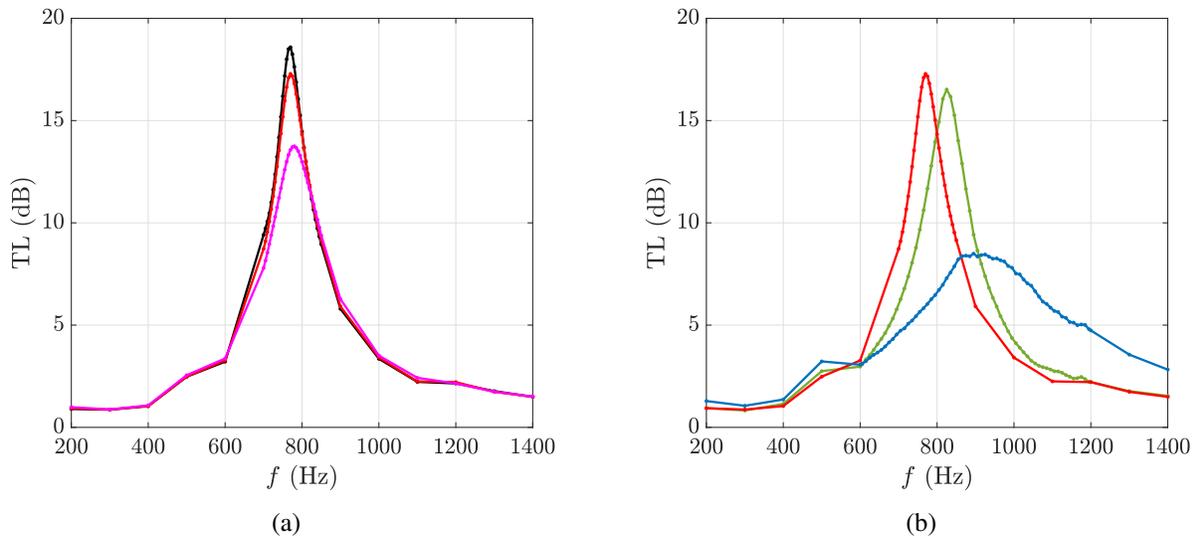


Figure 5: Transmission loss TL at different excitation levels without flow: **—** SPL =94 dB, **—** SPL = 114 dB and **—** SPL = 123 dB (a) and at different flow values: **—** $M=0$, **—** $M=0.05$ and **—** $M=0.1$ (b)

3.2 Multimodal semi-analytical model

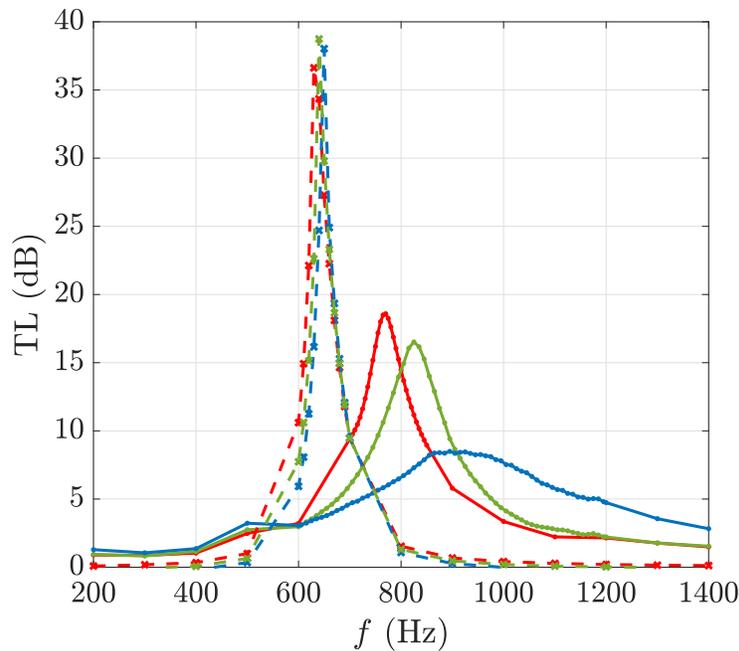


Figure 6: Comparison of experimental (solid line) and semi-analytical (dashed line) transmission loss TL at **—** $M=0$, **—** $M=0.05$ and **—** $M=0.1$

A semi-analytical model based on a multimodal approach [5] is adopted for the prediction of the pressure and velocity fields within the duct. Treated walls and the presence of a uniform mean flow can be considered in the model. The dimensions of the duct and of the liner are based on the actual set-up

described in section 3.1. The acoustic properties were then calculated in a frequency range of 200-1500 Hz.

A comparison of the experimental and semi-analytical TL is presented in Figure 6. It can be observed that the multimodal model yields higher TL values at lower frequencies for all the cases considered. This phenomenon can be attributed to imperfect actual setup conditions, such as the presence of leaks within the assembly and duct, which are not taken into account in the model.

4. Conclusions

This paper presents an experimental characterisation of the non-linear behaviour of a perforated liner in an acoustic wind tunnel. After acoustically characterising the material inside an impedance tube, the acoustic performance of a perforated liner inside a flow duct was tested. Transmission loss trends at different excitation levels and different Mach numbers were analysed. The experimental results are corroborated by an analytical model for the nonlinear acoustic behaviour of the material and a multimodal model for the liner acoustic performance in the flow duct. The results highlight the non-linear behaviour of the liner. Given the complexity of the phenomenon, the analytical results partially succeed in representing the behaviour. In future works, the authors aim to improve the analytical model and to implement a numerical model of the phenomenon. From an experimental point of view, it is intended to test the liner for higher Mach numbers and to implement different perforated liner configurations.

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