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Acoustic characterization of "locally" and "non-locally reacting" porous liners in flow with LDV measurements

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The traditional measurement methods to characterize an acoustic resonator in the presence of grazing flow (i.e. used in aeronautic domain) require the use of microphones, mounted to the upper / rear faces of the liner (for impedance) or upstream / downstream from the liner with microphones flush with the wall (Transmission loss). So, no information is known inside the flow. That is the reason why a new testing method using Laser Doppler Velocimetry technique (2D LDV) has been developed at ONERA to obtain acoustic quantities like pressure, impedance or intensity fields near the liner under flow condition and incident acoustic waves. These complementary quantities are very useful to understand how the liner absorbs acoustic waves. That method is based on measurement of *in flow* acoustic velocity perturbation, extracted by signal processing. Then Galbrun's theory (Eulerian-Lagrangian description of the perturbations) permits to accede to the pressure and intensity fields. In-duct flow LDV measurements are realised on a test-bench, called B2A: It is a 4 m long wind tunnel regulated in turbulent flow rate, with a maximum Mach number of 0.5. Two loudspeakers can generate plane waves on range 300-3000Hz, upstream from a square test cell where a small liner is mounted (30 x 150 mm² with a variable thickness). Acoustic velocities components are extracted from total velocity by cross-spectra with a reference signal (the loudspeakers'one), in order to reject turbulence. Measurements of (micro-)LDV fields have been performed, with or without flow (up to Mach 0.2), above different types of liner (perforated or micro-perforated facing sheet, upper honeycomb, fibres or hollow spheres) in order to bring to the fore "linearity" or "non-linearity" effect and "locally" or "non-locally" reaction. The absorbed acoustic power, extracted from intensity fields, allows comparing the behaviour of materials. This activity takes place as part of national project COMATEC.

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1 Introduction

A liner with locally acoustic behaviour, has an acoustic boundary condition independent of direction of input waves: only normal component of particle velocity must be taken into account at interface to obtain its acoustic impedance. Among these materials, we find; in particular, perforated liners as resistive plate backed by honeycomb cells SDOF / 2DOF / 3DOF whose acoustic and mechanical properties are known for several years. Many studies have tried to determine the influence of various parameters on the impedance and the absorption of resistive sheet. Gaeta & Ahuja [1] show in particular that to increase the perimeter of a resistive plate hole, with a same surface, allows increasing the absorption with low levels of particle velocity (< 1 m/s) but has not significant effect for higher levels. Presence of mean grazing flow generally generates an increase of resistance and a decrease of reactance [2]. Nevertheless, the more the porosity increases (with the same size of hole), the more the phenomena decreases [3]. Chandrasekharan et al. [4] show that an increase of ratio "plate thickness / hole diameter" increases the frequency band on which there is linear behaviour of the plate to the sound level, what allows in particular choosing a liner more easily.

Materials with non-locally reaction are for instance foams, fibres or hollow spheres. Their main disadvantage is that they have often a bad mechanical behaviour and present problems of fouling. However, their acoustic performances being wider in frequency, an important effort is led for conception of new materials of this type to find an alternative in the current materials. So, Lavieille [5] has noticed, experimentally (with LDV technique), a significant absorption of grazing plane waves above a metallic fibrous liner for M=0.1. But for an higher Mach number (M=0.4), there is a production of stationary acoustic vortex in the boundary layer due to non-locally reaction. The porous materials with hollow spheres (diameter around 1-5 mm) are usually used in car industry, only a little in aeronautic domain. Their behavior is close to classical foams with a particular flow resistivity. There are generally tested in impedance tube to validate models or sometimes in wave tube [6].

The purpose of authors is to show "linearity" or "non-linearity" effects and "locally" or "non-locally" reaction of different types of material thanks to the testing method using only Laser Doppler Velocimetry technique that allows investigating waves in flow above liners.

2 Measurement set-up

The Aero-Thermo-Acoustic test bench (Figure 1) is specifically used to perform in-duct flow Laser Doppler Velocimetry (LDV) measurements along an acoustic liner in presence of a grazing flow [7]. Two loudspeakers can generate plane waves, up to 3000 Hz, in the wind tunnel (cross-section of 50×50 mm²) with a turbulent flow (maximum bulk Mach =0.5). The test cell can contain, in its lower part, a sample of material to be studied (30 x 150 mm²).

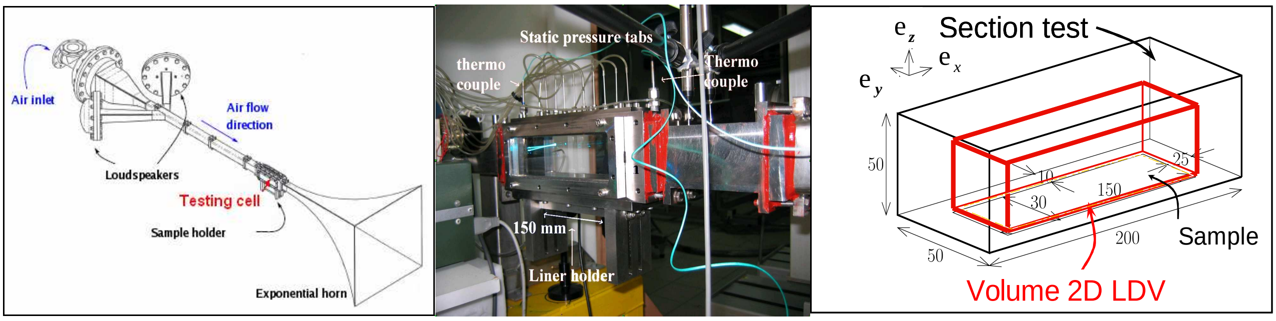

Figure 1: The Aero-thermo-acoustic bench B2A / test cell / measurement volume

To be able to measure the velocity components of the flow, particles, as incense smoke or aerosol, have to be injected into it. The emitting optics of the 2D LDV system produce a 100 µm-diameter measuring volume. The receiving optics are placed in forward scattering. The Laser Doppler system then records simultaneously the velocities and the reference signals with a random sampling due to the particles passing through (< 13000 measurements / second).

3 Assessment of acoustic parameters

The signals recorded by the LDV system must afterwards be analysed to extract acoustic components from velocity spectra. In fact, collected data contain a turbulence part that has to be rejected. Assuming that the turbulent fluctuations and the acoustic perturbations are not correlated, cross-spectra computations between the measured signals and the reference loudspeaker's signal hence allow extracting the acoustic velocity [7].

The small seeding particles arrive in the measurement volume at non-constant time intervals. For that particular reason, the LDV signals are randomly sampled, with a sampling time distribution following a Poisson's law. Data are then interpolated and re-sampled at a constant rate that is not far from the mean sampling frequency. In theory it is possible to compute the spectra up to several times the average sampling frequency, but, due to the dead time of the processor a maximum bandwidth of 30000 Hz can be achieved. Re-sampled signals are then transformed in the frequency domain by means of power spectral density calculations. The major advantage of this method is that it is simple but it presents the drawback that the frequency spectra are filtered. (low pass filter with a cut-off frequency f_c equal to $f_m/2\tilde{\pi}$). So, a correction scheme must be applied [5].

Acoustic quantities as displacement, pressure or energy can be deduced from velocity values thanks to the propagation model of Galbrun. Indeed Galbrun's approach leads to an exact conservation law concerning acoustic energy, for any rotational flow, with the only restrictive hypothesis that the flow must be an ideal gas. In contrast, the classical Eulerian description cannot give, in case of a strongly sheared flow, an exact expression to verify the energy conservation.

Supposing that the flow is quasi-unidirectional and by neglecting the viscosity effects, displacement perturbation components, ξ_x, ξ_y, ξ_z, are obtained by resolving the following system of equations:

$$V_x^{ref}\frac{\partial \xi_x}{\partial x} + i\omega\xi_x = v'_x - \frac{\partial V_x^{ref}}{\partial z}\xi_z$$
$$V_x^{ref}\frac{\partial \xi_z}{\partial x} + i\omega\xi_z = v'_z \quad (1)$$

where the mean longitudinal velocity V_x^{ref}, and the velocity perturbations v' are measured in a plane (x,z) by LDV (Figure 1). The streamwise direction x is also the direction of propagation of the acoustic waves generated by the loudspeakers. z is the vertical direction, perpendicular to the lined wall (Figure 1).

Given static pressure values P_{ref} and mean-flow density $\rho_{ref;}$ the pressure perturbation p' is expressed at each mesh point as function of the displacement perturbation:

$$p' = -\rho_{ref}c_{ref}^2 \, div\xi - \frac{dP_{ref}}{dx}\xi_x \quad (2)$$

Under the assumption of quasi-unidirectional flow, the longitudinal and vertical components of the active acoustic intensity read:

$$I_x = \frac{1}{2}\Re\left(-i\omega p'\xi_x^* + i\rho_{ref}V_x^{ref}\omega\left[\xi_x\left(v_x^{'} + \frac{\partial V_x^{ref}}{\partial z}\xi_z^*\right) + \xi_z v_x^{'*}\right]\right)$$
$$I_z = \frac{1}{2}\Re\left(-i\omega p'\xi_z^*\right) \quad (3)$$

where * stands for the complex conjugate and $\Re$ for the real part of the considered complex number.

Acoustic power balance (and thus the acoustic power absorbed by the liner) can then be evaluated from upstream and downstream measurements.

4 Experiments

The tested liners (Figure 2) have the following characteristics:

- perforated or micro-perforated resistive aluminium layer (porosity: 5 %, thickness: 0.8 mm, hole diameter: 0.3 or 1 mm)
- Honeycomb or metallic fibres or hollow spheres in terracotta (thickness: 20 mm) upper a rigid back.

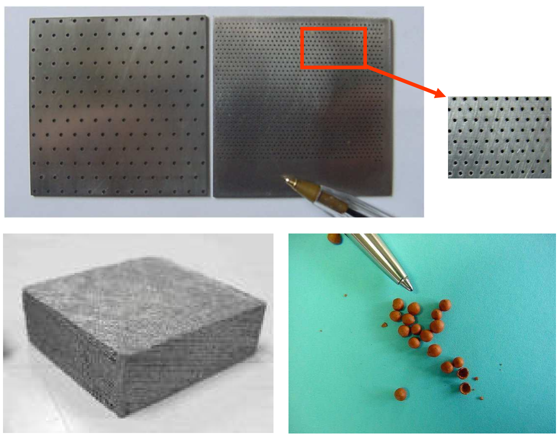

Figure 2: Resistive layers / metallic fibres or hollow spheres (manufactured by www.ateca-fr.com)

4.1 Perforated or micro-perforated resistive aluminium layer with honeycomb

The type of behaviour, linear or non-linear, due to incident sound pressure level (130 dB by tone / total OASPL l40 dB), can be brought to the fore thanks to a micro-field of transverse (direction z) acoustic velocity close to the liner (0.2 mm), without grazing flow. The Figure 3 shows that area of high magnitude above holes is proportional to the hole diameter (white circle), that is to say, on about 3 hole diameters at 1992 Hz (frequency of maximal absorption). On the other hand, the variation of phase depends on the kind of hole: for 0.3 mm holes (up), the phase is relatively constant on about 2 hole diameters and increases to reach a limit around the holes (linear effect). For 1 mm holes (down), appears an abrupt return of phase variation (red-yellow circle) representative of acoustic vortices (non-linearity effect with sound level). Moreover, there is not interaction between holes. So, the micro-perforations allow having a linear behaviour of acoustic velocity relative to incident pressure level, representative of a constant impedance, contrary to wider perforations (for the same thickness) where acoustic vortices increase resistance for a high level pressure (cf. [4]). In fact, the impedance measured for the 0.3 mm hole layer at 1992 Hz is closer to the optimal impedance of a liner placed in B2A configuration than the other one (Figure 4). So, the absorbed power is higher. With grazing mean flow (i.e M=0.2), the acoustic flows through holes are lower (Figure 5) and the longitudinal (direction x) velocity level increases between holes. So, there is an homogeneous spreading of acoustic vortices on a narrow area in the direction of mean flow (interaction between holes). For 0.3 mm holes, like [2,3], this effect is linked to an increase of measured resistance (but for a same reactance at 1992 Hz).

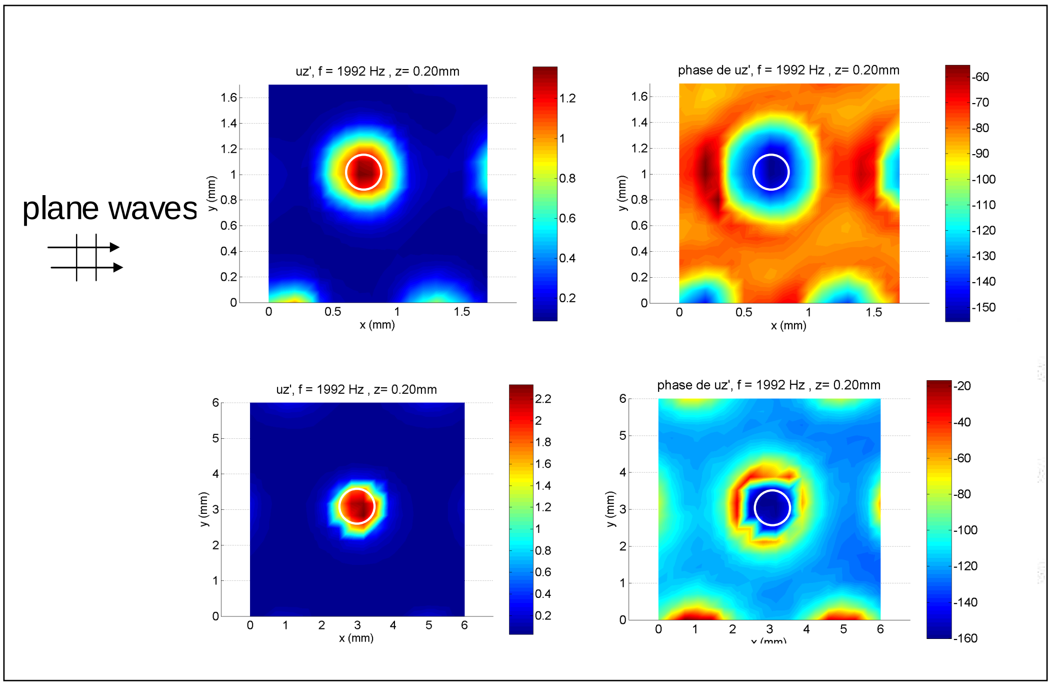

Figure 3: Micro-fields of transverse acoustic velocity above micro-perforated layer (up) and perforated layer (down) at 1992 Hz without grazing flow: amplitude (m/s) and phase (°)

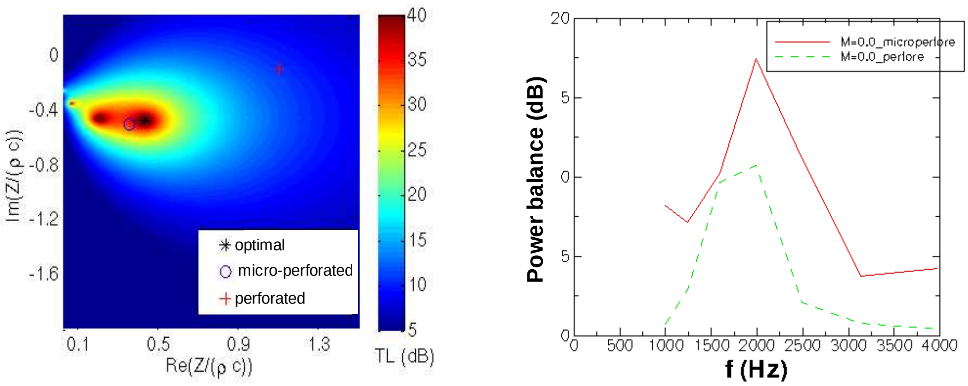

Figure 4: Impedance of micro-perforated and perforated resonators compared with optimal impedance (left) at 1992 Hz – Acoustic power balances of micro-perforated and perforated resonators without grazing flow (dB)

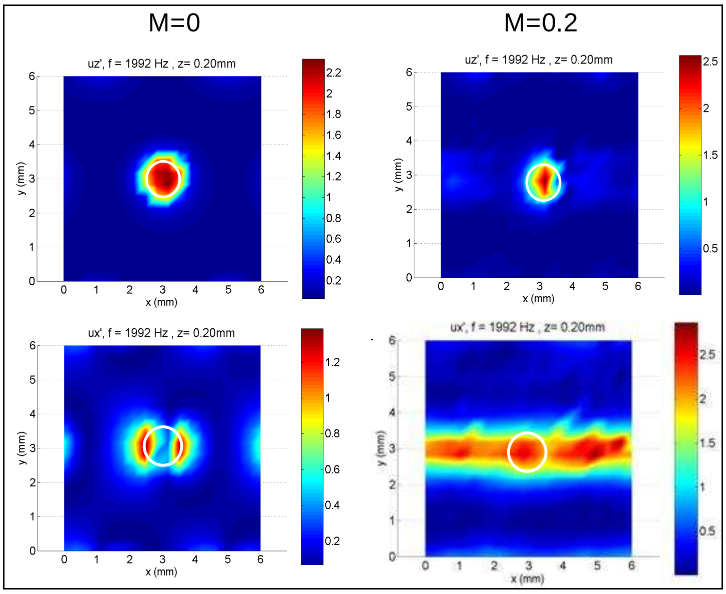

Figure 5: Micro-fields of transverse (up) and longitudinal (down) acoustic velocity above micro-perforated layer perforated layer at 1992 Hz with effect of grazing flow: amplitude (m/s)

4.2 Perforated or micro-perforated resistive aluminium layer with porous medium

We replace the honeycomb by metallic fibers and measure global velocity fields along materials. As there is no partitioning, the new liners have theoretically a non-locally reaction.

For a micro-perforated facing sheet, without grazing mean flow, the acoustic velocity fields are few influenced by the sound pressure level (total OASPL between 120 and 140 dB), as for the previous type of liner with honeycomb, in spite of the presence of porous medium behind the resistive sheet. On the other hand, an “acoustic streaming” phenomenon that produces a natural flow above the liner depends highly on the sound pressure level.

The comparison between the types of facing sheet is shown on power «balances» (Figure 6) and on the intensity fields (Figure 7) obtained from the «global» 2D LDV fields and (3), with and without grazing flows. The green arrows represent the area where the influence of the sample on the acoustic waves is the most important (if one extend the arrow, it intersects the sample). With fibres instead of honeycomb, the absorbed power is lower. It can be explained by a non-locally reaction in the fibrous medium that produces interferences above the liner along the acoustic propagation (Figure 7). Moreover, the presence of a mean flow reduces the maximal frequency of absorption. On the other hand, like with honeycomb, the micro-perforated layer supplies an higher absorption than the perforated layer, particularly in presence of grazing flow (Figure 6). With hollow spheres instead of honeycomb, the interferences of waves above the liner are yet more perceptible (non-local behaviour) which doesn't seem desirable (Figure 7).

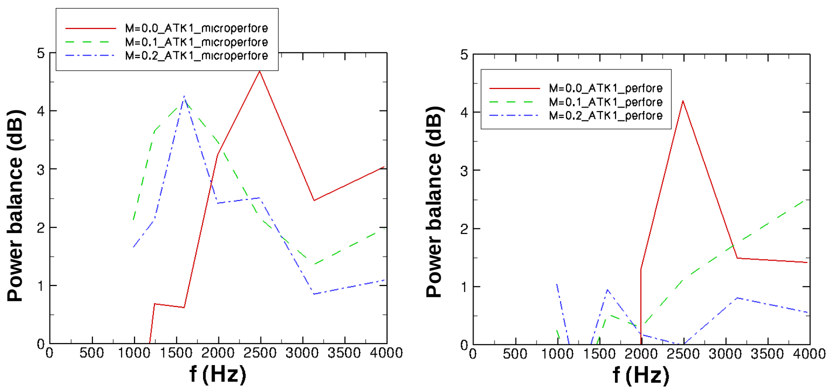

Figure 6: Acoustic power balances of micro-perforated (left) and perforated (right) facing sheet above fibers without and with effect of grazing flow (dB)

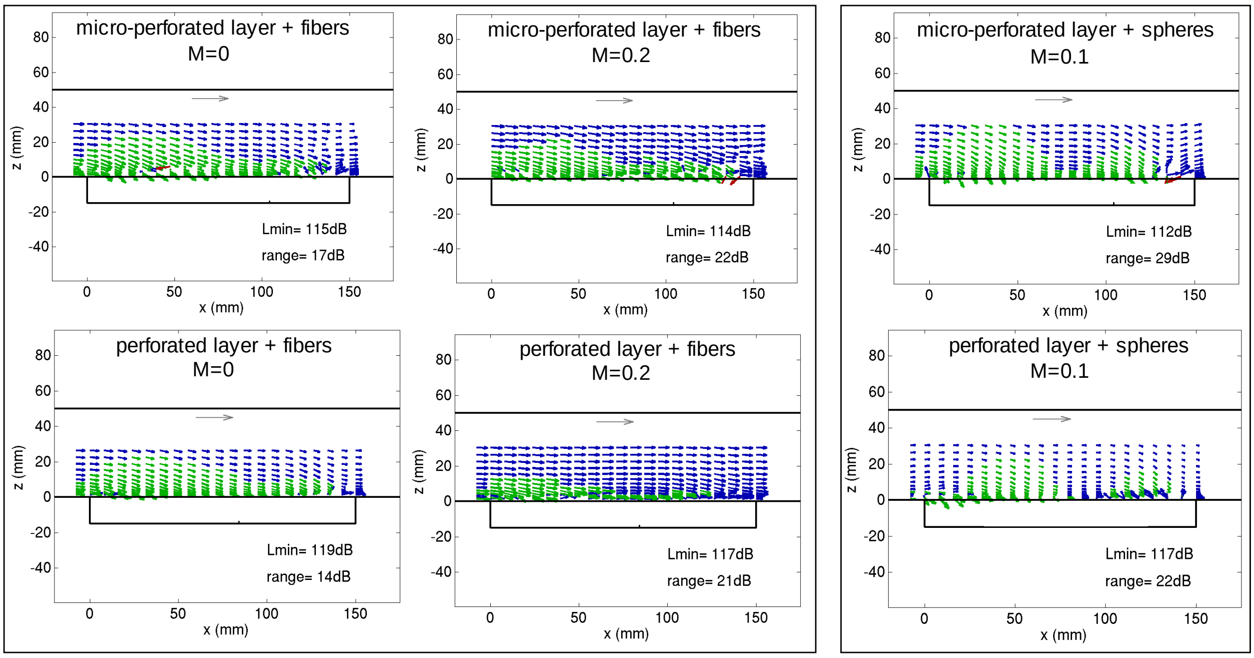

Figure 7: Acoustic intensity fields (dB) along micro-perforated or perforated facing sheet above fibers or spheres at 2500 Hz without and with effect of grazing flow

5 Summary

Aero-acoustic measurements with LDV upper acoustic liners have allowed showing locally "linearity" or "non-linearity" effects (above holes of resistive layer) due to sound pressure level, thus in relation with impedance values. Moreover, the influence of a "non-locally reaction" has been brought to the fore thanks to acoustic intensity field above material for different types of liners and Mach numbers. Finally, the acoustic power absorbed by liners has been acquired directly in the flow. So, the measurement process can be useful to validate aero-acoustic models and classical measurements with pressure sensors.

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