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LEONAR liner concept: multiphysics coupling in presence of grazing flow, thermal gradients and high sound levels

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The development of turbofans with larger fan diameters, shorter inlets, and thinner walls forces the acoustic liners to be placed closer to the hot parts of engines. This experimental study investigates the combined effects of important thermal gradients, grazing flow and acoustic level on the acoustic behavior of liners applied to the LEONAR (Long Elastic Open Neck Acoustic Resonator) liner concept. Previous studies have shown that a coupling between these three effects can exist. The objective is thus to understand the underlying coupled phenomena, in order to emphasize the interest of such a liner concept regarding a classical equivalent SDOF liner. Experiments are conducted in the grazing flow duct at ONERA (B2A) where the flow temperature can be accurately regulated and several types of acoustic excitation can be provided. A test section with a heating or cooling device is used to obtain a thermal gradient between the backplate and the perforated plate of the liner sample, and infrared (IR) thermography is used to measure the temperature distribution on the perforated plate. The measurement is conducted on several configurations and with different types of liners, to assess the behaviors of the LEONAR liner concept in the context of combined influence of grazing flow, thermal gradients and high sound levels.

Nomenclature

ϕ	=	Liner perforated sheet perforation diameter (mm)
δ	=	Liner perforated sheet thickness (mm)
l_t	=	Length of extended necks under perforate sheet (mm)
L_s	=	Sample thickness (m)
ρ_0	=	Density of the mean flow (kg/m ³)
M_b	=	Grazing flow bulk Mach number
q_m	=	Mass flow rate (g/s)
ω	=	Angular frequency (rad/s)

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ζ	=	Normalized acoustic impedance
r	=	Normalized acoustic resistance (real part of ζ)
χ	=	Normalized acoustic reactance (imaginary part of ζ)
a	=	B2A cross section height (mm)
S	=	B2A cross section area (mm ²)
(x, y, z)	=	Axial, transversal and vertical coordinates (mm)
c_0	=	Speed of sound in air (m/s)
k_{body}	=	Sample thermal conductivity (W.m ⁻¹ .K ⁻¹)
Bi	=	Biot number
h	=	Convective heat transfer coefficient (W.m ⁻² .K ⁻¹)
T_{flow}	=	Grazing flow static temperature (°C)
T_u	=	Perforated plate adiabatic temperature (°C)
T_b	=	Backplate temperature (°C)

I. Introduction

WITH the development of UHBR (Ultra High Bypass Ratio) engines optimized for maximum propulsion efficiency, new challenges arise regarding the implementation of conventional noise-absorbing liners. Indeed, the thinner and shorter nacelles leave less room to accommodate acoustic liners, whereas these same liners need to increase in height in order to properly absorb the lower-frequency noise generated by a larger fan. Moreover, the thinner walls between the combustion chamber and the bypass ducts will be likely to induce thermal gradients inside the liners' structure itself. Therefore, there is a growing need to propose new liner concepts that deal with these challenges. These concepts must be characterized as precisely as possible and their behavior must be assessed when thermal gradients, complex flows and high noise levels are involved simultaneously.

Conventional, single degree of freedom (SDOF) liners consist of a honeycomb structure topped with a thin perforated facesheet, forming a layout of small resonators closed at their bottom by a rigid backplate. The geometry of the honeycomb can be adjusted to match specific noise damping requirements [1]. The driving parameter for the noise damping power of "locally reacting" liners is their acoustic impedance, a complex number that is the ratio between acoustic pressure p and normal acoustic velocity v_n taken on the facesheet, normalized by the impedance of air $\rho_0 c_0$:

$$\zeta(\omega) = \frac{Z(\omega)}{\rho_0 c_0} = \frac{p}{\rho_0 c_0 v_n} = r(\omega) + j\chi(\omega),$$

where r and χ are respectively called the resistance and the reactance of the liner.

It is generally admitted that resistance can be increased by the sound pressure level (SPL) or by the grazing flow.

These effects are so-called nonlinear effects linked to a vortex shedding produced periodically near the perforations [2]. Having a varying resistance due to SPL could be a drawback in terms of designing liner solution. Several models exist and take into account these effects. Guess [3] for instance gave a solution to model the effect of SPL and grazing flow. It appears necessary to propose a solution that is as much as possible weakly nonlinear, for example, with a thicker perforated plate so the nonlinear effects are slightly reduced (because of a high ratio between the perforated plate thickness δ and the hole diameter ϕ [4, 5]). This solution is acoustically efficient but the thicker plate cannot be an acceptable solution in terms of mass. Similarly, the total height of the cavity is a driving parameter for the frequency selection: to absorb at lower frequencies, a higher cavity is required. Again, this is not fully compatible with aeronautical constraints in the UHBR context. The LEONAR concept (or HREN for Helmholtz Resonator with Extended Neck) [6–8] could be a good candidate to cope with these challenges. It consists in linking the perforated layer with hollow tubes introduced in the honeycomb, to shift resonance frequencies to lower frequencies by a prolongation of air column lengths. Recently, Guo et al. [9] proposed the design of an optimal liner constructed by 16 inhomogeneous HRENS which enables to have a sound absorption in a prescribed frequency range from 700 to 1000 Hz. The same authors applied this concept to a small-scale propeller [10] where the liner concept has to be very compact regarding the available space. These types of liner concepts are thus very interesting in order to design an optimal liner for a given application.

Thermal conditions also affect the impedance of liners. Elnady et al. [11] investigated the acoustic behavior of a single orifice over a cavity placed in an oven. The surface of the sample was hotter than the back of the cavity, the difference was up to 100 K. The measurements were conducted for several SPL, including nonlinear regime, but without any grazing flow. The impedance of the liner was measured with an in-situ technique and compared to existing semi-empirical models. It was found that an increase in temperature results in a decrease of the reactance, while the resistance slightly increases (at least when the nonlinear effects are small compared to the viscous ones). Modifying the properties of air in the model to account for the high temperatures appeared to be enough to predict quite well this impedance change; the decrease of the reactance is indeed due to the modification of the air density which impacts the sound speed inside the cavity.

The coupling between aerodynamic and acoustic effects is complex, as liners increase the viscous drag in the turbulent layer compared to a smooth surface. Howerton et al. [12] investigated the drag effect of several conventional or more advanced liner designs in the NASA GFIT. They found that the resistance factor λ (also known as the friction factor) was frequency-dependent in presence of acoustic excitation. This effect increased with SPL, but was mitigated by higher flow speeds. More recently, Jasinski et al. [13] highlighted that a dramatic increase in drag at frequencies near acoustic resonance and at high SPL is observed on classical SDOF liners. Zhang and Bodony [2] confirmed that high acoustic levels increased the liner drag by performing a series of Direct Numerical Simulations (DNS) reproducing the conditions of a single orifice-over-cavity liner undergoing a grazing flow. Leon et al. [14] used a high-magnification PIV

setup to obtain 2D acoustic velocity fields measured close to the perforations of a SDOF liner sample. They observed that high acoustic levels induced specific aerodynamic phenomena and that the "rough-wall" analysis was showing its limits to predict the effects.

Giachetti et al. [15] experimentally studied the influence of synthetic pulsating jets across a multi-perforated wall. They have studied the role of cross-flow and synthetic jet interactions and the effect on the convective thermal coefficient. It is the first experimental set up that enables to understand which types of coupling can be observed in the case of liners with grazing flow, acoustic excitations and thermal gradients present together. A numerical restitution of the previous experiment was proposed by Esnault [16]. Méry et al. [17] conducted a study on liner samples heated from the back wall, both with and without the presence of a cooler grazing flow. The acoustic response of the samples was investigated both in the linear and nonlinear regimes with respect to the acoustic level. They showed that the temperature changes mainly impacted the reactance as the sound speed inside the cavities was modified. They also highlighted the influence of the acoustic level on the temperature repartition: for high SPL, the temperature went down inside the cavity due to the sample entering the nonlinear regime. This highlighted strong multiphysics coupling between acoustics, flow and thermal phenomena. Especially, the nonlinear effect due to the SPL on the surface temperature and the thermal exchanges have been highlighted in Lafont et al. [18]

In this study, a multiphysics assessment will be performed on a LEONAR liner concept and insights will be given on its use in the UHBR context. This concept is compared to an acoustically equivalent SDOF liner. A specific experimental setup is designed and used to monitor precisely the evolution of a liner surface temperature when there is a thermal gradient inside it and in presence of high SPL. The measurements are conducted both with a hot and cool grazing flow and the experimental conditions are carefully controlled. In particular, the temperature is monitored in several places all along the measurement. Impedance education is performed based on [19].

The objective of this study is to highlight the differences in terms of impedance and thermal effects between two liners that should have a similar acoustic behavior. The LEONAR concept enables to reduce the total height of a given liner concept and thus reduce the overall mass. The impact of this architecture on the thermal repartition and the impedance evolution in presence of a grazing flow and a thermal gradient needs to be assessed. The first part will be dedicated to the liner definition, the experimental methods and the setup. The second part will address impedance education results on two liner concepts. Finally, thermography results on the skin surface liner will be presented and discussed.

II. Experimental methods and setup

A. Sample description

Two samples are used in this study. One is a simple SDOF liner that has already been studied previously at ONERA[17]. The second one is a LEONAR, a type of liner where the perforations of the facesheet are connected to hollow tubes extending inside the cavities (see Fig. 1). This specific geometry allows to increase the perceived thickness of the facesheet without modifying the total height of the liner [7], leading to a lower-band absorption and a very linear response with respect to incident SPL. The LEONAR sample is based on the geometry of the SDOF sample. Thus, the perceived thickness of the perforated sheet is the same but the total height is reduced. The LEONAR sample is expected to have similar acoustic characteristic but to differ in the thermal and grazing flow behavior. The two samples are metallic samples obtained by additive manufacturing.

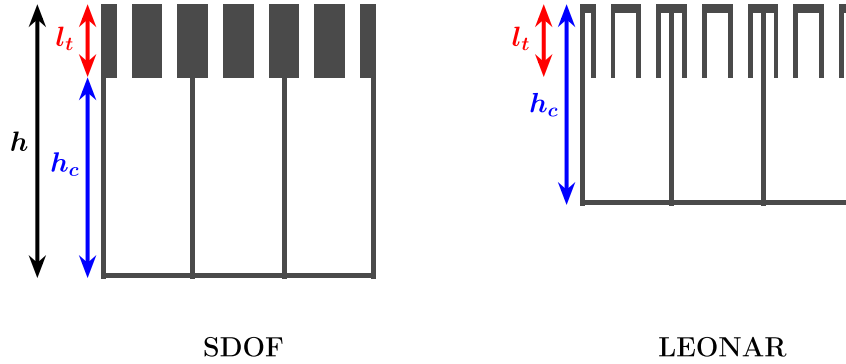


Fig. 1 Comparison of equivalent SDOF (left) and LEONAR (right). h_c is the inner cavity height, l_t the tube length ($=\delta$ for a SDOF sample)

Table 1 Geometric characteristics of the samples

Sample	ϕ (mm)	Porosity (POA)	l_t (mm)	Inner cavity height h_c (mm)	Total height h (mm)
SDOF	1.5	15%	8	41	50
LEONAR	1.5	15%	1 + 7	41	45

B. Acoustic setup

The B2A test bench is made of a stainless steel tube with a square section of side $a = 50$ mm and a total length of about 4 m. A mean flow of bulk Mach number M_b up to 0.5 can be provided, its temperature can be accurately regulated from room temperature up to 570 K. In the duct, the flow is in a fully-developed turbulent state, with axial velocity fluctuations on the centerline being a few percent of the bulk velocity U_b [14].

The test section is 0.2 m-long and equipped with two opposing silica windows for optical access. An exponential quasi-anechoic outlet terminates the duct, leading to a reflection coefficient smaller than 0.2 for frequencies higher than 500 Hz. The surface of the test liner forms a 150 mm-long portion of the lower wall of the flow duct and spans all the

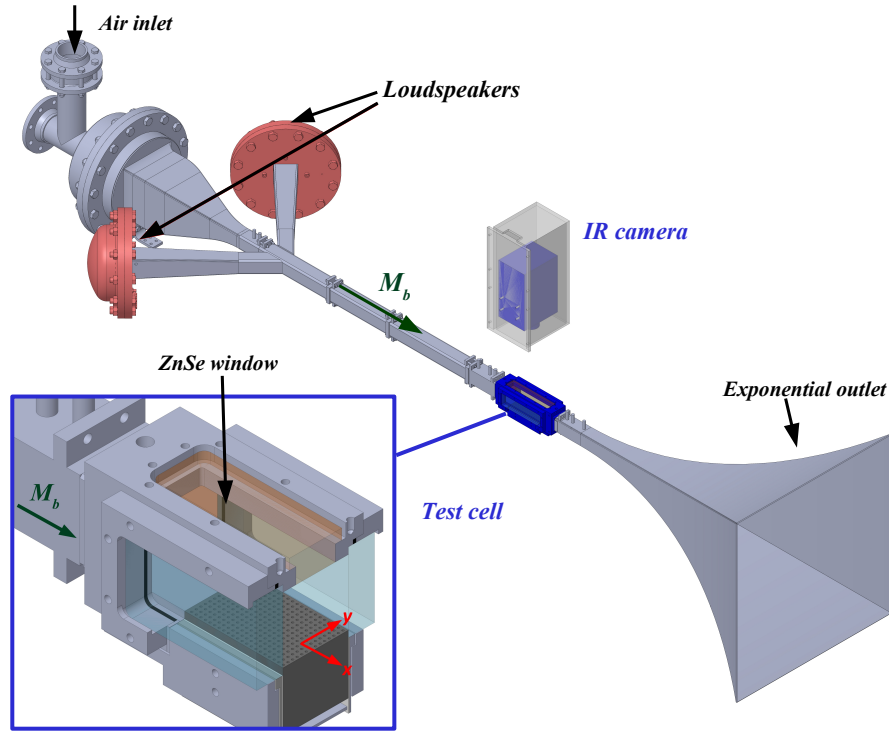


Fig. 2 The B2A bench

duct width [20].

Sixteen microphone sockets in the upper wall of the test section are used for acoustic measurements and impedance education. The upper wall with the microphone sockets is removable and can be replaced by a window for infrared measurements. Silica windows on both sides allow near-wall optical measurements (LDV or PIV).

Upstream of the test section, two speakers are used to generate tones (usually a multi-sine signal) at up to 150 dB over a frequency range of 0.3 to 3.5 kHz (i.e. the no-flow cut-off frequency of the duct for plane waves). Mono-sine or multi-sine acoustic excitation can be used. The multi-sine is made of 12 pure tones ranging from 504 Hz to 2824 Hz (see Table 2) and of equal SPL, while the mono-sine is only a single pure tone. Multi-sine excitations are used to study global behaviors at low and medium SPLs while mono-sine excitations are used for studying the behavior at higher SPLs and at specific frequencies, for example near the liner's resonance. When a multi-sine source is used, the overall SPL (OASPL) within the duct is much higher (usually 10 dB more) than the SPL at each tone frequency.

Table 2 Frequencies used (the frequency used for mono-sine excitations is written in bold).

Frequencies (Hz)											
504	616	760	992	1112	1240	1488	1736	1992	2248	2488	2824

In the duct, the flow is in a fully-developed turbulent state, with axial velocity fluctuations on the centerline being a

few percent of the bulk velocity U_b [14]. The parameter used to regulate the flow is the mass flow rate $q_m = \rho M_b c_0 S$ (in g/s), where $M_b = \frac{U_b}{c_0}$ is the bulk Mach number, $S = a^2$ is the duct cross-section, and c_0 is the sound speed in the duct. The flow temperature is also regulated.

This ensures that the conditions above the sample remain similar when the flow is heated or cooled. Table 3 shows the different flow rates used in this study and the corresponding bulk Mach numbers at different temperatures.

Table 3 Flow rates used and Mach numbers depending on the flow temperature

q_m (g/s)	M_b ($T_{flow} = 20$ °C)	M_b ($T_{flow} = 87$ °C)	M_b ($T_{flow} = 117$ °C)
50	0.048	0.054	0.056
100	0.097	0.107	0.112
150	0.145	0.161	0.168
200	0.194	0.215	0.224
260	0.251	0.278	0.290

C. Thermal design and setup

Two distinct thermal configurations are chosen in this study. They are defined by the sign of the temperature difference $\Delta T = T_b - T_{flow}$ between the flow and the bottom of the liner. In the positive case, the bottom wall of the liner is heated and the flow at room temperature acts as a cold thermostat to obtain a thermal gradient in the sample. In the negative case, the flow is heated and the bottom wall is kept at a lower temperature to obtain a temperature gradient (Figs. 3 and 4).

To ensure these two configurations can be obtained in a stable manner, a dedicated test cell has been designed (Fig. 5). It is partly based on the one developed for the study by Méry et al. [17] and can withstand high temperatures while remaining sealed and without undergoing significant thermal expansion. The sample holder has been designed to include as much thermal insulation as possible, so that significant thermal exchanges can only take place between the upper and lower walls of the sample and not on the four sides. The heating or cooling systems needed to obtain a thermal gradient are positioned under the sample and were designed to achieve thermal gaps between backplate and flow up to 150 K. During the experiment, the flow temperature and the bottom temperature are monitored using thermocouples.

In the positive configuration, the bottom of the sample is heated by two electric resistors that are screwed under a thin aluminum plate positioned just under the sample. This setup ensures a homogeneous heating distribution. In addition, the junction between the aluminum plate and the sample is sealed with thermal paste to ensure a good thermal conductivity. The heating is regulated by an external system allowing to have a constant given temperature on the bottom of the sample. This system combines a PID controller and a solid-state relay and works by setting a temperature target and controlling the resistors' power input to adjust to the true temperature measured with a type K thermocouple placed on top of the aluminum plate.

In the negative gradient configuration, the cooling of the sample's backplate is provided by circulating water through a metal block which is positioned under the sample. As with the heating plate, thermal paste is used at the junction between the block and the sample. The temperature regulation is obtained using a thermostatic bath that maintains a precise temperature and water flow rate. The water temperature is set to around 10 °C and the ideal water flow rate is determined by a 1D preliminary calculation. If P_d is the power transmitted between the bottom of the sample and the outside, then:

$$P_d = \frac{T_u - T_b}{L_s/k_{\text{body}}} = h_{\text{water}} S_e (T_b - T_{\text{water}}) \quad (1)$$

where S_e is the total exchange area between water and metal bloc and h_{water} is the corresponding convection heat coefficient. The water runs through tubes of diameter d_t drilled into the metal bloc, so h_{water} can be expressed as:

$$h_{\text{water}} = \text{Nu} \frac{k_{\text{water}}}{d_t} \quad (2)$$

where Nu is the Nusselt number and k_{water} is the thermal conductivity of water. The value of Nu is obtained through Colburn's correlation for a turbulent duct flow [21]:

$$\text{Nu} = 0.023 \times \text{Re}^{0.8} \times \text{Pr}^{1/3} \quad (3)$$

where Re and Pr are respectively the Reynolds and Prandtl numbers. For temperatures around 20 °C, we use $\text{Re} = 10^4 \times v_{\text{water}}$ where v_{water} is the water speed in m/s inside the tubes. The minimal flowspeed (in m/s) is then given by:

$$v_{\text{water}} = \left(\frac{P_d}{36.45 \times \text{Pr}^{1/3} \times \frac{k_{\text{water}}}{d_t} S_e (T_b - T_{\text{water}})} \right)^{\frac{1}{0.8}} \quad (4)$$

which, as we use 3 tubes ($d_t = 10$ mm) along the whole length of the sample, equals to a flow rate of around 3 to 5 L/min depending on the conditions of the air flow in the test section.

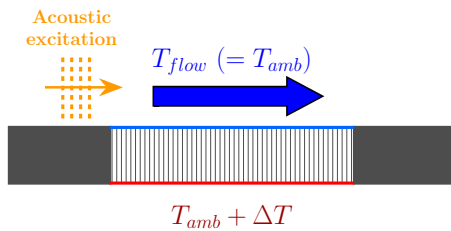


Fig. 3 Positive gradient

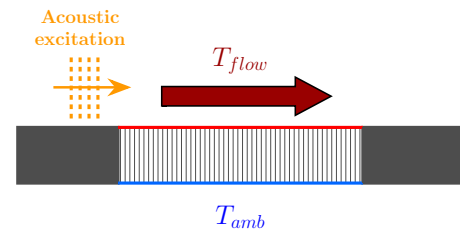


Fig. 4 Negative gradient

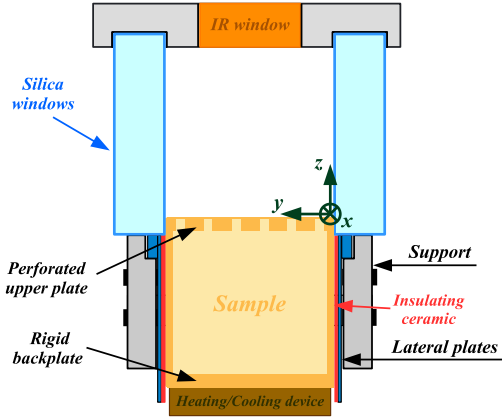


Fig. 5 Cross-section of the testing cell (facing downstream)

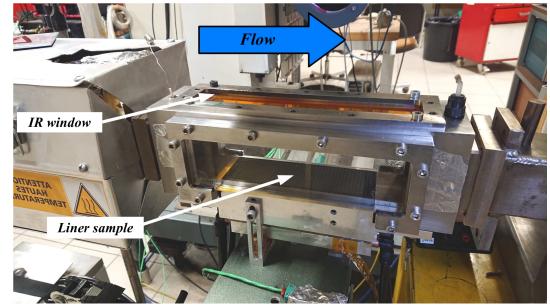


Fig. 6 Picture of the test section (the flow and x axis go from left to right)

D. Setup for infrared thermography

The temperature of the perforated plate T_u is obtained by infrared thermography (Fig. 6). Infrared (IR) thermography is a method of obtaining the temperature of a body by measuring the infrared radiation it emits. The technique relies on a good understanding of the physical phenomena involved and requires carefully controlled experimental conditions. An IR camera and a specific IR window with surface treatment adapted to transmit almost 100% of the incident infrared light are used. The IR window is placed in the top wall of the test section, allowing to see from above the perforated sheet of the sample. Two examples of raw infrared pictures are displayed in Figs. 7 and 8. The raw pictures are 640 pixels wide and 512 pixels high. The spatial resolution is approximately 4 pixels per millimeter. The camera is set up in order to have the area of interest centered in the picture, to minimize the impact of the distortion caused by the lens at the extremities. The camera's internal calibration law is established for several specific temperature ranges. In this study, the calibration used is valid for $15\text{ }^\circ\text{C} < T_u < 73\text{ }^\circ\text{C}$.

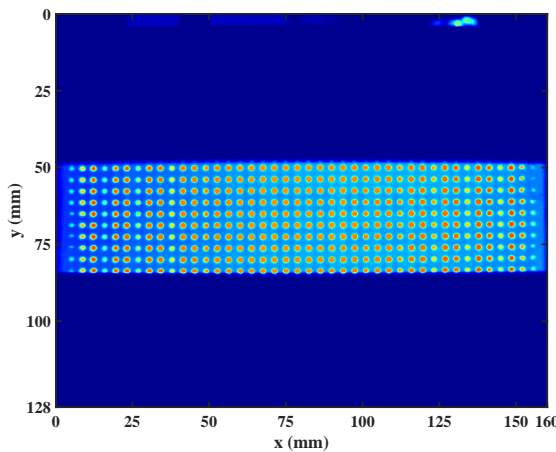


Fig. 7 Raw infrared picture, SDOF sample, $q_m = 50\text{ g/s}$, $T_{flow} = 20\text{ }^\circ\text{C}$

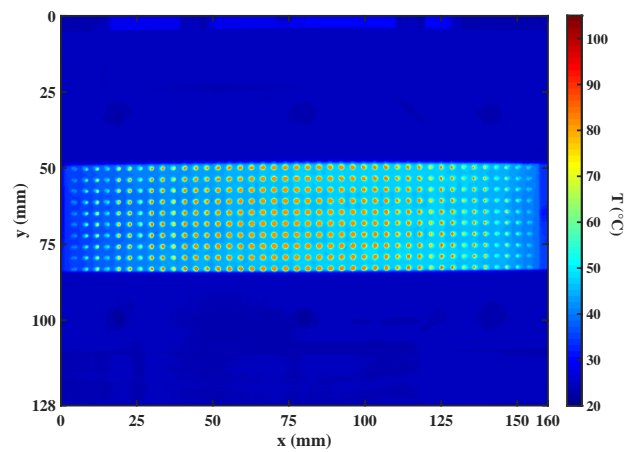


Fig. 8 Raw infrared picture, LEONAR sample, $q_m = 50\text{ g/s}$, $T_{flow} = 20\text{ }^\circ\text{C}$

An assessment of the complete setup’s thermal stability was conducted using a plain rigid aluminum sample; this preliminary study is detailed in [18].

III. Impedance and acoustic results

This section focuses on studying the acoustic behavior of the two liner samples in presence of grazing flow and thermal gradient. This is done on the B2A bench with the acoustic measurement techniques detailed in the previous section. The goal is to assess the similarities and discrepancies between the two samples regarding their acoustical properties and to evaluate the impact of grazing flow and thermal gradient on their respective impedances.

A. Transmission Loss

The global behavior of the samples is determined by measuring the transmission loss between upstream and downstream sections when the samples are mounted in the B2A test cell.

The incident acoustic wave p_i^I is a multi-sine set to 130 dB per tone. A two-microphone method [17, 22] is used to measure the acoustic pressures p_i and p_r in the upstream and downstream section (see Fig.9). The transmission loss in dB is then obtained by the ratio between the incident power and the transmitted power, since the downstream part ends into an anechoic termination. As the frequencies used are below the cut-off frequency of the duct, only plane waves are considered and the incident and transmitted powers are directly linked to the SPL of p_i^I and p_i^{II} .

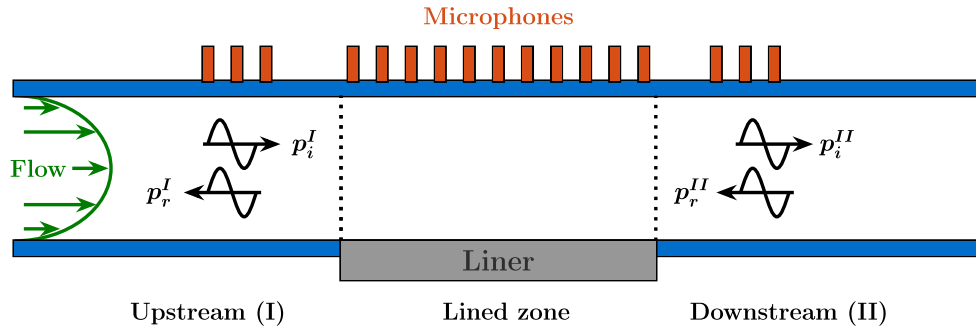


Fig. 9 Sketch of the measurement process

The transmission losses measured on the SDOF and LEONAR samples for $q_m = 100$ g/s are given in Figs. 10 and 11. The optimal absorption band of the sample is the frequency band where the transmission loss is maximal. For the SDOF and LEONAR samples, this band is located around 1 kHz. The maximal TL values of these samples are close, and the width of the band is similar as well. The acoustic behavior of the LEONAR sample is thus very similar to the behavior of the SDOF. The TL is not significantly modified in presence of a thermal gradient. The main effect appears to be a slight shift of the maximum loss band towards higher frequencies, indicating a similar change in the resonance frequency. This result is coherent with Mery et al. [17]: the shift is due to the variation of the temperature inside the cavity, which directly impacts the Helmholtz resonator characteristics.

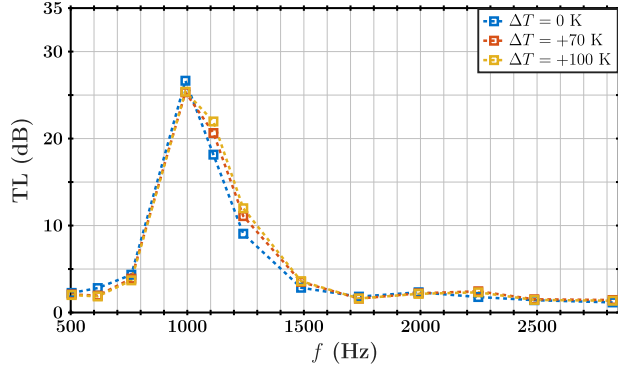


Fig. 10 Transmission Loss (TL), $q_m = 100$ g/s, sample SDOF

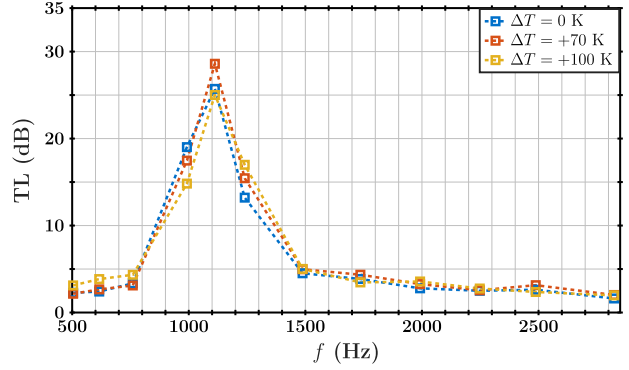


Fig. 11 Transmission Loss (TL), $q_m = 100$ g/s, sample LEONAR

B. Impedance eduction

The impedance of both samples is determined with an impedance eduction method based on the two-dimensional time-harmonic linearized Euler equations (LEE). This method relies on measuring the acoustic pressure on the wall opposite the liner with flush-mounted microphones, as shown in Fig. 9 and using a minimization method where experimental and numerical results are compared. The numerical resolution of the LEE is done with a discontinuous Galerkin (DG) scheme, accounting naturally for the presence of a shear grazing flow in the simulation [19, 23, 24].

Figures 13 to 16 show the impedance eduction results on both samples for $q_m = 100$ g/s and $q_m = 260$ g/s, with an incident SPL set to 130 dB per tone and for three thermal gradient conditions. The acoustic similarity between both samples appears clearly: their respective impedances have the same behavior over the considered frequency range, and their resonance frequencies (i.e. the frequency at which $\chi = 0$) are very close. The influence of the grazing flow is visible and similar on both samples: the resistance r increases when q_m is greater. Yang et al. [25] studied the variations of the impedance of several LEONAR-like liner samples when a grazing flow was applied. Using Guess's model [3] as a basis, they expressed the variation of the impedance taking into account the grazing flow Mach number and the end corrections for the extended tube. The variation of the resistance Δr linked to an increase of the grazing flow Mach number by ΔM_b is then expressed as:

$$\Delta r = \frac{K_M \Delta M_b}{\sigma} \quad (5)$$

where σ is the ratio between the tube and the cavity areas (equal to 0.18 for our LEONAR sample) and K_M is a constant worth 0.12 according to Yang. This value is lower than the constant used in Guess's model, which is worth 0.3 for a SDOF liner; the effect of the grazing flow is expected to be lower on a LEONAR liner than on a classical SDOF liner (in the sense of a thin perforated plate). Using the corresponding values of M_b in Table 3 and Equation , the increase of r when q_m varies from 100 to 260 g/s on the LEONAR sample should be equal to $\Delta r = 0.10$. Figure 12 shows a comparison between this predicted increase and the measured increase, taking in both cases the measured resistance at

$q_m = 100$ g/s as a reference. Around the resonance of the liner (1 kHz), the agreement between the two values (r_p , orange circles, and r , blue squares) is quite good; but at higher frequencies (i.e. far from the resonance) the discrepancy increases. This was also noted by Yang et al. and attributed to higher uncertainties on the eduction process due to less acoustic absorption.

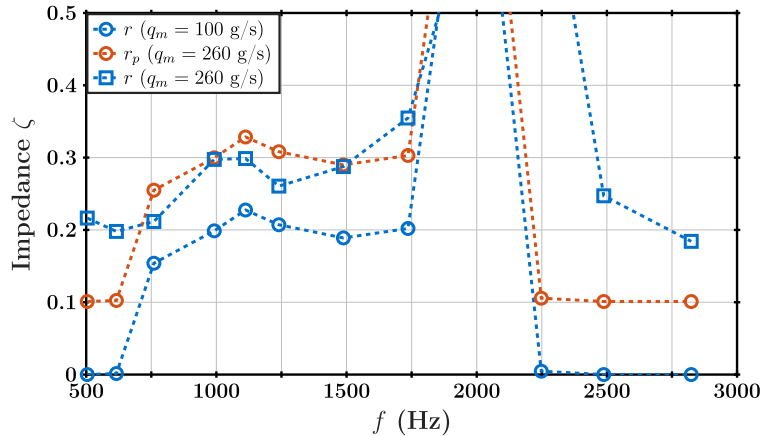


Fig. 12 Comparison of predicted (orange circles) and measured (blue squares) resistance increase at $q_m = 260$ g/s, taking the measured resistance at $q_m = 100$ g/s as a reference (blue circles)

On the other hand, the thermal conditions do not seem to affect much the resistance and the reactance of the two liners: the only significant and consistent effect is a slight shift of the resonance towards the higher frequencies previously highlighted in [17]. This effect seems to be confirmed for the SDOF liner but is reduced on the LEONAR liner. The extended necks of the LEONAR sample apparently have an impact on the temperature distribution inside the cavities; this impact appears significant enough to counterbalance the effect of the thermal gradient on the reactance.

IV. Thermal characterization results

The work by Giachetti et al. [15] and Esnault et al. [16] highlighted the influence of synthetic jets on the heat transfer coefficient of a heated perforated plate subjected to a grazing flow. Since the synthetic jets were emerging from the perforations, this configuration is very similar to our liner subjected to grazing flow, thermal gradients and an acoustic excitation that induces the synthetic jets; thus, similar couplings between aeroacoustic and thermal effects are expected. The goal is thus to assess the existence and intensity of the couplings between grazing flow, thermal and acoustic effects for each thermal configuration and each sample. This is achieved by comparing the surface temperatures of the liner with and without acoustic excitation, and using a 1D-approach to link temperature variations to the heat transfer coefficient, following the methodology developed in [18].

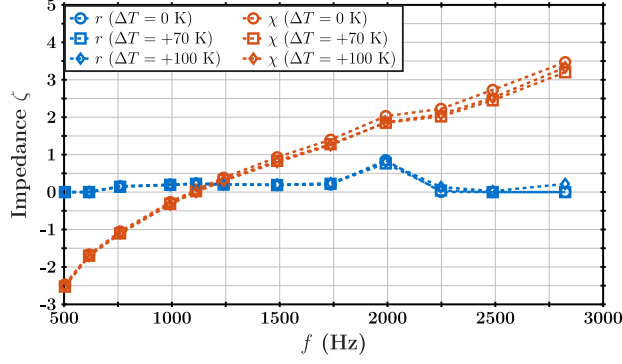


Fig. 13 LEONAR, $q_m = 100$ g/s

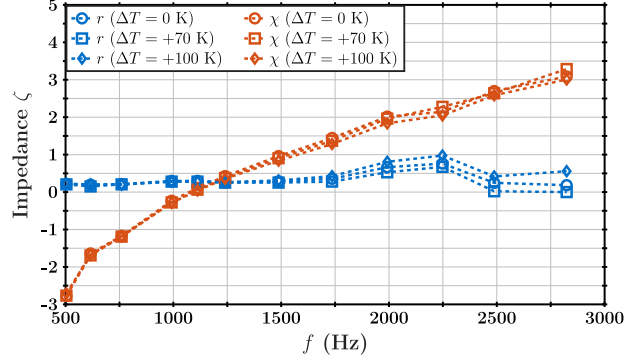


Fig. 14 LEONAR, $q_m = 260$ g/s

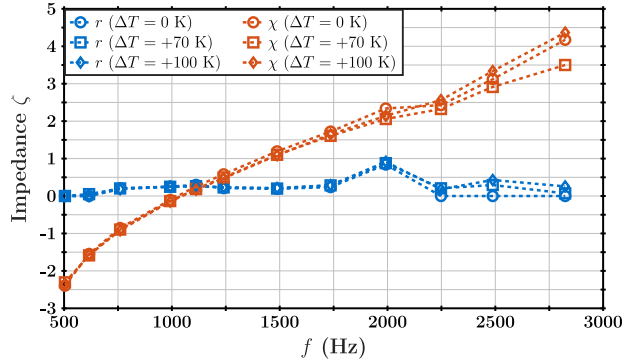


Fig. 15 SDOF, $q_m = 100$ g/s

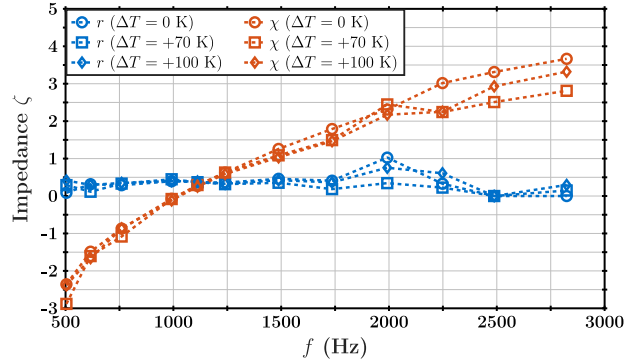


Fig. 16 SDOF, $q_m = 260$ g/s

A. Influence of the type of liner

Figures 17 to 20 show the measured surface temperature on SDOF and LEONAR liner samples at two different flow rates, with a positive thermal gradient defined by $\Delta T = +100$ K. Three acoustic conditions are presented: without excitation, with a multi-sine excitation of SPL = 130 dB/tone, and with a single tone excitation near the resonance (992 Hz for both samples) of SPL = 140 dB. A fourth acoustic condition is also tested on the SDOF sample, only for $q_m = 50$ g/s: a single tone at 1992 Hz, far from the resonance. The profiles are taken in the streamwise direction. The asymmetry of the streamwise profiles is explained by the thermal discontinuities that result in locally higher values of the convective heat transfer coefficient h [18].

The surface temperature is lower on the LEONAR sample than on the SDOF sample in all cases. This is explained by the differences in their internal structures which impacts their respective thermal conductivities. The equivalent thermal conductivity of the samples is indeed determined taking into account the conductivity of the material they are made of and the conductivity of the air trapped inside the cavities. A different internal geometry, such as tubes in the case of the LEONAR sample, results in a different thermal conductivity and thus a different surface temperature. The model used in this study to compute the equivalent thermal conductivity is a simple geometrical approach, thus the values given should be taken with caution; however the values obtained for k_{body} ($1.8 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for the SDOF sample

and $1.1 \text{ W.m}^{-1}.\text{K}^{-1}$ for the LEONAR sample) still give a coherent trend. Indeed, both samples have roughly the same cavity volume, but the LEONAR sample has less material and that material is also less conductive than the material used for the SDOF sample, therefore the thermal conductivity of the LEONAR sample is lower than the conductivity of the SDOF sample.

Without any acoustic excitation (blue curves), the heat convection effect at the surface is visible on both samples. For each sample, when the flow rate increases, the surface temperature decreases as the heat convection at the liner surface increases. The multi-sine acoustic excitation (red curves) leads to a decrease of the surface temperature. This effect is due to the increase of heat convection at the surface, caused by an interaction between the flow, the acoustic waves and the perforations. The reaction is a global one: the decrease is similar over the whole liner length. The temperature decrease is less important when q_m is higher, highlighting the competition between grazing flow and acoustic effects.

On the SDOF sample, when the acoustic excitation is a single tone with a frequency close to the resonance of the sample (yellow curves), the coupling phenomenon is growing. The surface temperature decreases a lot at the beginning of the liner but then increases gradually along the liner until it matches again the value in the case without acoustic excitation. This behavior is explained by the acoustic absorption along the sample: as the acoustic energy is absorbed, the SPL decreases and the thermo-acoustic coupling effect fades out. Indeed, the thermo-acoustic coupling is mainly due to the vortex-shedding phenomenon that increases the heat convection at the liner surface. This localized effect is not visible on multi-sine excitations, even if the overall SPL is the same, because the frequencies far from the resonance are not absorbed by the liner and thus counterbalance the high near-resonance absorption. This specific behavior near resonance does not appear as clearly on the LEONAR sample, highlighting that the thermal behavior of this sample differs from the thermal behavior of the SDOF sample. This could be explained by the differences in the internal structure. Indeed, the thermocouple measurements made by Méry et al. [17] on the same SDOF sample showed that most of the temperature gradient occurs in the first few millimeters below the perforated plate; in the case of the LEONAR, the extended necks may change this temperature distribution inside the cavities, making the vortex shedding effect much less effective as the air is trapped in the space between the extended necks. A numerical investigation made by Yang et al. [25], where a conventional and an extended-tube liner were compared, has confirmed that in an extended-tube configuration such as the LEONAR sample, the vortices shed at the bottom of the tubes are indeed weaker than in the conventional case.

B. Influence of the direction of the thermal gradient

The thermal effects at the liner surface can also be described using the Biot number Bi instead of the temperature, as it allows easier comparisons between thermal configurations thanks to its link to the convective heat transfer coefficient. The Biot number is defined by:

$$Bi = \frac{L_s h}{k_{\text{body}}} \quad (6)$$

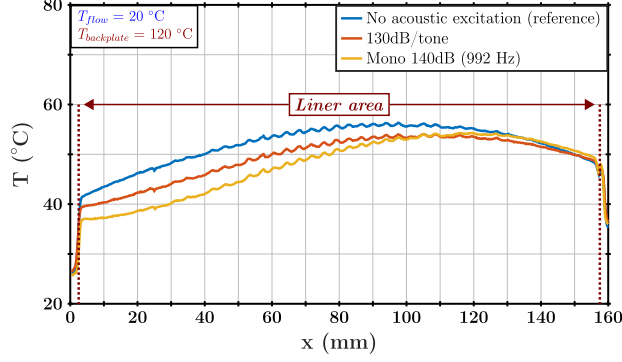


Fig. 17 Sample SDOF, $q_m = 50$ g/s, $\Delta T = +100$ K, different sound excitations, streamwise profile.

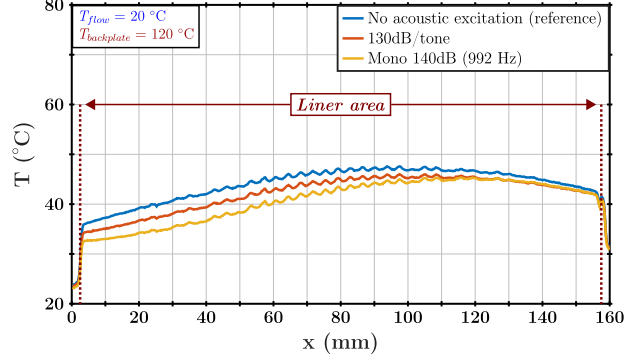


Fig. 18 SDOF, $q_m = 100$ g/s, $\Delta T = +100$ K, different sound excitations, streamwise profile.

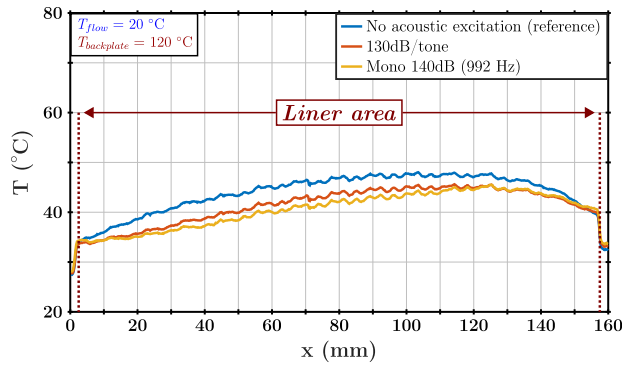


Fig. 19 Sample LEONAR, $q_m = 50$ g/s, $\Delta T = +100$ K, different sound excitations, streamwise profile.

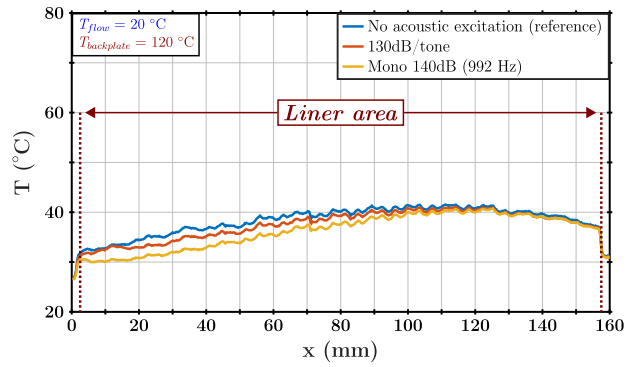


Fig. 20 LEONAR, $q_m = 100$ g/s, $\Delta T = +100$ K, different sound excitations, streamwise profile.

where h is the convective heat transfer coefficient L_s is the sample's height (in the z direction) and k_{body} is the computed equivalent thermal conductivity of the sample.

In our setup, solving the 1D heat equation yields:

$$\text{Bi} = \frac{T_b - T_u}{T_u - T_{\text{flow}}} \quad (7)$$

where T_b , T_u and T_{flow} are the temperatures of the backplate, the perforated plate and the grazing flow respectively.

When the coupling between acoustics and thermal effects is homogeneous on the whole liner surface, the averaged Biot number over the whole liner surface is a good description of the phenomena involved. As shown in Fig. 21, when the acoustic is on, the averaged Biot number increases: as all other boundary conditions remain unchanged, this means that the heat convection increases at the surface of the sample. The increase is similar on both samples, even if the reference value is not the same due to a lower surface temperature on the LEONAR sample. The higher Biot numbers on the LEONAR sample are linked to its lower thermal conductivity compared to the SDOF sample.

Using the Biot number allows to compare directly different thermal configurations, as it eliminates the influence of

the sign of the thermal gap ΔT : Bi is always positive and it increases with h no matter the actual temperature of the flow. Table 4 presents the values of Bi obtained on both samples, as well as the absolute and relative variations ΔBi and $\Delta\text{Bi}/\text{Bi}_{ref}$, at several flow speeds and different thermal gradient values. For both samples, ΔBi decreases when q_m increases, no matter the value of ΔT ; this confirms that the grazing flow dominates the coupling effect at higher flow speeds. At a given flow speed, the values of the Biot number are identical when $\Delta T = +70$ K and when $\Delta T = +100$ K. The same result can be observed in cases with $\Delta T < 0$. This suggests that the value and direction of the gradient have little impact on the intensity of the coupling between thermal and acoustic effects.

The slight discrepancy between the values of the Biot number for positive and negative thermal gradient configurations at the same flow rate is explained by the differences between the experimental setups. Indeed, for the experiments the flow rate was taken as the reference, but it is in fact the Mach number M_b that is linked to the intensity of the flow and thus to the intensity of the coupling. Since M_b is higher in negative configurations due to the higher flow temperature, the flow effect is stronger and thus the increase of Bi is lower than in the equivalent (in terms of flow rate) positive configurations. Moreover, in the positive case, the bottom of the liner is heated but the rest of the test section stays at ambient temperature, while in the negative case the whole duct heats up with the flow; the convective effects are thus different. Figure 22 present the data from the last column of Table 4, plotted as a function of the Mach number instead of the flow rate to illustrate this effect. Apart from the measurements at $q_m = 150$ g/s which appear to be off, the general behavior is consistent no matter the thermal configuration, and the observed differences between negative and positive gradients indeed seem to be linked to the increase of M_b in negative thermal configurations. There is a clear gap between the behavior at low flow speeds (M_b smaller than 0.1) and at higher flow speeds; this gap confirms that the coupling between thermal and acoustic effects is competing with the grazing flow effect. This competition between the influences of high SPL and high flow speeds has been previously studied [24]: it was found that for Mach numbers lower than 0.1, the acoustic effects dominate, but are gradually overwhelmed by the grazing flow until they become too small to be captured.

V. Conclusion

The behavior of two different types of liners under the influence of grazing flow, high SPL and thermal gradients has been studied using infrared thermography. Both liners are almost identical; the differences between them lie in their internal structure. Thus, their acoustic behaviors, characterized using a classical impedance eduction method, are very similar. A specific experimental setup allowed to create precise thermal gradients and to measure the samples' surface temperature with infrared thermography. The influence of these thermal gradients on the impedance of the samples was found to be small, but a coupling between high acoustic levels and the surface temperature of liners has been exhibited. This thermo-acoustic coupling is linked to an increase of the heat convection at the surface of the liner caused by the incident acoustic waves. Hence, the Biot number Bi was used to describe it and compare the behaviors of different

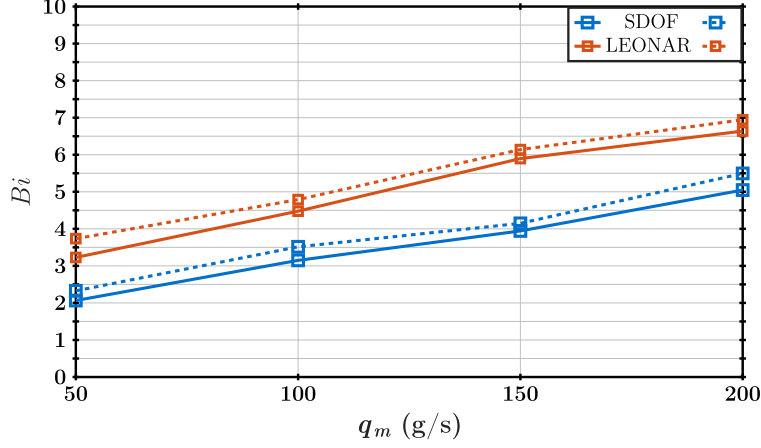


Fig. 21 Biot number (averaged over the whole surface) as a function of q_m , comparison between reference value (solid lines) and with acoustic excitation of SPL=130 dB/tone (dashed lines) for each sample, $\Delta T=+100$ K.

Table 4 Biot number evolution for different thermal conditions on both samples. Bi is averaged over the whole liner surface.

Sample	q_m (g/s)	ΔT	M_b	Bi_{ref}	Bi_{130}	ΔBi	$\Delta Bi/Bi_{ref}$
SDOF	50	+100	0.048	2.15	2.59	0.44	20.5%
		+70		2.15	2.61	0.46	21.4%
		-70	0.054	1.6	1.87	0.27	16.9%
		-100		1.57	1.83	0.25	16.9%
	100	+100	0.097	3.14	3.52	0.37	11.8%
		-100		2.55	2.71	0.16	6.3%
	150	+100	0.145	3.94	4.15	0.21	5.1%
	200	+100	0.194	5.04	5.49	0.45	8.9%
	260	+100	0.251	6.19	6.39	0.2	3.2%
		-100		5.8	5.87	0.07	1.2%
LEONAR	50	+100	0.048	3.16	3.7	0.54	17.1%
		+70		3.12	3.76	0.64	20.5%
	100	+100	0.097	4.68	4.95	0.27	5.8%
		+70		4.43	4.69	0.26	5.9%
	150	+100	0.145	5.89	6.14	0.25	4.2%
	200	+100	0.194	6.63	6.94	0.31	4.7%

liners in various conditions. The flow speed seems to be the main driving parameter for the intensity of the coupling: the additional heat convection effect is high at low flow rates but is reduced for higher flow rates due to the grazing flow effect overwhelming the acoustic level effect. This behavior is similar on both samples when the acoustic excitations are broadband, and the existence and intensity of the coupling turn out to be independent of the actual value and direction of the thermal gradient between the sample's top and bottom. The coupling effect observed is thus clearly linked to the acoustic behavior of the liners, which explains the competition with the influence of the grazing flow. Near the acoustic resonance, the thermo-acoustic coupling becomes spatially localized; this is mainly linked to the structure and behavior

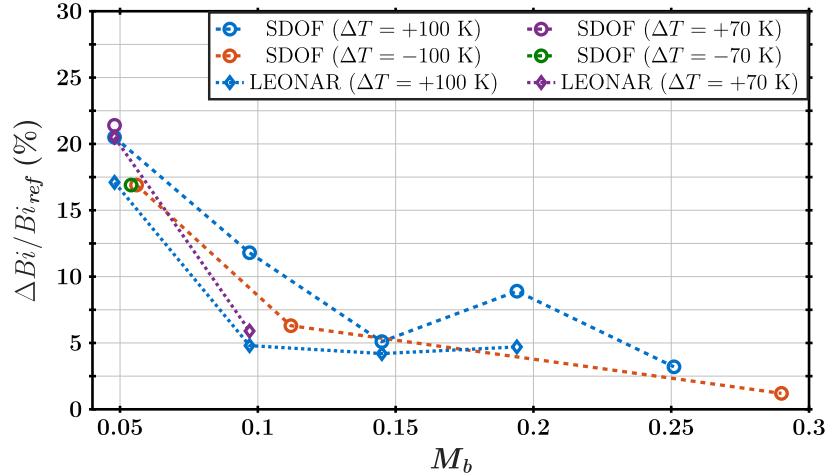


Fig. 22 Relative variations of the Biot number as a function of M_b , comparison between the two samples in different thermal configurations. SPL set to 130 dB/tonne.

of the sample with respect to high incident SPL, as it appears mostly on the SDOF sample which is less linear than the LEONAR concept regarding SPL effects. The thermo-acoustic coupling observed on these two samples is still smaller than the coupling that appears on SDOF sample with thin facesheets, which are even more nonlinear with respect to incident SPL [18]. The LEONAR sample presents an interest in the context of the UHBR since its acoustic behavior is similar to the equivalent SDOF sample and it takes less space and mass. Moreover, this study has shown that the surface temperature of the LEONAR sample is less affected by incident acoustic waves near the acoustic resonance due to its specific internal structure.

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