Experimental Investigation of Shear Grazing Flow Effects on Extended Tube Acoustic Liners

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EXPERIMENTAL INVESTIGATION OF SHEAR GRAZING FLOW EFFECTS ON EXTENDED TUBE ACOUSTIC LINERS

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ABSTRACT

Aircraft engines are one of the dominant noise sources for subsonic aircraft. In current turbofan engines, the inlet, by-pass and exhaust parts of the nacelle are lined with acoustic liners. Liners consist essentially of a perforated plate backed by an air cavity, and have a resonator behavior.

To meet the demand of future industry standards in terms of engine efficiency, ultra high bypass ratio engines are now considered. The acoustic emission of these engines is at lower frequencies, motivating the design of acoustic liners than can target this frequency regime, at an ever reduced thickness. To do so, one possible solution is to implement tubes that extend within the cavity in order to reduce the resonance frequency. Perforated plates are known to have a non-linear behavior regarding the presence of a shear grazing flow. However, such studies have yet to be performed for materials possessing extending tubes in the cavity. The focus of the present work is put on an experimental investigation on the influence of a shear grazing flow on the acoustic impedance of liners whose upper sheet perforations are extended with tubes. An impedance eduction process is performed on 6 different liners, at Mach numbers ranging from 0 (reference no flow case) to 0.3 and at frequencies close to the resonance frequency.

1. INTRODUCTION

Ultra High Bypass Ratio engines are one of the technological solutions currently under investigation in Europe to reduce the environmental impact of short and medium range aircrafts. The integration of such a power plant system will require shorter and thinner nacelles, while the noise emission will be at lower frequencies than the usual turbofan engines. Consequently, efficient noise abatement via the acoustic lining of the inner walls of the nacelle will be all the more challenging. That is why ONERA is developing new acoustic liners based on the LEONAR concept [1] to improve the noise efficiency at low frequencies while keeping the liner thickness as small as possible. In this paper, an experimental investigation has been conducted in a laboratory facility to analyze the influence of a shear grazing flow on the acoustic response of such liners.

The acoustic surface impedance

$$Z = R + \mathrm{j}\chi = \frac{p}{\vec{u}\cdot\vec{n}}, \quad (1)$$

with R the resistance and χ the reactance, is a complex quantity relating pressure p and normal velocity $\vec{u}\cdot\vec{n}$ at the surface of an acoustic material ($Z = +\infty$ for a rigid wall, $Z = 0$ for a pressure release condition). Understanding the effects of a complex flow on the effective acoustical impedance of nacelle liners is of prime importance for current nacelle liner design and has been the focus of many research studies in the past [2–11]. While classical liners display an absorption ability that is limited to medium and high frequencies, LEONAR materials (Long Elastic Open Neck Acoustic Resonator), which consist of perforated plates linked to a cavity via tubes, can target the low frequency range. This is of particular interest due to the ever increasing constraints in material thicknesses allowed in engine nacelles. However, there has not been, to date, an experimental investigation aimed at studying the effect of a grazing flow on these types of materials.

To correctly study such a behavior, one has to measure the impedance of a liner when it is subject to aeronautic conditions. Inverse "eduction" methods have been widely used to retrieve the impedance of liners with indirect non-intrusive measurements, while in the presence of a grazing flow [9, 12].

The goal of this work is to conduct and analyze impedance measurements in flow conditions of extended-tube materials, to assess the validity of current semi-empirical models for impedance prediction. The paper is organized as follows. In Sec. 2, the sample geometry is recalled, and a classical "flow nonlinearity" model from the litterature is introduced. The experimental and numerical tools are given in Sec. 3. Impedance eduction results are analyzed in Sec. 4, and a conclusion is drawn in Sec. 5.

2. MODELING

2.1 LEONAR materials

A LEONAR consists of a perforated panel with a lattice of extended tubes in the back cavity, as shown in Fig. 1. Different modeling are readily available to evaluate the acoustic response (impedance) of such a material [1, 13–15],

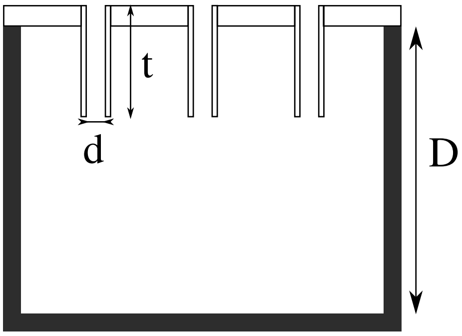

Figure 1: Schematics of a LEONAR cell

which allows for the optimization of its properties (tube diameter d and length t). In the present work, the properties of the samples that were tested were chosen in order for the material to be absorbent in the frequency range where our eduction process was known to be optimally precise, i.e. around 1kHz.

2.2 Nonlinear flow effects

Guess [5] used the model of Ingard and Ising [16] as a basis to describe non-linear effects on the resistance, caused by both a high sound pressure level and a grazing flow, as

$$\frac{R_{NL}}{\rho_f c_f} = \frac{1-\phi^2}{\phi}\left[\frac{|u_0|+|v|}{c}\right], \tag{2}$$

where u_0 is the acoustic velocity of the incident wave (neglected in this work), and v is an estimate of the magnitude of the turbulent velocity fluctuation due to a turbulent boundary layer. In Guess model, the simplification

$$\frac{|v|}{c} = k_r M, \quad k_r \approx 0.3 \tag{3}$$

is made, where k_r represents the degree of nonlinearity of a given material, and is assumed constant initially.

The model structure appears much simpler than that of the Kirby and Cummings (KC) model [17]. The reason for which it is considered here, and not the KC model, is that the latter involves in its definition a ratio of perforation length over diameter t/d. The KC model was calibrated with different experiments where the t/d ratio ranged from 0.286 to 0.484 [17, Table 1]. In the case of LEONAR materials, this ratio is often greater than 5, and this leads to abberant predictions by the KC model (i.e., a large diminution of the resistance is predicted at all frequencies). While the Guess model appears initially simpler and less "local" (i.e., it uses an average Mach number instead of a friction velocity, and a porosity instead of a perforation diameter and thickness), it seems to be more robust in our case (i.e., it always predicts an increase in the resistance, which is what is often seen in practice).

The goal of this work is to evaluate this $k_r = 0.3$ factor, and see if we can derive a more accurate expression for LEONAR materials.

3. IMPEDANCE EDUCTION

To obtain this impedance value of an acoustic sample subject to a grazing flow, different steps are required. In Subsec. 3.0.1, the experimental method is recalled, where an aeroacoustic bench is used in conjunction with a microphone array. In Subsec. 3.0.2, the numerical problem is presented, in which the aeroacoustic bench is modeled. Then, the inverse problem is introduced in Subsec. 3.0.3.

3.0.1 Experimental method

The ONERA B2A flow duct is a $4\mathrm{m}$ long stainless steel tube of square section $50\mathrm{mm} \times 50\mathrm{mm}$.The termination is equipped with a quasi-anechoic outlet, leading to an upstream reflection coefficient smaller than 0.2 for frequencies higher than $500\mathrm{Hz}$. Only the plane wave duct mode is considered, up to a frequency of $\approx 3400\mathrm{Hz}$. A fully developed turbulent duct flow of bulk Mach numbers up to 0.6 can be provided, where the turbulence rate is of a few percent at the center of the test section. However, the flow Mach number is kept below or equal to 0.3 in practice, to allow for acoustic waves to "enter" the duct. At higher flow velocities, the acoustic refraction caused by the shear flow at the loudspeaker junction is too high to let any acoustic wave enter the duct.

3.0.2 Direct problem

To make the numerical simulations tractable, a simplified 2D case is considered, as sketched in Fig. 2. In practice,

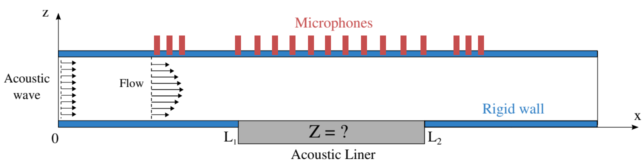

Figure 2: Schematics of an aero-acoustic bench for liner impedance eduction

the flow is 3D, but the lined section spans the wall width of the duct, so it is estimated that the simplification does not alter significantly the educed impedance values. Obtaining the numerical acoustic fields necessary for the impedance eduction strategy requires solving the equations of acoustic propagation in the presence of a grazing flow. To do so, the two-dimensional time-harmonic Linearized Euler equations (LEE) are used. The underlying model is briefly summarized here for convenience, but all details can be found e.g. in Ref. [18].

The LEE, written in non-conservative form with an $e^{\mathrm{j}\omega t}$ time dependence and assuming homentropic flow, are given by

$$\mathbf{L}\varphi = 0, \tag{4}$$

where

$$\mathbf{L}\varphi = \mathrm{j}\omega\varphi + \boldsymbol{A}_x\frac{\partial\varphi}{\partial x} + \boldsymbol{A}_y\frac{\partial\varphi}{\partial y} + \boldsymbol{B}\varphi, \tag{5}$$

and

$$\boldsymbol{A}_x = \begin{pmatrix} U & 0 & c_f \\ 0 & U & 0 \\ c_f & 0 & U \end{pmatrix}, \quad \boldsymbol{A}_y = \begin{pmatrix} V & 0 & 0 \\ 0 & V & c_f \\ 0 & c_f & V \end{pmatrix}, \quad (6)$$

$$\boldsymbol{B} = \begin{pmatrix} \partial_x U & \partial_y U & 0 \\ \partial_x V & -\partial_x U & 0 \\ 0 & 0 & 0 \end{pmatrix}. \quad (7)$$

Components of vector $\varphi = \left(u, v, \frac{p}{\rho_f c_f}\right)$ represent the acoustic perturbations around the mean shear flow of axial and transverse velocities U and V, respectively. Due to the homentropy condition, the energy equation is replaced by the state equation $p = c_f^2 \rho$, with ρ the acoustic density.

As we consider a mean shear flow profile, the impedance boundary condition on the lined wall is the standard one

$$p = \pm \rho_f c_f Z v, \quad (8)$$

where the sign is chosen depending on whether the upper or lower wall is considered.

A Discontinuous Galerkin (DG) scheme is chosen to solve Eq. 4 and the associated boundary conditions. In this method, discontinuities are allowed at the interface between two elements. An example of how such a method can handle discontinuities at hard-soft wall interfaces is found in Refs. [19, 20]. To ensure the connection between elements and to apply the boundary conditions, a numerical flux is defined. An upwind numerical flux is used to ensure connection between interior cells, while a centered flux is chosen at the boundaries (see previous papers [18, 21] for more details).

3.0.3 *Inverse problem*

Now that the direct problem has been derived, the inverse problem can be tackled. It consists in retrieving the impedance value (process called eduction) from experimental measurements of an acoustic field (acoustic pressure measurements here). All details regarding the deterministic eduction procedure can be found e.g. in Ref. [18], but the gist is recalled here for completness.

An experimental observation q_{obs} is performed in the duct, by means of a microphone array. A numerical operator G_{LEE} is created, that takes as input an impedance value Z, and yields as an output the projection of the numerical field onto the observation space. By minimizing the numerical and experimental mismatch, the "true" impedance is educed. The process is summarized in the equation below:

$$Z = \underset{\zeta}{\text{argmin}} \left(\| G_{\text{LEE}}(\zeta) - q_{\text{obs}} \|_2 \right). \quad (9)$$

where ζ is an optimization variable. Note that the operator G_{LEE} depends on the flow profile and on the frequency. In addition, the source coefficient and the outlet impedance are also taken as variables in the minimization above, but have been removed from the explanation for simplicity since they are not relevant in the following discussions.

Sample	d(mm)	t(mm)	ϕ	D(mm)
1	2	5	0.122	19
1-1	2	5	0.084	19
1-2	2	5	0.050	19
2	3	10	0.094	19
2-1	3	10	0.071	19
2-2	3	10	0.047	19

Table 1: LEONAR cell properties

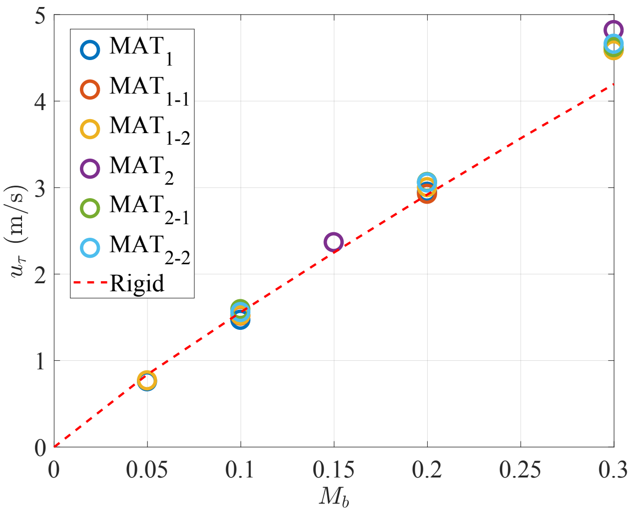

Figure 3: Friction velocity of all materials. The dashed red curve represents the values of the rigid wall case, from Ref. [22]

4. RESULTS

To complete the previous experiments, 6 LEONAR samples were designed for testing in the B2A at bulk Mach numbers ranging from 0 to 0.3. The goal was to observe, near the resonance of single-cell LEONARs, the evolution of impedance with flow. The properties of these materials are summarized in Table 1. The 6 materials have circular cylindrical tubes. For each material, different flow Mach numbers were tested. The acoustic content was set to multitones close to the resonance frequency of the liner. For each tone, each Mach number and each material, an impedance eduction was performed, resulting in 474 different eductions. In addition to these acoustic measurements, the friction velocity was also evaluated at each configuration, using static pressure measurements to obtain the pressure loss created by the liner (see Fig. 3). Overall the friction velocity presents a linear behavior with the Mach number in the range considered, and can simply be taken at $u_\tau = \epsilon M_b$, with $\epsilon \approx 15$m/s. The range of values obtained is quite close to the one that was calculated on the same bench, in a previous study with a rigid wall [22].

Once the impedance was educed in all the 474 cases, it was possible to evaluate the experimental k_r of the Guess model (see Eq. 3) to evaluate the degree of nonlinearity of the samples with respect to the flow. To do so, the reference Mach=0 impedance is subtracted from subsequent educed impedance, and the difference is normalized as

$$k_r = (R_{\text{tot}} - R_0) \,/\, \left(\frac{1-\phi^2}{\phi} M_b\right).$$

An equivalent definition is taken for k_i, that represents the nonlinear effect of the flow on the reactance:

$$k_i = (\chi_{\text{tot}} - \chi_0) \,/\, \left(\frac{1-\phi^2}{\phi} M_b\right).$$

Results are displayed in Figs. 4a–4b.

Interestingly, the ratio of $k_r = 0.3$ proposed in Guess model seems to overestimate the nonlinearity factor observed in the present experiments. This means that for the set of samples tested, the nonlinearity with respect to flow is less than predicted by Guess model. As the Mach number increases, the k_r factor also increases. At low Mach (≤ 0.1), a negative nonlinearity factor is observed for the resistance. This relates to the previous observation made in Ref. [6], where the nonlinear resistance was shown to be negative at low Mach numbers. If a linear relationship is assumed between M_b and k_r, the updated Guess model for LEONAR materials would be, for the resistance,

$$R_{\text{tot}} = R_0 + \frac{1-\phi^2}{\phi} a M_b \left(M_b - b\right), \tag{10}$$

with R_0 the resistance at Mach 0, $a = 0.39$ and $b = 0.17$. The regression is performed on the average of k_r at each Mach number, and the regression coefficient is $r^2 = 0.98$.

For the reactance, things are less clear cut. While a positive nonlinear factor is obtained at $M_b = 0.05$, it is negative at higher Mach on average. This is in adequation with the trend observed for classical liners: slight reactance decrease as the flow velocity increases. A Guess-like model for the reactance could be taken as

$$\chi_{\text{tot}} = \chi_0 + \frac{1-\phi^2}{\phi} a M_b, \tag{11}$$

with χ_0 the reactance at Mach 0 and $a = -0.0027$ (two orders of magnitude lower than the original Guess model for the resistance). The a parameter is found by averaging all k_i values.

At low Mach numbers, both the resistance and the reactance do not behave as initially expected. This might be a sign that at these velocities, an unpredicted interaction between acoustics and local flow at the perforations is present.

5. CONCLUSION

This work has focused on the evaluation of the influence of a shear grazing flow on liners based on the concept of LEONAR materials (extended tubes in the cavity). These materials are particularly attractive due to their ability to absorb sound at low frequencies. A total of 474 impedance eductions were performed on a new set of 6 materials, at Mach numbers ranging from 0 to 0.3. These samples consisted of single-cell LEONARs (only one type of tube). The tests showed that increasing the flow velocity had a different effect on LEONAR materials than what was predicted by the models from the literature. In particular, the increase in resistance (real part of the impedance) usually observed when the flow speed increases, was not as marked in our new tests. This confirms that a high ratio of tube length over tube diameter t/d is a significant marker for shear grazing flow effects on impedance. However, this trend was not reproduced in previous models, in particular in the widespread Kirby & Kummings model, where for these materials, a reduction in the resistance is predicted at high Mach numbers, instead of an increase.

a Guess-like model was given for both the resistance and the reactance. Further tests are warranted to continue exploring the t/d design space and enrich the proposed modeling.

6. FUNDINGS

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7. REFERENCES

[1] F. Simon, "Long elastic open neck acoustic resonator for low frequency absorption," *Journal of Sound and Vibration*, vol. 421, pp. 1–16, 2018.

[2] U. Ingård and S. Labate, "Acoustic circulation effects and the nonlinear impedance of orifices," *The Journal of the Acoustical Society of America*, vol. 22, no. 2, pp. 211–218, 1950.

[3] D. Tack and R. Lambert, "Influence of shear flow on sound attenuation in a lined duct," *The Journal of the Acoustical Society of America*, vol. 38, no. 4, pp. 655–666, 1965.

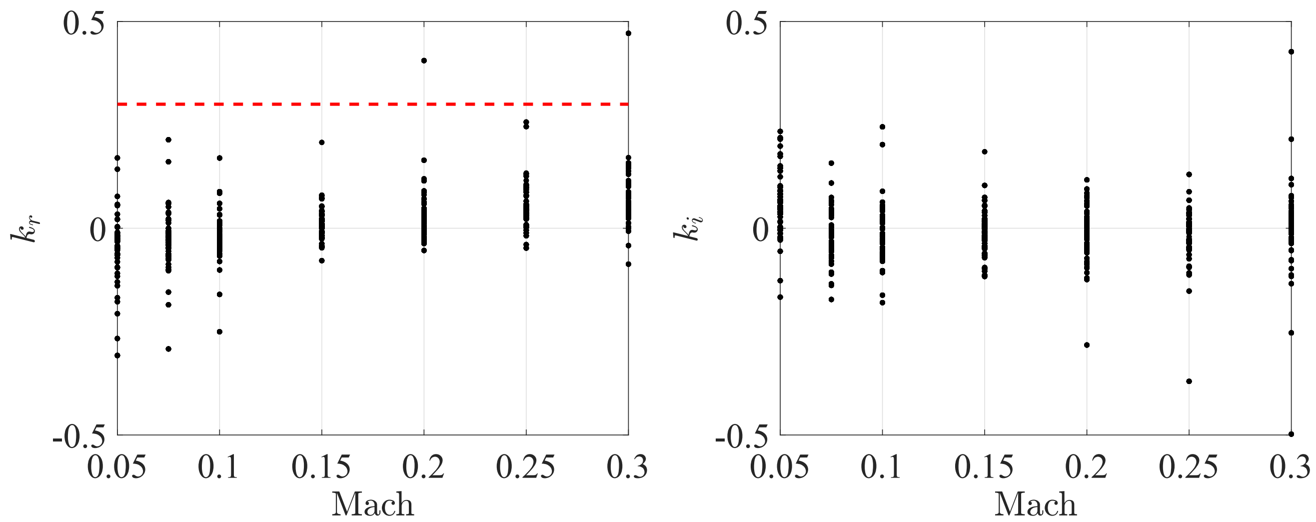
[4] B. Tester, "The propagation and attenuation of sound in lined ducts containing uniform or "plug" flow," *J. Sound Vib.*, vol. 28, no. 2, pp. 151–203, 1973.

[5] A. Guess, "Calculation of perforated plate liner parameters from specified acoustic resistance and reactance," *J. Sound Vib.*, vol. 40, no. 1, pp. 119–137, 1975.

[6] A. Goldman and R. L. Panton, "Measurement of the acoustic impedance of an orifice under a turbulent boundary layer," *The Journal of the Acoustical Society of America*, vol. 60, no. 6, pp. 1397–1405, 1976.

[7] W. R. Watson, M. G. Jones, S. E. Tanner, and T. L. Parrott, "Validation of a numerical method for extracting liner impedance," *AIAA journal*, vol. 34, no. 3, pp. 548–554, 1996.

[8] X. Sun, X. Jing, H. Zhang, and Y. Shi, "Effect of grazing–bias flow interaction on acoustic impedance



(a) Nonlinearity factor for the resistance. Red dashed line represents the Guess model value for k_r

(b) Nonlinearity factor for the reactance

Figure 4: Quantification of the nonlinearity of the samples by use of Guess criterion

of perforated plates," *J. Sound Vib.*, vol. 254, no. 3, pp. 557–573, 2002.

[9] M. G. Jones, W. R. Watson, and T. L. Parrott, "Benchmark data for evaluation of aeroacoustic propagation codes with grazing flow," *AIAA paper*, vol. 2853, p. 2005, 2005.

[10] Q. Zhang and D. J. Bodony, "Numerical investigation of a honeycomb liner grazed by laminar and turbulent boundary layers," *J. Fluid Mech.*, vol. 792, pp. 936–980, 2016.

[11] R. Roncen, F. Méry, E. Piot, and F. Simon, "Statistical inference method for liner impedance eduction with a shear grazing flow," *AIAA Journal*, pp. 1–11, 2018.

[12] W. Eversman and J. M. Gallman, "Impedance eduction with an extended search procedure," *AIAA journal*, vol. 49, no. 9, pp. 1960–1970, 2011.

[13] F. Simon, "Low frequency sound absorption of resonators with flexible tubes," in *Proceedings of Meetings on Acoustics ICA2013*, vol. 19, p. 030012, Acoustical Society of America, 2013.

[14] D. Li, D. Chang, and B. Liu, "Enhancing the low frequency sound absorption of a perforated panel by parallel-arranged extended tubes," *Applied Acoustics*, vol. 102, pp. 126–132, 2016.

[15] D. Li, D. Chang, and B. Liu, "Enhanced low-to mid-frequency sound absorption using parallel-arranged perforated plates with extended tubes and porous material," *Applied Acoustics*, vol. 127, pp. 316–323, 2017.

[16] U. Ingard and H. Ising, "Acoustic nonlinearity of an orifice," *The journal of the Acoustical Society of America*, vol. 42, no. 1, pp. 6–17, 1967.

[17] R. Kirby and A. Cummings, "The impedance of perforated plates subjected to grazing gas flow and backed by porous media," *J. Sound Vib.*, vol. 217, no. 4, pp. 619–636, 1998.

[18] J. Primus, E. Piot, and F. Simon, "An adjoint-based method for liner impedance eduction: Validation and numerical investigation," *J. Sound Vib.*, vol. 332, pp. 58–75, January 2013.

[19] L. Pascal, E. Piot, and G. Casalis, "Discontinuous Galerkin method for the computation of acoustic modes in lined flow ducts with rigid splices," *Journal of Sound and Vibration*, vol. 332, no. 13, pp. 3270 – 3288, 2013.

[20] L. Pascal, E. Piot, and G. Casalis, "Discontinuous galerkin method for acoustic modes computation in lined ducts," in *18th AIAA/CEAS Aeroacoustics Conference (33rd AIAA Aeroacoustics Conference)*, p. 2153, 2012.

[21] E. Piot, J. Primus, and F. Simon, "Liner impedance eduction technique based on velocity fields," in *18th AIAA/CEAS Aeroacoustics Conference (33rd AIAA Aeroacoustics Conference)*, p. 2198, 2012.

[22] O. Léon, F. Méry, E. Piot, and C. Conte, "Near-wall aerodynamic response of an acoustic liner to harmonic excitation with grazing flow," *Experiments in Fluids*, vol. 60, no. 9, p. 144, 2019.