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Smart Acoustic Lining for UHBR Technologies Engine Part 1: design of an electroacoustic liner and experimental characterization under flow in rectangular cross-section ducts

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Abstract

The new generation of Ultra-High-By-Pass-Ratio (UHBR) turbofan
engine while considerably reducing fuel consumption, threatens higher

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noise levels at low frequencies because of its larger diameter, lower number of blades and rotational speed. This is accompanied by a shorter nacelle, leaving less available space for acoustic treatments. In this context, a progress in the liner technology is highly demanded, prospecting alternative solutions to classic liners. The SALUTE H2020 project has taken up this challenge, proposing electro-active acoustic liners, made up of loudspeakers (actuators) and microphones (sensors). The electro-active means allow to program the surface impedance on the electroacoustic liner, but also to conceive alternative boundary laws. Test-rigs of gradually increasing complexities have allowed to raise the Technology Readiness Level (TRL) up to 3-4. In this first part, we describe the control laws employed in the experimental campaigns, and present the scattering performances in rectangular waveguides with monomodal guided propagation. These results have assessed the isolation capabilities, stability and robustness of such programmable boundary technology, allowing to gain confidence for the successive implementation in a scaled turbofan test-rig.

1 Introduction

The acoustic problem of interest here, is the noise transmission mitigation in an open duct, by treatment of the parietal walls with the so-called liners. Examples of industrial fields where this problem is particularly felt are the Heating and Ventilation Air-Conditioning Systems (HVAC) and the aircraft turbofan engines. The new generation of Ultra-High-By-Pass-Ratio (UHBR) turbofans, in order to comply with the significant restrictions on fuel consumptions and pollutant emissions, present larger diameter, lower number of blades and rotational speed and a shorter nacelle. These characteristics conflict with the equally restrictive regulations on noise pollution, as the noise signature is shifted toward lower frequencies, which are much more challenging to be mitigated by parietal treatments. The acoustic liner technology applied nowadays for noise transmission attenuation at the inlet and outlet portions of turbofan engines is the so-called Single or Multi-Degree-of-Freedom liner, whose working principle relates to the quarter-wavelength resonance, and demands larger thicknesses to target lower frequencies. They are made of a closed honeycomb structure and a perforated plate which is used to provide the dissipative effect, to add mass in order to decrease the resonance frequency, and also to maintain the aerodynamic flow as smooth as possible on the internal wall of the nacelle. As the honeycomb structure is impervious, propagation is prevented transversely to the wall, therefore it can be considered as *locally reacting* as long as the incident field wavelength

is much larger than the size of the honeycomb cells [Ma and Su(2020)]. A first interest for active control is the possibility to tune the resonators to different frequencies. Many adaptive Helmholtz resonator solutions have been proposed by varying either the acoustic stiffness (i.e. the cavity as in [Hermiller and Maddux(2013)]), or the acoustic mass (i.e. the orifice area, as in [Esteve and Johnson(2004)]), but both these techniques tended to present complex structure, excessive weight and high energy consumption [Ma and Su(2020)].

Active Noise Cancellation (ANC) have provided alternative solutions for achieving higher attenuation levels. From the seminal idea of Olson and May [Olson and May(1953)], first active *impedance control* strategies [Guicking and Lorenz(1984), Galland et al.(2005)Galland, Mazeaud, and Sellen] proposed an “active equivalent of the quarter wavelength resonance absorber” for normal and grazing incidence problems, respectively. The same technique was slightly modified by [Betgen and Galland(2011)] in the attempt to reproduce the Cremer’s liner optimal impedance for the first duct modes pair [Cremer(1953), Tester(1973)]. As such impedance could not be achieved in a broadband sense, this approach remained limited to monotonal applications.

These are examples of impedance control achieved through secondary source approaches combined with passive liners, but the collocation of sensor and actuator suggested also another avenue: the modification of the actuator (loudspeaker or else) own mechano-acoustical impedance. The objective shifts from creating a “quite zone” at a certain location, to achieving an optimal impedance on the loudspeaker diaphragm. This is the Electroacoustic Resonator (ER) idea, which have found various declinations, such as electrical-shunting [Fleming et al.(2007)Fleming, Niederberger, Moheimani, and Morari], direct-impedance control [Furstoss et al.(1997)Furstoss, Thenail, and Galland] and self-sensing [Leo and Limpert(1999)]. In order to overcome the low-flexibility drawback of electrical shunting techniques, minimize the number of sensors, meanwhile avoiding to get involved into the electrical-inductance modelling of the loudspeaker, a pressure-based current-driven architecture proved to achieve the best absorption performances in terms of both bandwidth and tunability [Rivet et al.(2017)Rivet, Karkar, and Lissek]. It employs one or more pressure sensors (microphones) nearby the speaker, and a model-inversion digital algorithm to target the desired impedance by controlling the electrical current in the speaker coil. Compared to classical ANC strategies, the impedance control is conceived to assure the acoustical passivity of the treated boundary, and hence the stability of the control system independently of the external acoustic environment [Goodwin

et al.(2007)Goodwin, Graebe, and Salgado]. The correlation between passivity and stability of the ER, has been analysed in [De Bono et al.(2019)De Bono, Collet, Karkar, Matten, Lissek, and Laurence,De Bono et al.(2022)De Bono, Collet, Matten, Karkar, Lissek, Ouisse, Billon, Laurence, and Volery]. The same architecture of ER has also been exploited to conceive an alternative control algorithm capable of enforcing nonlinear acoustical responses of the ER at low excitation levels [De Bono et al.(2024a)De Bono, Morell, Collet, Gourdon, Ture Savadkoochi, Ouisse, and Lamarque,Morell et al.(2024a)Morell, Gourdon, Collet, Ture Savadkoochi, De Bono, and Lamarque, da Silveira Zanin et al.(2023)da Silveira Zanin, Labetoulle, De Bono, Gourdon, Collet, and Ture Savadkoochi,Morell et al.(2023)Morell, Collet, Gourdon, and Savadkoochi,Morell et al.(2021)Morell, De Bono, Collet, Gourdon, and Savadkoochi,Morell et al.(2024c)Morell, Gourdon, Collet, Ture Savadkoochi, and De Bono]. In [Collet et al.(2006)Collet, David, and Berthillier], for the first time, a boundary operator involving the spatial derivative was targeted by distributed electroacoustic devices. It was the first form of the Advection Boundary Law (ABL), then implemented on ER arrays lining an acoustic waveguide in [Karkar et al.(2019)Karkar, De Bono, Collet, Matten, Ouisse, and Rivet], where it demonstrated non-reciprocal sound propagation. The performances of such *generalized impedance* control law have been studied both in its local and nonlocal declination in [De Bono et al.(2024b)De Bono, Collet, and Ouisse,De Bono et al.(2023)De Bono, Ouisse, Collet, Salze, and Mardjono,Salze et al.(2024)Salze, De Bono, Billon, Gillet, Volery, Collet, Ouisse, Lissek, and Mardjono,Billon et al.(2022a)Billon, De Bono, Perez, Salze, Matten, Gillet, Ouisse, Volery, Lissek, Mardjono, and Collet,Billon et al.(2021)Billon, De Bono, Perez, Salze, Matten, Gillet, Ouisse, Volery, Lissek, Mardjono, and Collet,Billon et al.(2022b)Billon, Collet, Salze, Gillet, Ouisse, Volery, Lissek, and Mardjono,Billon et al.(2023)Billon, Gillet, Salze, Volery, De Bono, Ouisse, Lissek, Collet, and Mardjono].

The SALUTE projects has the objective to prompt the Technology-Readiness-Level (TRL) of a liner made up of ERs. Compact cells, each one integrating 4 microphones, a speaker and a microprocessor to execute the control algorithm, compose an array which can replace the parietal walls of a duct. In order to protect the electromechanical devices from the turbulent flow, a wiremesh, sustained by a perforated plate, is placed in front of the electroacoustic liner. Such protective liner is supposed to be quasi-transparent with respect to the acoustic field. In this first part of our contribution, we analyse the results obtained by the numerical and experimental campaign to characterize the performances of the electroacoustic liner in presence of flow. The importance of these achievements rely in the assessment of such innovative boundary

control technology, for noise isolation in acoustic waveguides with flow. We report here the results achieved at two intermediate test-bench, which allowed to gain the necessary confidence for testing our liner in a scaled 1:3 reproduction of turbofan engine, called PHARE-2 [Pereira et al.(2019)Pereira, Salze, Regnard, Gea-Aguilera, and Gruber]. The experimental campaign on PHARE-2 follows in the Part 2 of this work.

2 Numerical simulations without flow

First of all, let us define the boundary operator we target by our electroacoustic liner. It is called Advection Boundary Law (ABL), which writes:

$$Z_{Loc}(\partial_t) * \partial_t v_n = \partial_t p + U_b \partial_x p, \quad (1)$$

where $Z_{Loc}(\partial_t)$ is a Single-Degree-Of-Freedom (SDOF) local impedance convolution operator in time, $*$ is the convolution operation, v_n is the normal velocity at the boundary, p the pressure. For classical locally reacting liners, $Z_{Loc}(\partial_t)$ relates the local acceleration to the time derivative of the local sound pressure $\partial_t p$. Our *generalized impedance* operator includes an additional term, given by U_b times the spatial gradient of pressure. U_b is the artificial advection speed introduced at the boundary. We can define $M_b = U_b/c_0$. Notice that for $M_b = 0$, we retrieve a classical SDOF local impedance.

In this section we simulate the scattering performances in the plane wave regime of a 3D acoustic waveguide, of square cross section with 5 cm lateral sides, without flow. The ABL is applied along each side of the duct for a length of 30 cm. In order to investigate the effect of discretizing the ABL by individual ERs lining the parietal walls of a rectangular cross section duct, as in the experimental test-rig of Section 3, the ABL is applied on separate disks of diameter 3.6 cm, simulating the ERs (6 per each duct edge), as showed in Fig. 1. The dynamics of each speaker is simulated according to the Thiele-Small SDOF model [Beranek and Mellow(2012)].

The loudspeaker model is reported in Eq. (2), in terms of the Laplace variable s :

$$Z_0(s)\bar{v}(s) = \bar{p}(s) - \frac{Bl}{S_e}\bar{i}(s). \quad (2)$$

In Eq. (2), $\bar{p}(s)$ and $\bar{v}(s)$ are the acoustic pressure and velocity, respectively, on the speaker diaphragm, $\bar{i}(s)$ is the electrical current in the speaker coil, $Z_0(s) = M_0s + R_0 + K_0/s$ is the acoustical impedance of the loudspeaker

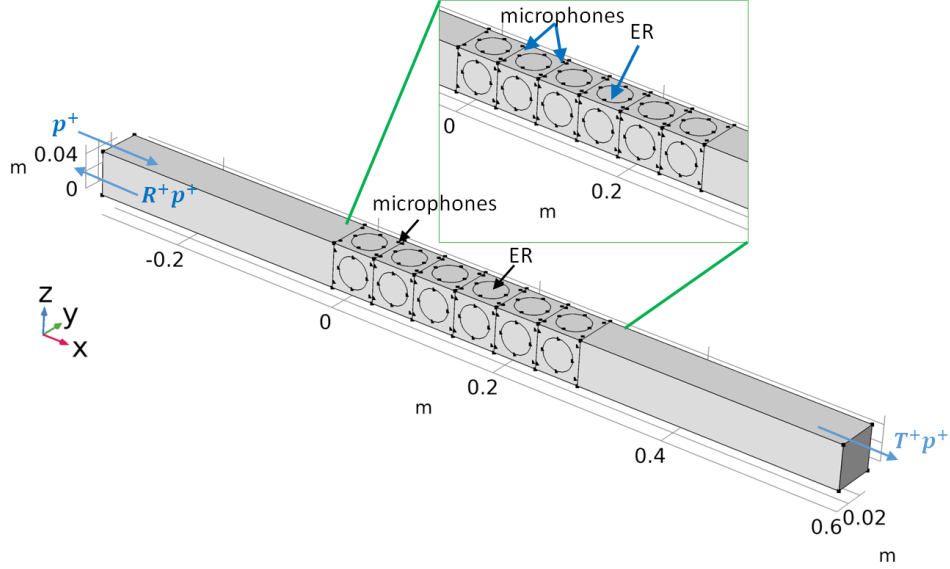


Figure 1. 3D geometry for scattering simulations, in case of ERs disks applied flush on the duct boundary.

in open circuit, with M_0 , R_0 and K_0 the corresponding acoustical mass, resistance and stiffness. The electrical current $\bar{i}(s)$ is multiplied by the force factor Bl to get the electromagnetic force, and divided by the effective area S_e to retrieve an equivalent pressure. The ABL is implemented by defining the electrical current $i(s)$ as in Eq. (3):

$$i(s) = H_{loc}(s)\hat{p}(s) + H_{grad}(s)\hat{\partial}_x\bar{p}(s), \quad (3)$$

where $\hat{p}(s)$ and $\hat{\partial}_x\bar{p}(s)$ are the estimated local pressure and its x-derivative on each speaker diaphragm, in the Laplace domain. The local sound pressure is estimated by averaging the four microphones on the corners of each ER $\hat{p} = (p_A + p_B + p_C + p_D)/4$, while the x-derivative is estimated by a first-order finite difference $\hat{\partial}_x p = \left((p_C + p_D) - (p_A + p_B) \right) / \Delta x$, with $\Delta x \approx 4$ cm the distance between the microphones before (A,B) and after (C,D) each ER speaker, along the x-direction, as showed in Fig. 2. A time delay of $\tau = 2 \times 10^{-5}$ seconds between the pressure inputs and the electrical current, is considered by multiplying the microphones pressures by $e^{-j\omega\tau}$, in order to simulate the physiological latency of the digital control algorithm of the ER [De Bono et al.(2022)De Bono, Collet, Matten, Karkar, Lissek, Ouisse,

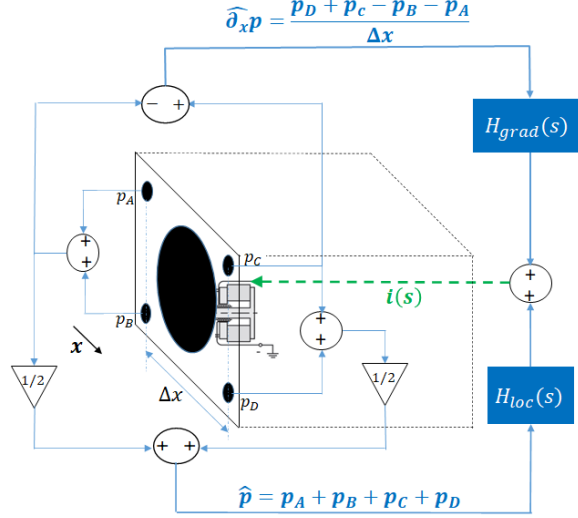


Figure 2. Sketch of the 4-microphones ER control, corresponding to Eq. (3).

Billon, Laurence, and Volery].

The transfer functions $H_{loc}(s)$ and $H_{grad}(s)$ are defined based upon the loudspeaker model of Eq. (2). Equating the velocity of the speaker diaphragm from Eq. (2), and the velocity corresponding to the ABL (Eq. (1)), we get the expressions in the Laplace space of H_{loc} and H_{grad} , in Eq.s (4) and (5), respectively.

$$H_{loc}(s) = \frac{S_e}{Bl} \left(1 - \frac{Z_0(s)}{Z_{Loc}(s)} \right), \quad (4)$$

$$H_{grad}(s) = -\frac{S_e}{Bl} \frac{Z_0(s)}{Z_{Loc}(s)} \frac{U_b}{s} F_{hp}(s), \quad (5)$$

where $F_{hp}(s)$ in $H_{grad}(s)$ is a high-pass filter necessary in order for $H_{grad}(j\omega)$ not to become infinite for $\omega \rightarrow 0$. The synthesis of our corrector transfer functions, is also called *model inversion* [Devasia(2002)] approach, as the objective of the controller is to cancel out the loudspeaker proper dynamics, and replace it with a desired acoustic behaviour.

Both Eq.s (4) and (5) are implemented in the Comsol model. From the microphones estimation of \hat{p} and $\hat{\partial_x p}$, the electrical current i is obtained from Eq. (3). Hence, the loudspeaker dynamics Eq. (2) is solved for $\bar{v}(s)$, which is then imposed on the disks representing the speaker membranes in

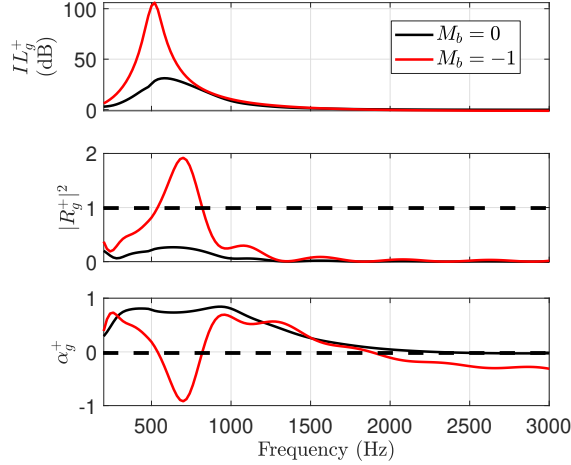


Figure 3. Comparison between local impedance control ($M_b = 0$) and ABL ($M_b = -1$), in terms of scattering coefficients in the 3D waveguide.

the numerical model.

In Fig. 3, the scattering coefficients achieved by the ABL with $M_b = -1$, are plotted along with the ones relative to local impedance control ($M_b = 0$), applied on each ER. The ABL demonstrates higher isolation capabilities, though being non-passive slightly after resonance. Notice also the loss of passivity at high frequencies (above 2 kHz). This is mostly due to the time delay [De Bono et al.(2022)De Bono, Collet, Matten, Karkar, Lissek, Ouisse, Billon, Laurence, and Volery].

3 First test bench without flow

In this section, the advection control law is experimentally tested on an array of 24 ER prototypes lining a squared cross-section duct of about 0.05 m side, as illustrated in the photos of Fig. 4. The ERs are placed 6 per each side of the duct, as showed in Fig. 4. Each ER has a surface area of about $0.05 \times 0.05 \text{ m}^2$, for a total lined segment length of about 0.3 m in the duct. The four scattering coefficients have been estimated according to the two-source method [Munjal and Doige(1990)]. Fig. 5 shows the experimental scattering coefficients for incident field toward $+x$, with varying M_b . Fig. 5 confirms the higher isolation achieved by increasing the absolute value of $M_b < 0$. Observe, in Fig. 5, the reduction of passivity from 1.8 kHz and

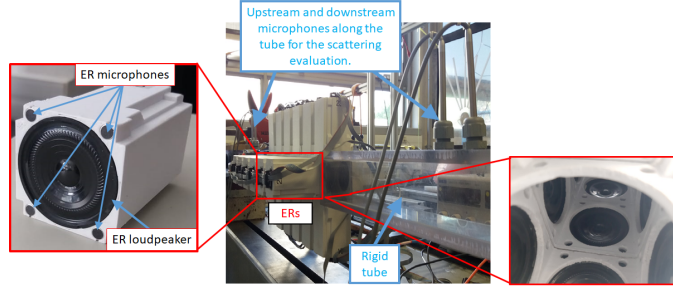


Figure 4. ER prototype (left); waveguide (middle) for the scattering evaluation, with internal view of the lined segment (right).

above with higher $|M_b|$. This is due to a combined effect of time delay and the first order approximation of $\hat{\partial}_x p$, which is clearly amplified for higher values of $|M_b|$.

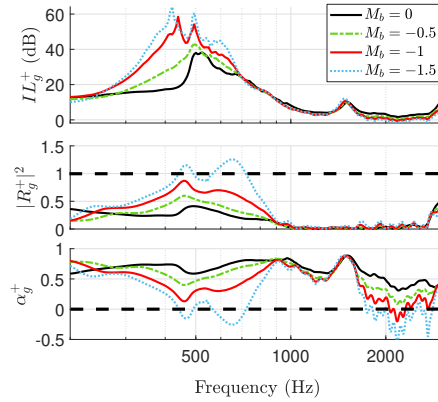


Figure 5. Experimental scattering performances for incident field propagating toward $+x$, achieved by the ABL with varying M_b .

4 Caiman test-bench: monomodal propagation with flow

Here we report the results of the experimental campaign on the test-bench Caiman, in the Laboratory of Fluid Mechanics and Acoustics (LMFA) of the École Centrale de Lyon. In the operative frequency range of our electroacoustic liner, the Caiman duct exhibits monomodal propagation (plane waves in the rigid segments). A connected wind-tunnel allows to reach up to Mach 0.3

in the waveguide. Appropriate noise sources are placed on both sides of the lined segment, in order to solve the full scattering problem according to the two-source method [Munjal and Doige(1990)]. The experimental test-bench is reported in Fig. 6. On the left of Fig. 6, the entire waveguide is visible, with the two grey boxes containing the noise sources on each side of the lined segment, and the indication of the downstream (+) and upstream (-) senses of propagation. On the right of Fig. 6, the lined segment is showed, comprising 6 ERs covered by a wiremesh sustained by a perforated plate to protect the electromechanical devices from the flow.

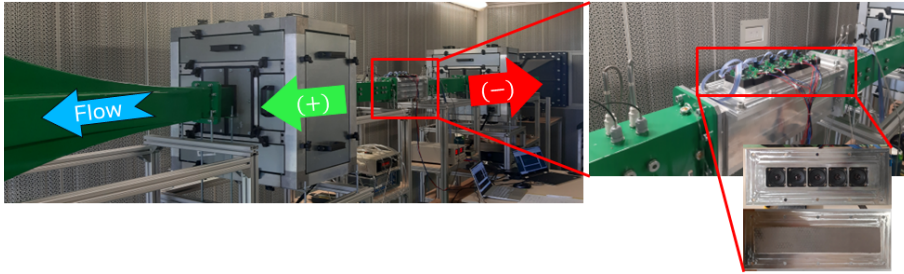


Figure 6. Left: “Caiman” wind tunnel, available in the Laboratory of Fluid Mechanics and Acoustics in the Ecole Centrale de Lyon. The downstream and upstream sense of propagation are indicated by the green and red arrows respectively. Right: zoom on the treated section with our electroacoustic liner covered by a wiremesh.

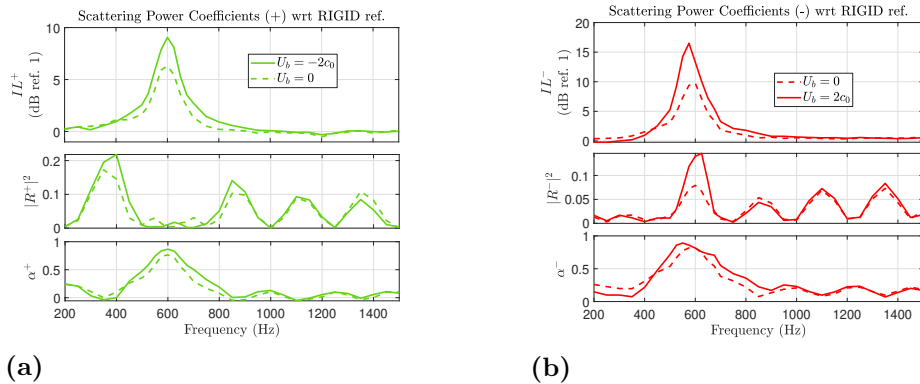


Figure 7. Scattering power coefficients with respect to the rigid reference, in case of Mach 0.15, and targeted resonance frequency 600 Hz, for downstream (+) and upstream (-) senses of propagation. Both local impedance control ($U_b = 0$) and ABL ($|U_b| = 2c_0$) performances are reported.

In case of mean-flow, we must distinguish the downstream from the upstream propagation. In Fig. 7), we report the scattering performances achieved for the downstream (Fig. 7a) and upstream sense of propagation (Fig. 7b), when Mach is 0.15. The ABL still demonstrates higher isolation performances with respect to local impedance control, for both upstream and downstream propagation. Observe how, in case of mean-flow, the advection speed amplitude on the boundary $|U_b|$ is increased to $2c_0$, with opposite sign with respect to the sense of propagation to attenuate. This is so, in order to efficiently oppose the sound propagation in the waveguide convected by a Mach 0.15. Notice also, that the upstream isolation is enhanced by the air-flow convection in the waveguide, as expected [Rice(1979)].

5 Conclusions

In this paper, we have reported the results which have assessed the isolation performances, robustness and stability of the electroacoustic liner technology, first without flow (both numerically and experimentally), and then with flow. The Advection Boundary Law keeps its higher effectiveness with respect to classical local impedance operators. This considerations open to the second part of this work, related to the assessment of the electroacoustic liner performances to reduce the noise radiation from the intake of a turbofan nacelle reproduction.

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