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Electroacoustic Liner for tonal and broadband noise attenuation of turbofans

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ABSTRACT

The new generation of Ultra-High-By-Pass-Ratio (UHBR) turbofan engine while considerably reducing fuel consumption, threatens higher 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. Therefore, alternative solutions to classic liners are required. 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 paper, we illustrate the control strategies and the experimental results achieved on the Phare2 test-bench. Phare2 is a reproduction of a real turbofan (scale 1:3), available in the Laboratory of Fluid Mechanics and Acoustics in the Ecole Centrale of Lyon. The noise attenuation accomplished by the electroacoustic liner is assessed by an antenna of microphone surrounding the nacelle inlet, and two rings of microphones upstream and downstream the liner. Both broadband and tonal noise are targeted with very promising results.

1. INTRODUCTION

The industrial contest is the noise transmission control in turbofan aircraft engines, where higher performances are demanded to the acoustic liners by the UHBR turbofan technologies. In order to overcome the limitations of classical liners, the Salute project designed an electroacoustic liner made up of Electroacoustic Resonators (ER) [1–10]. Four collocated microphones and a speaker allow to implement generalized impedances, also involving the first spatial derivatives of sound pressure on the boundary. In this contribution, we study local and a non-local control law, called Advection Boundary Law (ABL). In Section 2, we present the control strategy. Then, in Section 3, we present the attenuation of the azimuthal modes achieved on the Phare2 test-bench [11, 12], confirming the potentiality of such innovative liner.

2. CONTROL STRATEGY

The advection boundary law reads:

$$Z_{Loc}[\partial_t v_n(t)] = \partial_t p + U_b \partial_{arc\theta} p, \tag{1}$$

where the operator $Z_{Loc}[\bullet]$ is the local impedance operator applied to the normal boundary acceleration $\partial_t v_n(t)$. For classical locally reacting liners, this operator relates the local acceleration to the time derivative of the local sound pressure $\partial_t p$. Our advection law includes an additional term, given by U_b times the spatial gradient of pressure. U_b can be called advection speed, and we can define $M_b = U_b/c_0$. This boundary condition involves a first order spatial gradient, which hence implies nonlocality of the boundary reaction and non-reciprocity (as it is of first order). In Equation 1, the symbol $\partial_{arc\theta}$ denotes the derivation along the azimuthal sense of the cylindrical waveguide (the turbofan nacelle). This operator has been implemented on a programmable boundary made up of electroacoustic resonators (ER), as described in [3, 5, 8–10, 13] by piloting the electrical current $i(s)$ in the speaker coil. Its expression in the Laplace domain is given in Equation 2:

$$i(s) = H_{loc}(s)\hat{p}(s) + H_{grad}(s)\hat{\partial}_x p(s), \tag{2}$$

where $\hat{p}(s)$ and $\hat{\partial}_x p(s)$ are the estimated local pressure and its x-derivative on each speaker diaphragm, in the Laplace variable s. Experimentally, on each ER, the local pressure is estimated by averaging the four microphones on the EA corners, while the x-derivative is estimated by a first-order finite difference. The transfer function $H_{loc}(s)$ is in charge of cancelling out the loudspeaker own dynamics (classically written in terms of Thiele-Small parameters [14]), and enforce the local target dynamics, whilst the transfer function $H_{grad}(s)$ enforces the spatial gradient dependence.

3. EXPERIMENTAL RESULTS

We wondered if such advection boundary control could be interesting for reducing noise radiation from a turbofan reproduction (scale 1 to 3), where the intake boundaries of the nacelle were treated by a circular electroacoustic liner, see Figure 1. In Figure 1, we also report the photo of the ER, the unit cell where the ABL is applied. Two rings of microphones are placed upstream and downstream the liner, in order to retrieve the azimuthal modal content of the sound field before and after the electroacoustic liner.

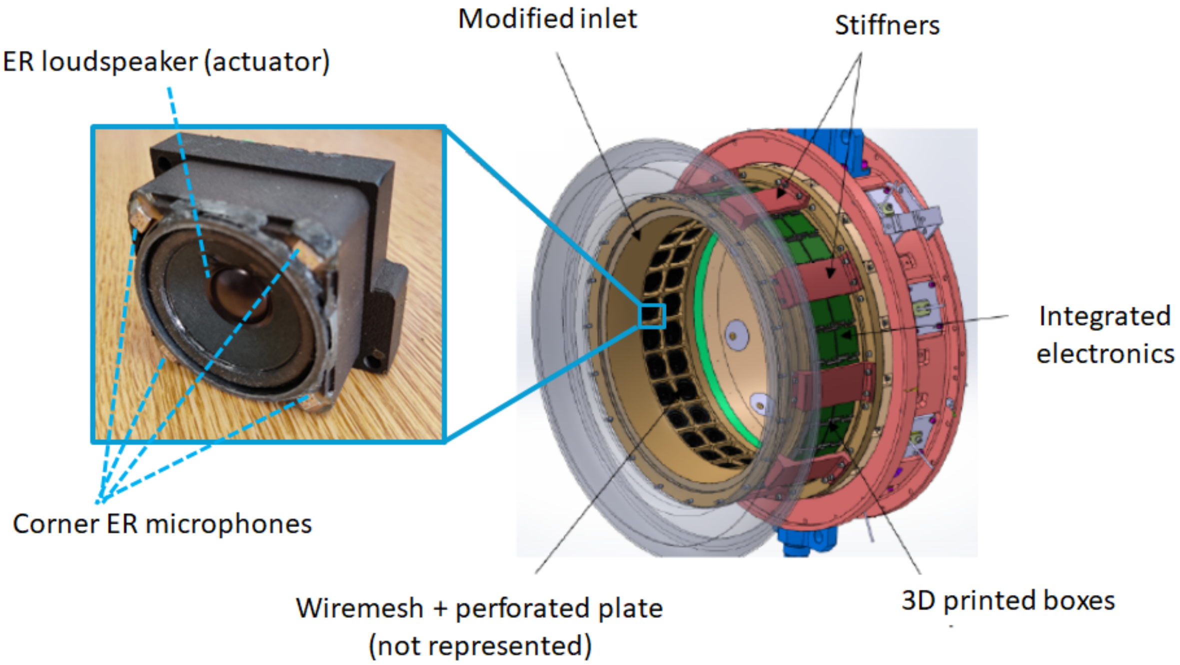


Figure 1: Photo of the single ER cell, and sketch of the modified inlet accommodating the electro-active liner.

Due to the rotational speed of the turbofan, the predominant modes propagating in the nacelle are typically of spinning type. From that, the idea to adapt the advection boundary control, by imposing an advection speed along the azimuthal direction on the boundary, in opposite sense with respect to the rotational sense of the turbomachinery. Figure 3 shows what appeared in measurements: you see the average level of azimuthal modes around the Blade Passing Frequency (BPF), upstream and downstream the liner with respect to the airflow direction. Observe that here we are interested in reducing the radiation upstream the liner. Both measurements demonstrate that an $M_b = 2$ leads to an enhancement of the attenuation of mode $m = -3$, with respect to the case $M_b = 0$. Mode $m = -3$ is the most significant mode at this frequency, which is close to the cut-on frequency of mode $m = \pm 3$. Notice that introducing the advection speed M_b allows to improve attenuation of azimuthal modes having $\text{sign}(m) = -\text{sign}(M_b)$, while modes with $\text{sign}(m)=\text{sign}(M_b)$ are less attenuated, respect to the case $M_b = 0$. Notice also that the passivity issues found in the numerical simulations, are not featured in this experimental test bench.

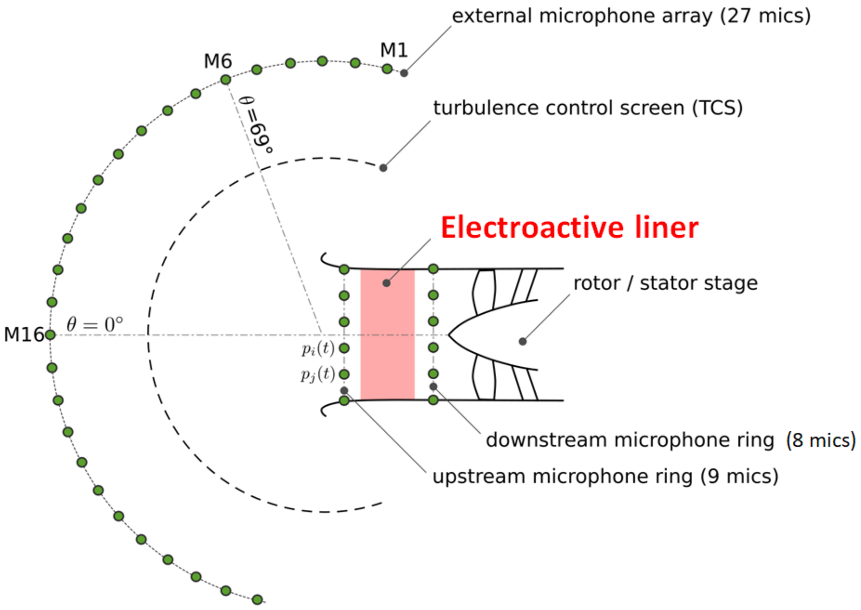
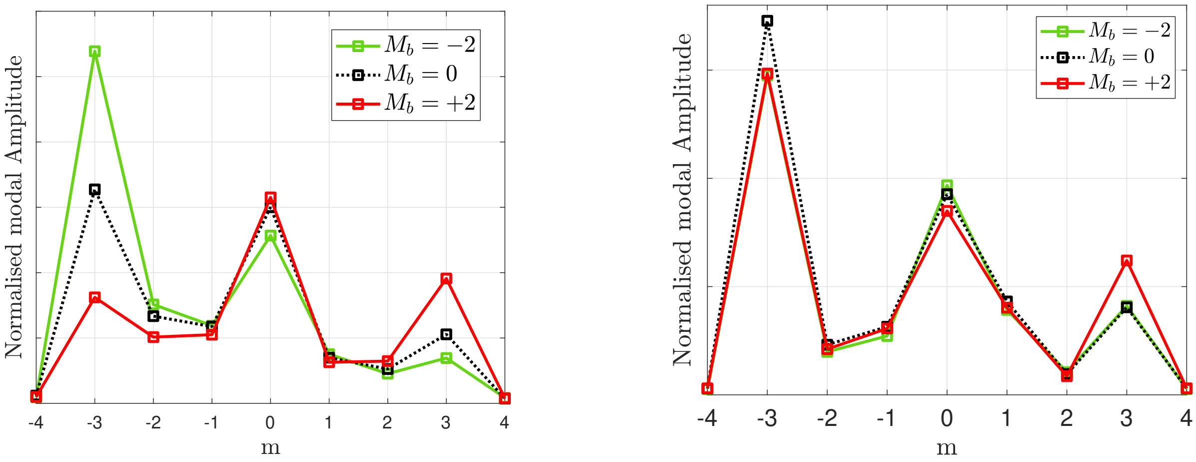


Figure 2: Sketch of the Phare2 duct stage.



(a)

(b)

Figure 3: Normalized modal amplitude upstream (**a**) and downstream (**b**) the lined segment, around the Blade-Passing-Frequency (BPF) at 30% of the nominal engine speed, with varying U_b.

The IL plot of Figure 4 demonstrates how a counter-rotating azimuthal advection ($U_b = +2c_0$) is capable to reduce the noise radiation around the Blade-Passing-Frequency (BPF) with respect to a purely local impedance control ($U_b = 0$). This is due to an enhanced attenuation of the principal azimuthal mode at the upstream section, as shown in Figure 3a.

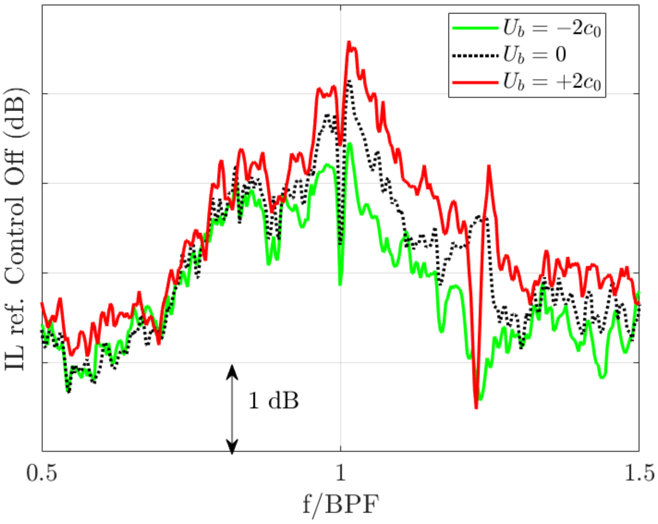


Figure 4: Results in terms of IL on a microphone of the antenna, in case of $U_b = 2c_0$ (green line), $U_b = 0$ (dotted black line) and $U_b = -2c_0$ (red line).

4. CONCLUSIONS

We have presented the Advection Boundary Law to attenuate the spinning modes which are the one concerning noise radiation from turbofan engines. Numerical simulations have allowed to gain confidence about the potentiality of such boundary control strategy. After having briefly introduced the control law, we showed some experimental results on the Phare2 experimental test-bench, in terms of attenuation of spinning modes, and Insertion Loss on a microphone of the surrounding antenna.

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