A nonlocal boundary control, from plane waves to spinning modes control.

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ABSTRACT

Reducing fuel pollution of airplanes has brought up another equally complex challenge for the aeronautic industry: the noise pollution. The new generation of Ultra-High-By-Pass-Ratio 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. 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 control the local impedance, but also to conceive alternative boundary laws. The objective of this contribution is to present the potentialities of such electro-active liner against higher-modal-order sound propagation, in particular spinning modes. Different test-rigs help in appreciate the gradual steps in the experimental validation of an interesting nonlocal boundary control. In this contribution, we focus on the so-called boundary advection law, capable of enlarging the spectrum of sound control.

Keywords: electro-active acoustic liner, programmable metasurface, spinning modes, impedance control

1. INTRODUCTION

Let us start with the main industrial contests which could benefit from this work: the noise transmission control such as in the HVAC systems or in aircraft engines, where higher performances are demanded to the acoustic liners by the UHBR turbofan technologies. But other applications can be envisaged for noise control in enclosed environments, such as building acoustics or fuselage treatments (another hot topic in the aeronautic industry). The classical techniques for sound control rely on viscous and heat dissipation mechanisms (as for porous materials), or resonance (as for Helmholtz or membrane resonators). Both these phenomena are exploited in the classical liners employed in aircraft nacelles. Nevertheless, all passive absorbers must obey an integral constraint (related to local causality),[1] which limits their performances as they require larger thicknesses to control lower frequencies. Even electro-active techniques for local impedance control must obey to local causality, and hence they are limited by a similar integral constraint.[2] For this reason nonlocality is an interesting avenue to break out from the local causality constraint.

2. FIRST TEST-BENCH, NO-FLOW.

The nonlocal approach for sound wave control presented here, is given in Eq. 1

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

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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 nonlocal operator includes an additional term, given by U_b times the spatial gradient of pressure. U_b can be called advection speed. 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). This operator was implemented on a programmable boundary made up of electroacoustic resonator (ER).[3] It is showed in Figure 1.

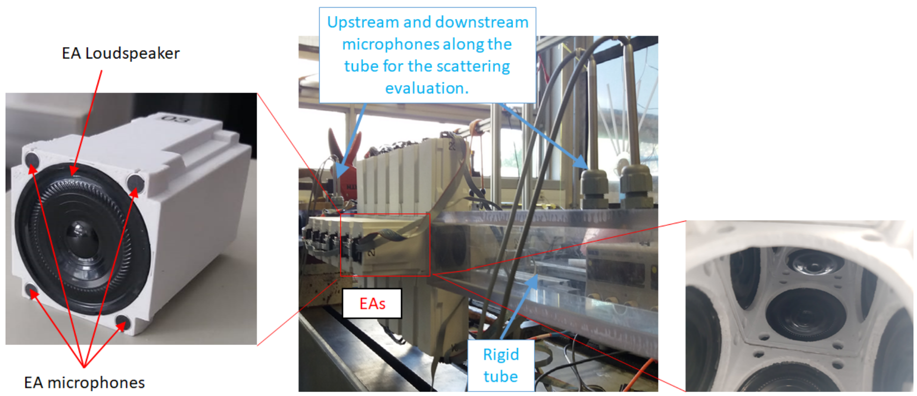

Figure 1. Unit ER (left); waveguide (middle) for the scattering evaluation, with internal view of the lined segment (right).

Each ER is equipped with a loudspeaker actuator, and 4 microphones able to retrieve both the local pressure and its first x-derivative approximation. All four sides of an acoustic waveguide had been treated by such electroacoustic liner. The insertion loss (IL) is measured in the plane wave regime. The IL in Figure 2 shows that such advection boundary control can outstand the isolation achieved by the classical local impedance control, along one sense of propagation (the one opposite to the advection speed U_b). Notice also the strong nonreciprocal behaviour if we consider the sound transmission in the other sense (green curve with respect to red curve).

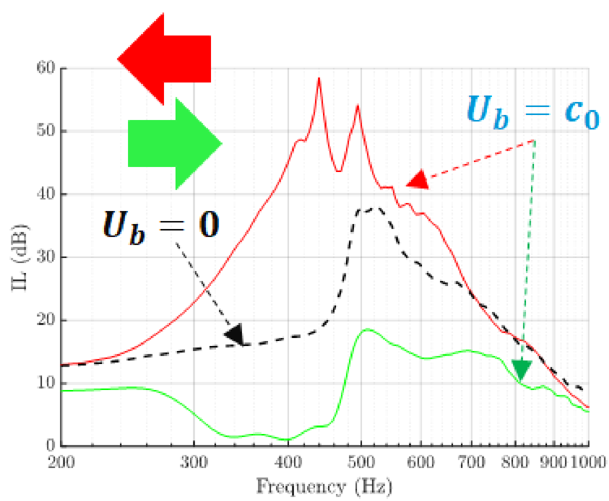

Figure 2. IL obtained in case of local impedance control ($U_b = 0$), or advection operator with $U_b = c_0$ in both senses of propagation.

3. SECOND TEST-BENCH, ALLOWING FLOW.

Such boundary control has then been applied on another testbench, where only one side of the duct was treated by our electroacoustic liner, see Figure 3. The liner was then covered by a thin wiremesh in order to protect it from the airflow. Here we are still interested only in the plane wave regime. Once again, the advection boundary control demonstrated its higher IL performances with respect to classical local impedance control, see Figure 4. Moreover the target frequency bandwidth could also be tuned as for tunable resonators.

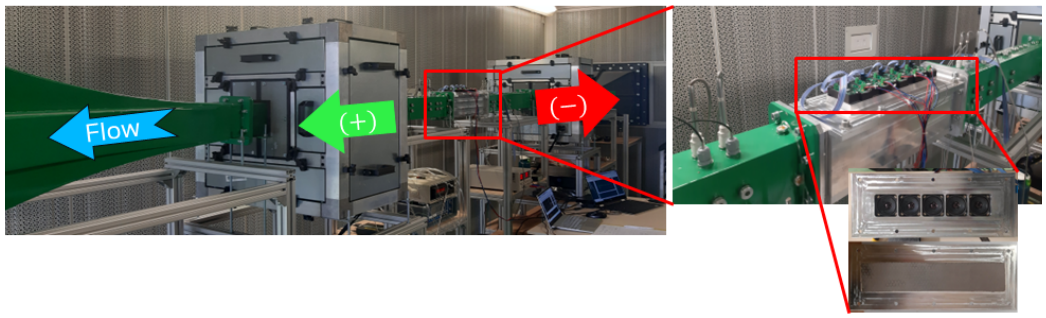

Figure 3. Left: "Caiman" wind tunnel, available in the Laboratory of Fluid Mechanics and Acoustics in the Ecole Centrale de Lyon. The downstream and upstream sense of propagation are indicated by the green and red arrows respectively. Right: zoom on the treated section with our electroacoustic liner covered by a wiremesh.

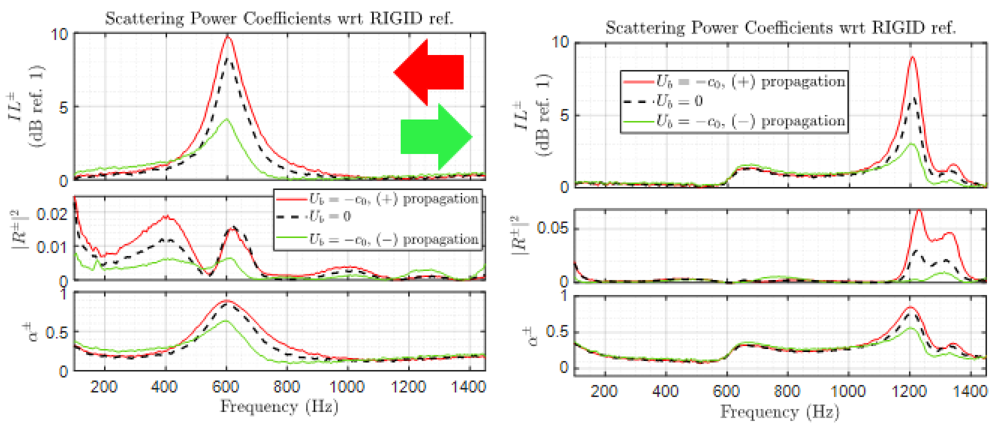

Figure 4. Scattering power coefficients with respect to the rigid reference. Left: Performances at the ER resonance in case of local impedance control ($U_b = 0$) and advection operator ($U_b = -c_0$) in both senses (+) and (−). Right: doubling the target frequency.

In case of mean-flow (Figure 5), we must distinguish the downstream (plus sign, in green) from the upstream propagation (minus sign, in red). For a Mach of 0.15, the advection control still demonstrated higher capacities with respect to local impedance control, for both upstream and downstream propagation. When the Mach number reached 0.3 (Figure 6), the isolation performances in the downstream sense no longer show a significant difference between the local and the nonlocal approaches. The reasons are probably to be found in the effect of the wiremesh in front of the electroacoustic liner, which alters the interaction between the programmed boundary and the acoustic domain.

4. THIRD TEST-BENCH, TURBOFAN.

Finally, we wondered if such advection boundary control could be interesting for reducing noise radiation from a turbofan reproducation (scale 1 to 3), where the intake boundaries of the nacelle were treated by a circular electroacoustic liner, see Figure 7. The radiated sound field was recovered by a movable antenna of microphones placed all around the intake, see Figure 8. Moreover, 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. The gray ball in the picture is a turbolance screen to reduce the turbolance level sucked in the engine.

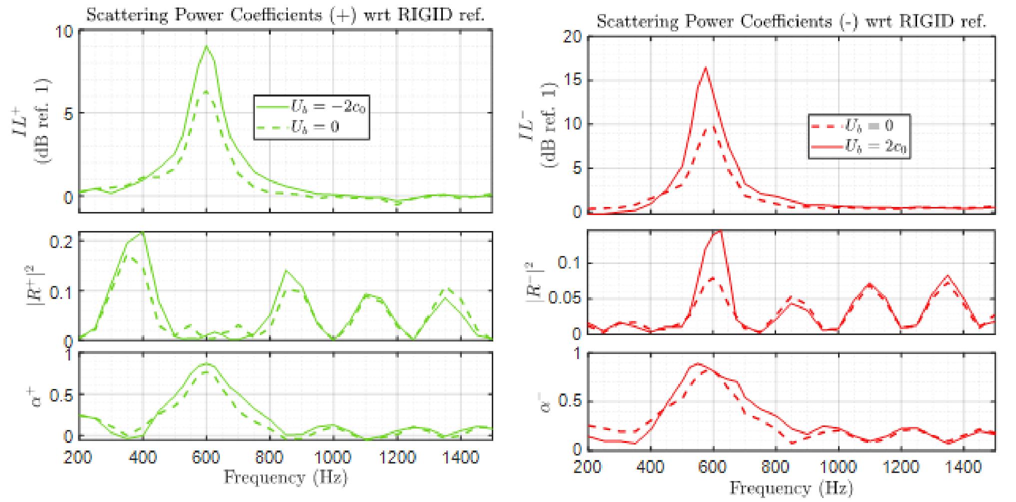

Figure 5. Scattering power coefficients for Mach 0.15 in the downstream (left) and upstream (right) senses. Advection operator ($U_b = -2c_0$, solid lines), or local impedance control ($U_b = 0$, dashed lines).

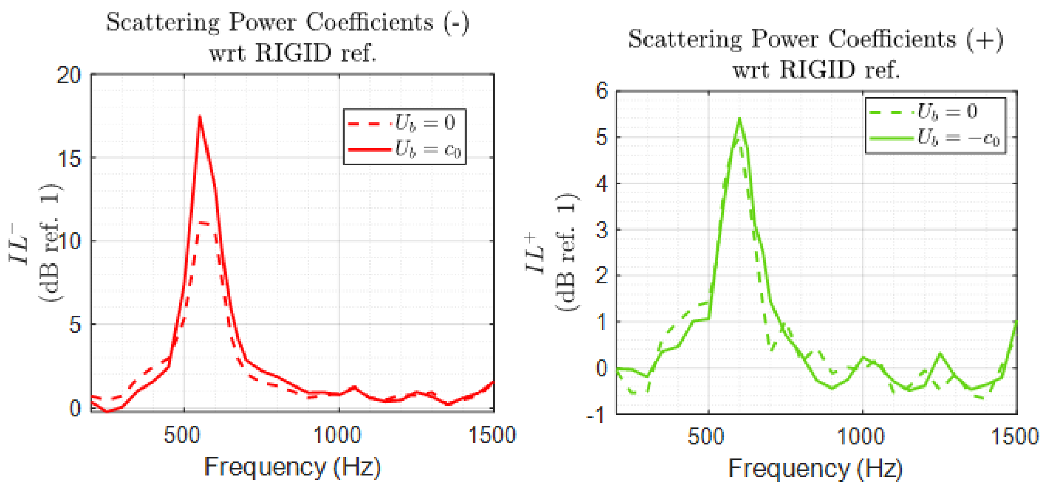

Figure 6. Scattering power coefficients for Mach 0.3 in the downstream (left) and upstream (right) senses. Advection operator ($U_b = -2c_0$, solid lines), or local impedance control ($U_b = 0$, dashed lines).

In this case, the sound field is much more complex. But, 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 9 shows what appeared in measurements: on the top you see the insertion loss relative to the antenna's microphones, with respect to a control-off reference level. On the bottom, you see the average level of azimuthal modes around the target frequency, upstream and downstream with respect to the liner. Observe that here we are interested in reducing the radiation upstream the liner. Both measurements demonstrate that such nonlocal boundary operator is capable to strongly oppose the propagation of sound in the opposite (azimuthal) sense with respect to the advection speed imposed on the boundary.

5. CONCLUSIONS.

In conclusions, we have presented an elegant boundary condition operator, called Advection Boundary Law, which is an interesting example of nonlocal control of sound waves. For plane waves, and in absence of mean-

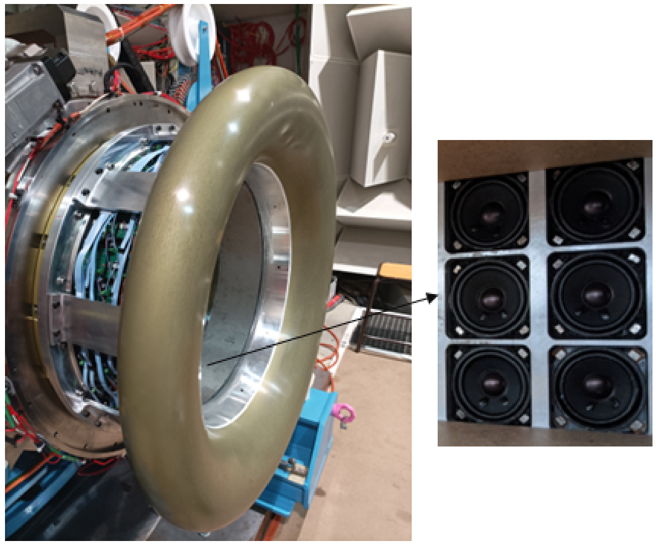

Figure 7. Electroacoustic liner at the intake of the nacelle of “Phare 2”.

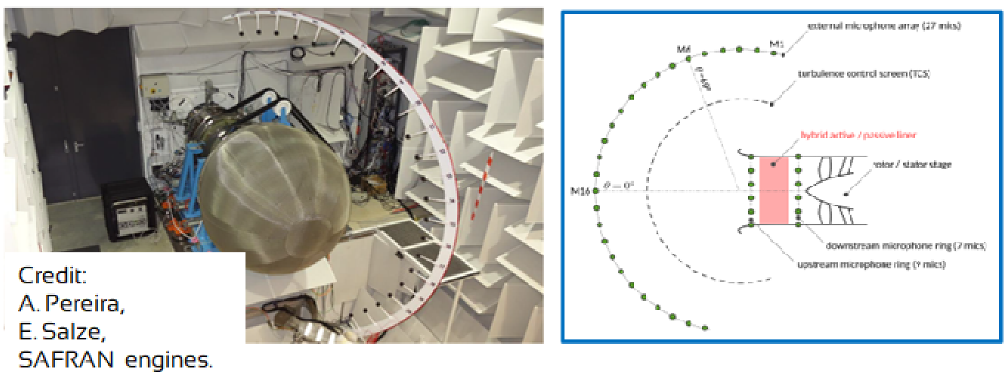

Figure 8. “Phare 2” facility.

flow (and frontal wiremesh), such boundary control outstands the isolation performances of local impedance control approaches. The air-flow, and the necessary frontal wiremesh, modify the advection B.C. performances: downstream isolation is weakend for higher Mach numbers. The advection B.C. has been adapted to turbofan noise, when spinning modes are predominant. Nevertheless, its non-natural character demands further analyses, while keeping the doors open for other innovative sound control applications. Other nonlocal operator could be studied for more challenging sound control.

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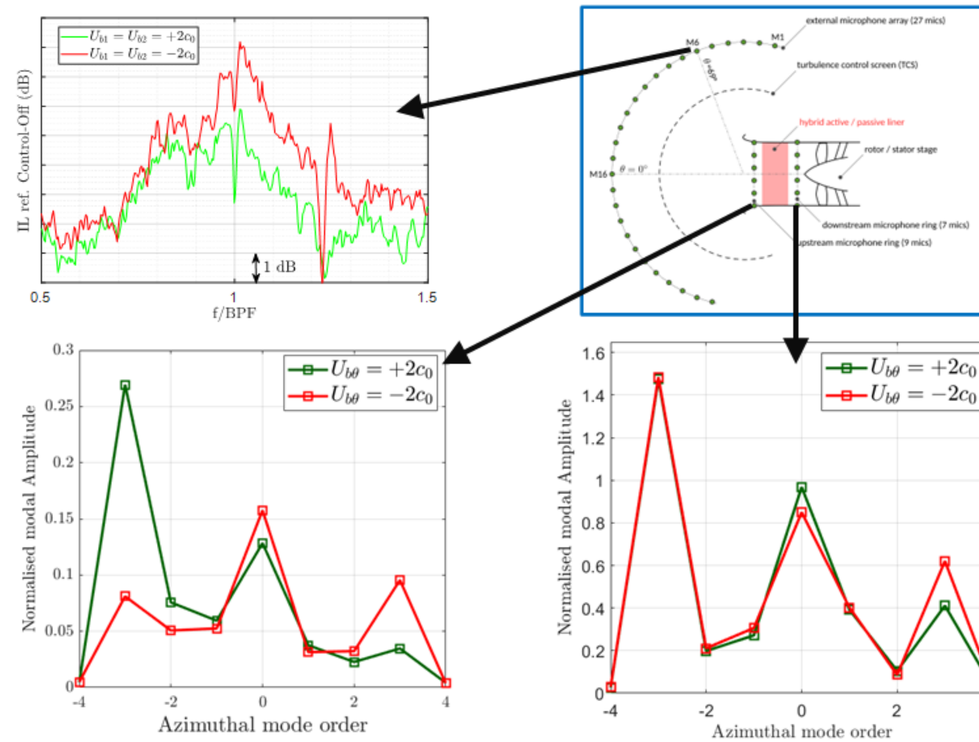

Figure 9. Results in terms of IL (upper left), and modal contents upstream (bottom left) and downstream (bottom right).

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