Available online at www.eccomasproceedia.org
Eccomas Proceedia SMART (2023) 47-52

ECCOMAS
Proceedia

X ECCOMAS Thematic Conference on Smart Structures and Materials
SMART 2023
D.A. Saravanos, A. Benjeddou, N. Chrysochoidis and T. Theodosiou (Eds)

PROGRAMMABLE ELECTROACOUSTIC BOUNDARIES IN ACOUSTIC WAVEGUIDES: ENHANCED ATTENUATION AND NON-RECIPROCAL SOUND PROPAGATION.

Emanuele De Bono*, Morvan Ouisse*, Manuel Collet†, Edouard Salze, Hervé Lissek††, Maxime Volery†† and Jacky Mardjono*****

*Univ. Bourgogne Franche-Comté, FEMTO-ST Institute, Department of Applied Mechanics,
CNRS/UFC/ENSMM/UTBM, 24 Chemin de l'Épitaphe, 25000 Besançon, France.
e-mail: emanuele.bono@femto-st.fr

† Univ. Lyon, Ecole Centrale de Lyon, LTDS UMR 5513, F-69134 Ecully, France
** Univ Lyon, Ecole Centrale de Lyon, LMFA UMR CNRS 5509, 69134 Ecully, France
†† École polytechnique Fédérale de Lausanne, Laboratoire de traitement des signaux LTS2, Route Cantonale, 1015 Lausanne, Switzerland
*** Safran Aircraft Engines, F-75015, Paris, France

Abstract. Sound attenuation along a waveguide is a highly demanded research field, for applications ranging from heating and air-conditioning ventilation systems, to aircraft turbofan engines. Electroacoustic devices and digital control have provided the tools for crafting innovative liners where the boundary condition can be programmed. Hence, the question about "optimal" boundary conditions for noise transmission attenuation becomes more and more urgent. The most straightforward idea is to program classical local impedance operators, as these are the ones generally employed for modelling the current state-of-art of acoustic liners, especially for aeronautic applications. A strategy which has been proved to be at the same time simple and sufficiently robust, is to pilot the vibration of each speaker diaphragm based upon the sensed pressure on it (obtained by quasi-collocated microphones), in order to modify the resonator dynamics (varying its quality factor, or resonance frequency). Nevertheless, it might be worthy to navigate off the beaten track, and try to exploit the progammability of our electro-active systems, in order to target boundary operators which could never be physically produced by purely passive treatments. In this contribution, we focus the attention on a particular boundary law, called "advective", as it possesses a convective character achieved thanks to the introduction of the first spatial derivative. We implement such boundary condition on our electroacoustic liner and demonstrate its potentialities in reducing the noise transmission and radiation in a circular waveguide. Numerical simulations and experimental implementation on a scaled turbofan mock-up show promising results.

Key words: programmable boundary, electroacoustic liner, noise control, sound transmission, acoustic waveguide, nonreciprocal propagation

doi: 10.7712/150123.9763.444480

Figure 1: Illustration of the scattering problem in acoustic waveguide, with guided modes amplitudes definition on the left side, into and on the right side of the acoustically treated segment.

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. 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. In this contribution we present some results obtained by a special boundary control, called advection law [3], and its application for reducing the noise radiation from a turbofan engine.

1.1 Simulations

In order to investigate the potentialities of generally impedance controlled liner for noise mitigation in a waveguide of large circular cross-section characterized by a multi-modal acoustic environment, some numerical simulations have been conducted in COMSOL Multyphisics. In particular, the performances of the boundary treatment in a waveguide are obtained by the multi-modal Scattering matrix, where the reflection or transmission coefficients of the Scattering matrix links two possibly different acoustic modes.

In this section we aim at solving the multi-modal scattering problem in case of absence of mean-flow ($M_x = 0$). It is defined as in Eq. (1), where the terms C_μ^+, A_γ^-, A_ν^+ and C_σ^- are illustrated in Figure 1. The transmission coefficient matrix for example, $[T_{\mu,\nu}^+]$, links the amplitudes of the incident guided modes $\{A_\nu^+\}$ (with varying mode index "ν") to the amplitudes of the transmitted guided modes $\{C_\mu^+\}$ (of varying index "μ").

$$\begin{bmatrix} \{C_\mu^+\} \\ \{A_\gamma^-\} \end{bmatrix} = \begin{bmatrix} [\boldsymbol{T}_{\mu,\nu}^+] & [\boldsymbol{R}_{\mu,\sigma}^-] \\ [\boldsymbol{R}_{\gamma,\nu}^+] & [\boldsymbol{T}_{\gamma,\sigma}^-] \end{bmatrix} \begin{bmatrix} \{A_\nu^+\} \\ \{C_\sigma^-\} \end{bmatrix} \tag{1}$$

In COMSOL Multiphysics, a Finite-Element (FE) model of a cylinder of radius 0.25 m, with a treated segment of 0.1 m, has been created, see Figure 2. The segments on the left and

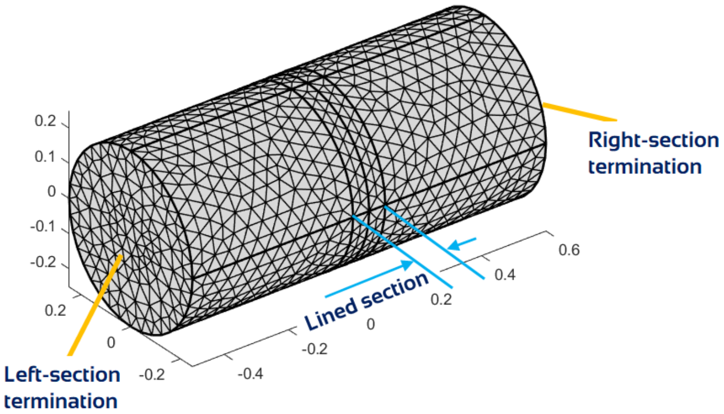


Figure 2: Mesh of the cylinder FE model, with the treated (lined) segment specified, as well as the right and left terminations.

on the right side of the treated segment has been defined sufficiently far from the respective terminations in order to avoid border effects.

After having defined the multi-modal scattering problem, we present now some interesting results concerning the attenuation of sound propagation achieved by both a purely local impedance B.C., and an *advected* boundary law. This boundary law is defined in [4] and reported below:

$$Z_{Loc}[\partial_t v_n(t,x,R,\theta)] = (\partial_t + U_b \partial_{arc\theta}) p(t,x,R,\theta). \tag{2}$$

In Eq. (2), $Z_{Loc}[\bullet]$ is the local impedance operator, $v_n(t,x)$ is the normal velocity and U_b is the boundary advection speed. By defining the boundary advection along the azimuthal direction, we can impede the propagation of the spinning modes, which are the most interested by rotating sources as turbofans.

We present here the simulation results obtained by a control law which has been also tested experimentally on the test-bench “Phare” of Section 1.2. It is hence helpful for the interpretation and appreciation of the experimental results as well.

Figure 3 shows the comparison of the intensity scattering coefficients performances between purely local ($U_b = 0$) and advected ($U_b = -2c_0$) boundary control, plotted in solid and dotted lines respectively. Observe that the boundary advection significantly reduces the transmission of energy (mostly by enhancing the backward reflection) for spinning exciting modes, without altering the performances relative to the non-spinning ones.

1.2 Experimental test-bench

The test-bench is a reproduction (scale 1 to 3) of a turbofan engine [5], where the intake boundaries of the nacelle were treated by a circular electroacoustic liner, see Figure 4. The radiated sound field was recovered by a movable antenna of microphones placed all around the intake, see Figure 5. Moreover, two rings of microphones are placed upstream and downstream

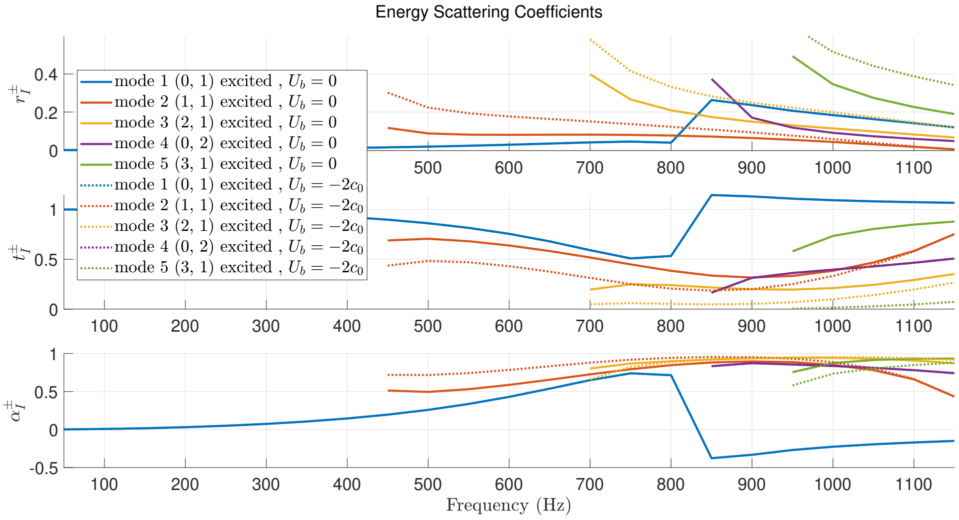
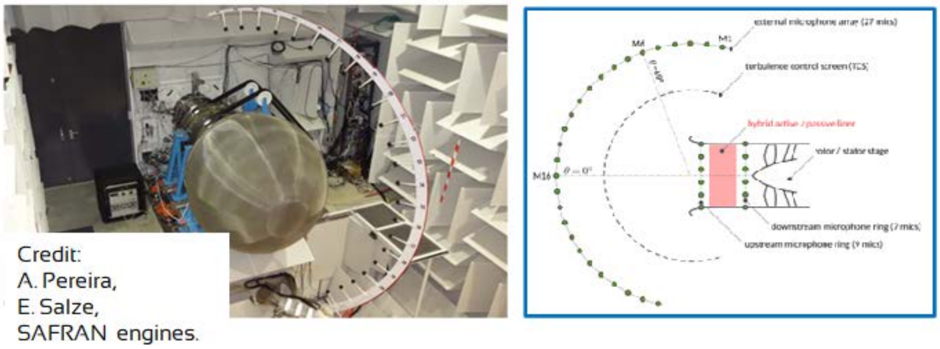


Figure 3: Comparison of intensity scattering coefficients in case of $U_b = 0$ (solid lines) and $U_b = -2c_0$ (dotted lines).

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 4: Electroacoustic liner at the intake of the nacelle of “Phare 2”.

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



Credit:
A. Pereira,
E. Salze,
SAFRAN engines.

Figure 5: “Phare 2” facility.

turbomachinery. Figure 6 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.

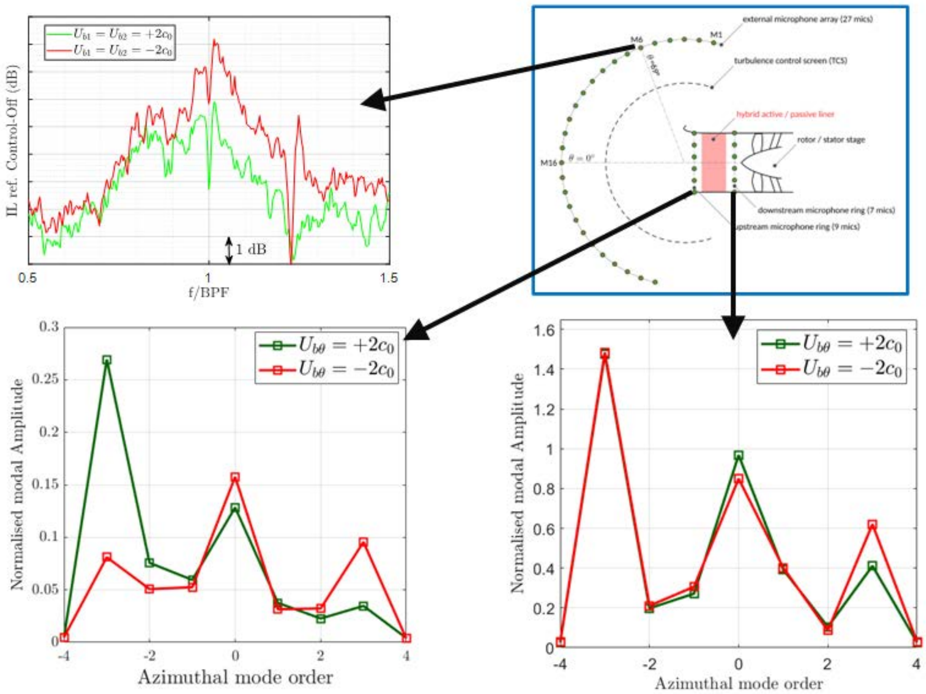


Figure 6: Results in terms of IL (upper left), and modal contents upstream (bottom left) and downstream (bottom right), in case of $U_b = 2c_0$ (green line) and $U_b = -2c_0$ (red line).

2 Conclusions

In conclusions, we have presented a boundary condition operator, called Advection Boundary Law, which is an interesting example of nonlocal control of sound waves. Such B.C. has been adapted to turbofan noise, when spinning modes are predominant, demonstrating its potentiality in overcoming the limitations of purely local impedance control laws.

ACKNOWLEDGMENTS

The SALUTE project has received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement N 821093. This publication reflects only the author's view and the JU is not responsible for any use that may be made of the information it contains.

REFERENCES

[1] M. Yang, S. Chen, C. Fu, and P. Sheng, "Optimal sound-absorbing structures," *Materials Horizons* **4**(4), pp. 673–680, 2017.

[2] E. De Bono, M. Collet, G. Matten, S. Karkar, H. Lissek, M. Ouisse, K. Billon, T. Laurence, and M. Volery, "Effect of time delay on the impedance control of a pressure-based, current-driven Electroacoustic Absorber," *Journal of Sound and Vibration* , p. 117201, 2022.

[3] M. Collet, P. David, and M. Berthillier, "Active acoustical impedance using distributed electrodynamical transducers," *The Journal of the Acoustical Society of America* **125**(2), pp. 882–894, 2009.

[4] E. De Bono, *Electro-active boundary control for noise mitigation: local and advective strategies*. PhD thesis, Université de Lyon, 2021.

[5] A. Pereira, E. Salze, J. Regnard, F. Gea-Aguilera, and M. Gruber, "New modular fan rig for advanced aeroacoustic tests-Modal decomposition on a 20" UHBR fan stage," in *25th AIAA/CEAS Aeroacoustics Conference*, p. 2604, 2019.