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► To cite this version:

Emanuele de Bono, Manuel Collet, Sami Karkar, Gaël Matten, Morvan Ouisse. Non-local boundary control for broadband non-reciprocal propagation: analytical demonstration and experimental validation. 3rd Euro-Mediterranean Conference on Structural Dynamics and Vibroacoustics, Feb 2020, Naples, Italy. ⟨hal-04672061⟩

HAL Id: hal-04672061

<https://hal.science/hal-04672061v1>

Submitted on 17 Aug 2024

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NON-LOCAL BOUNDARY CONTROL FOR BROADBAND NON-RECIPROCAL PROPAGATION: ANALYTICAL DEMONSTRATION AND EXPERIMENTAL VALIDATION

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ABSTRACT

The semi-active impedance control techniques can offer new perspectives for acoustic treatment in the nacelle inlet of the new generation of Ultra-High-By-Pass-Ratio turbofan engines. In this contribution we present a non-local boundary condition capable of achieving broadband non-reciprocal propagation in a waveguide, envisaging the possibility of energy harvesting, other than acoustic transmission attenuation. The non-local boundary control concept is first illustrated analytically, and then it is implemented experimentally through a liner of electroacoustic devices.

1 INTRODUCTION

The new generation of ultra-high-by-pass-ratio (UHBPR) turbofan engines have a reduced number of blades with lower rotational speeds, this shifts the noise signature toward the lower frequencies. In addition, they present reduced space for the acoustic treatment of the internal walls of the nacelle. These new requirements and constraints must be accomplished by a new generation of liners. The main working principle of the classical Single/Multi Degree-of-Freedom liners is the quarter-wavelength resonance, which limits their performances to narrow frequency bandwidths and make them cumbersome for low-frequency targeting.

The Active Noise Cancellation (ANC) in the feedback configuration, from the "electronic sound absorber" of Olson and May [1] to the "active equivalent of the $\lambda/4$ resonator" of Guicking and Lorentz [2], further developed by Galland et al. [3], produced interesting results, but can hardly comply with the complexities of airflow noise cancellation in a UHBPR nacelle, and the problem of broadband attenuation was still unsolved. The quasi-colocation of pressure sensor and actuator has lead to another approach to the noise attenuation, that is the impedance control strategy. Boulandet et al. [4] analyzed numerically and experimentally the potentiality of the impedance control achieved through the ajustement of the loudspeaker membrane velocity, based upon the pressure measurement and a model of the loudspeaker mechanical dynamics. The main result was the possibility to tune, relatively easily, the resonance frequency of the loudspeaker and target lower frequencies. In 2009, Collet et al. [5] proposed a "generalized" impedance control approach, where the actuator velocity was function not only of the local pressure, but also of the pressure gradient along the longitudinal direction of the duct. In this contribution, we take up the same non-local boundary control as in [5] and analytically and experimentally show the non-reciprocal acoustic propagation effect. Apart from being a hot topic in metamaterials field of research, acoustic non-reciprocity can be highly attractive in view of acoustic energy harvesting and broadband noise mitigation.

2 ANALYTICAL ANALYSIS ON A 1D REDUCED MODEL

The non-local boundary condition proposed in [5] is:

$$\rho_0 \partial_t v_n = -\partial_n p = \frac{1}{c_a} \partial_t p - \partial_x p \quad (1)$$

where v_n is the velocity normal to the boundary and c_a is an advection celerity, used as a tunable parameter of the control. In order to analytically show how this boundary law is capable of producing non-reciprocal acoustic propagation, we reduce the waveguide problem to one dimension. Integrating the wave equation over the cross-section of the waveguide, and applying the divergence theorem to the integral of the y and z double derivatives (y and z being the dimensions along the cross section), we get:

$\forall t \in \mathbb{R}, \quad x \in \mathbb{R},$

$$\frac{1}{c_0^2} \partial_{tt} \tilde{p}(x, t) - \partial_{xx} \tilde{p}(x, t) = \frac{1}{S} \oint_{\partial\Omega} \partial_n p(x, s, t) ds \quad (2)$$

where $\tilde{p}(x, t) = \frac{1}{S} \iint_{\Omega} p(x, y, z, t) dy dz$ is the mean acoustic pressure over the section Ω , s is a curvilinear coordinate along the boundary $\partial\Omega$, and ∂_n is the gradient along the outward direction.

Inserting the boundary control law, expressed in Equation (1), in the right-hand side in Equation (2), it reads:

$$\frac{1}{c_0^2} \partial_{tt} \tilde{p}(x, t) - \partial_{xx} \tilde{p}(x, t) = -\frac{1}{d} \left(\frac{1}{c_a} \partial_t p_b(x, t) - \partial_x p_b(x, t) \right). \quad (3)$$

Where $p_b(x, t) = \frac{1}{L_p} \oint_{\partial\Omega} p(x, s) ds$ is the mean acoustic pressure field along the boundary contour, and $d = S/L_p$ is the ratio between the cross-section area and perimeter of the waveguide.

2.1 Dispersion relation

We now suppose monomodal acoustic propagation in this waveguide, and drop the tilda above p and assimilate p_b and p . Assuming a time-harmonic wave propagation with angular frequency ω

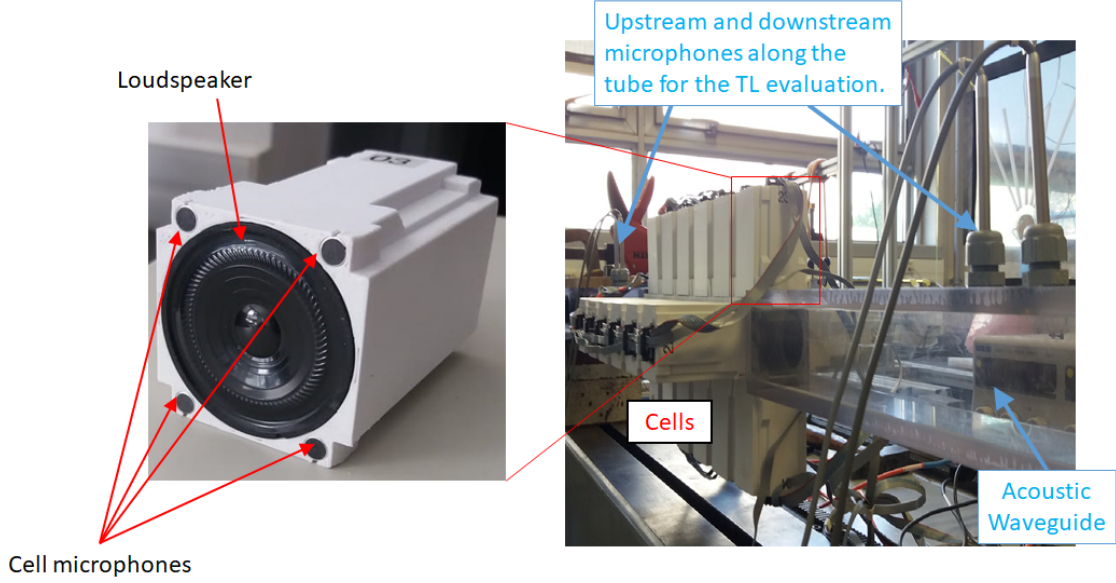


Figure 1: Left: Unit cell. Right: Perspective of the lined waveguide, with upstream and downstream microphones for the TL evaluation through the transfer matrix method.

and wavenumber k , we now seek solutions of the form:

$$p(x, t) = p_0 e^{j(\omega t - kx)}. \quad (4)$$

Inserting this ansatz in the propagation Equation (3), comes:

$$(j\omega/c_0)^2 - (jk)^2 = -\frac{1}{d}(j\omega/c_a + jk). \quad (5)$$

In the special case where $c_a = c_0 = c$ (that is the advection celerity is in tune with the sound speed), Equation (5) has two solutions: either $k^{(-)} = -\omega/c$, or $k^{(+)} = \omega/c - j/d$. The first solution corresponds to waves with purely real and negative wave numbers. The group velocity is negative, and equal to the phase velocity: this type of wave is propagating in the (-) direction ("backward waves"). Given the purely real wavenumber, they pass through the isolator without attenuation. The second solution corresponds to waves with $\text{Re}(k) > 0$ that propagate in the (+) direction ("forward waves"), given their positive group velocity, but with an exponential attenuation. It is equivalent to an evanescent guided mode, just like a waveguide higher mode under its cut-on frequency. Therefore, the 1D reduced model of the non-locally boundary controlled waveguide, shows the non-reciprocal relationship between forward and backward propagation.

3 EXPERIMENTAL IMPLEMENTATION

We now present the experimental results of an application of this boundary control strategy on a test-bench waveguide of square cross section of 5.5cm side (see Figure 1 on the right), lined with actively controlled devices which were capable of reproducing the boundary control law expressed in Equation (1). Evidently, the boundary control law has been discretized in order to be applied through units of electrodynamic devices. Each unit cell consisted of a loudspeaker (actuator) and four microphones (sensors) placed at the cell corners, see Figure 1 on the left. Six cells have been applied on each side of the duct, amounting to 24 cells in total.

3.1 Results

The insertion losses (IL) are plotted in Figure 2 (on the right), for incident waves coming from both directions. It has been evaluated according to the ASTM E2611-09 standard (single-load transfer matrix method). The synthesized algorithm for the implementation of the control law was able to invert the dynamics of the loudspeaker after its first resonance which is between 500 and 550

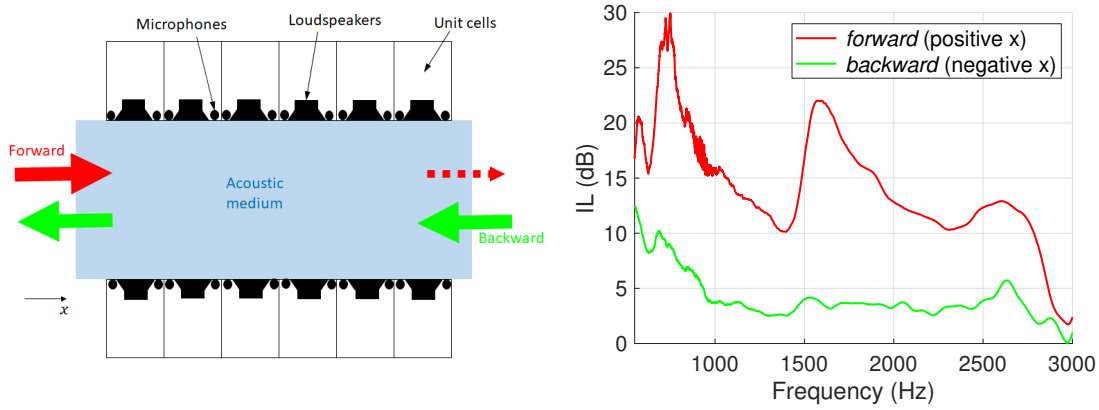


Figure 2: Left: 2D sketch of the lined waveguide. Right: Insertion Loss measurements relative to incident waves directed towards the positive x (*forward*), and towards the negative x (*backward*).

Hz for all loudspeakers, that is why the plot is limited to frequencies beyond 550 Hz. The higher frequency limit (3 kHz) corresponds to the cut-on of the first higher-order duct mode, beyond which the plane wave assumption for the TL evaluation is not valid anymore. Both the ILs relative to the *forward* and *backward* direction of propagation vary significantly with frequency. This is due to the modal behaviour of the speaker membrane and the limits of the synthesized control to invert the loudspeaker proper dynamics. As a consequence, the acoustic isolation (described by the Isolation Index, $IS = 20 \log_{10}(|S_{12}/S_{21}|)$) is achieved with a variable amplitude: from maxima of 20 dB to minima of 8 dB, from 550 Hz up to 2800 Hz. The loss of efficiency above 2800 Hz is likely to be mainly caused by the spacing between the microphones, which is close to half the acoustic wavelength, thus causing aliasing effect in the pressure evaluation.

4 CONCLUSIONS

In this contribution we analyzed a non-local boundary condition. This boundary law has been implemented through semi-active electroacoustic prototypes, on a test-bench waveguide. Despite some limitations due to the practical implementation of the control strategy at its early stage design, it demonstrates the capability of achieving non-reciprocal acoustic propagation in a much broader sense with respect to all other present techniques.

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