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Acoustic metamaterial design for aeronautical purposes

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Abstract. Labyrinth-shape quarter wavelength tubes are numerically studied under plane wave excitation, with analytical comparison. These labyrinth resonators (LRs) are tuned at 60, 90 and 120 Hz, and their sound absorption response exhibits maximum peak at those frequencies with high fidelity and performance. These objects can absorb tonal sources at very low frequencies, with an incredibly competitive thickness, resulting in the possibility of considering them for the design of acoustic liners for an aerospace engine, but also for the automotive and naval industries. They are put together to form an acoustic metamaterial which exhibits multiple tonal peaks, demonstrating that the performance of each resonator is not affected by their coupling.

Introduction

The importance of environmental noise control has increased with modern urbanization, transportation traffic and associated noise-induced health impairments, such as irritation, sleep disruption, or even ischemic heart disease [1]. In this context, the transportation industry has to cope with several not-trivial compromises without affecting performance of the present models

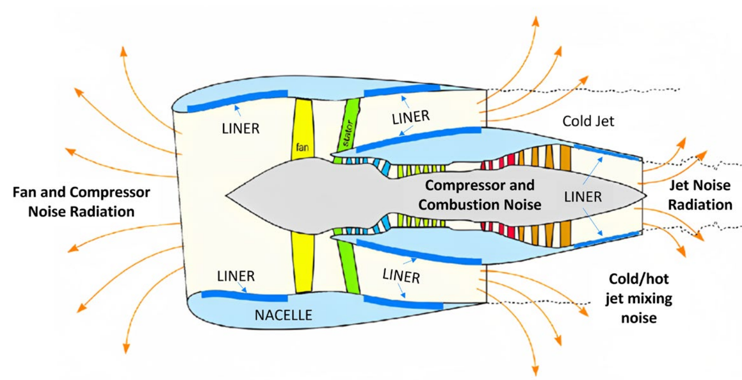

Figure 1: schematization of main noise source caused by an aircraft engine and actual disposition of conventional acoustic liners.

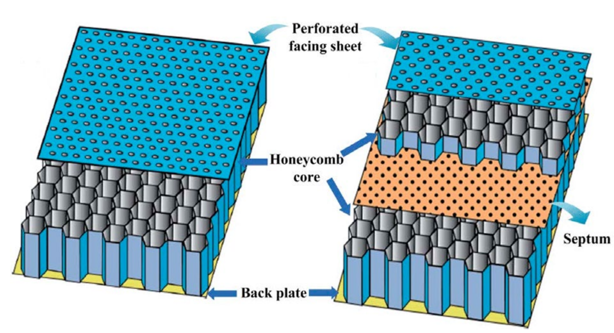

Figure 2: acoustic liner configurations.

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and/or relative costs. For instance, an aircraft design procedure cannot neglect sound emission considerations and an aircraft will not be sold or be certified if too noisy. Nevertheless, sound reduction systems or sound packages should be as lightweight as possible and placed in available spaces that are usually limited. Acoustic liner represents the most used solution to suppress aircraft engine noise; they are generally placed in the internal sides of the nacelle of a turbofan engine where it is not passing hot air (Fig. 1). An acoustic liner is made by a sandwich structure with one or multiple layers of micro-perforated panels and honeycomb core for structural purpose (Fig. 2). The perforated plate is responsible of acoustic resistance, while cavities are accounted for acoustical reactance [2]. Since each cavity is divided by the others, liners in question are local reacting liners, with the resonance frequency tuned by Helmholtz Resonator formula, which depends on the holes and cavity geometry. The Helmholtz Resonator has just one resonance frequency, hence it cannot be considered as an effective solution for sound suppression, because its peak is narrow and can be affected by flow conditions. At the actual state-of-the-art, there are no available and feasible solutions which guarantee wide bandwidth low-frequency sound suppression with space accounted for acoustic purpose limited and weight increase that should be minimized.

The present study wants to present alternative unitary cells for the design of conventional liners. To this aim, quarter wavelength tubes (QWTs) represent interesting local resonators for low-frequency sound absorption. A quarter wavelength tube is an open-closed tube that has resonant frequencies when its length L is an odd-integer multiple of the quarter of the acoustic wavelength:

$$f_{res} = \frac{(2m-1)c_0}{4L}. \qquad \boldsymbol{m = 1, 2, 3 \dots} \tag{1}$$

In correspondence of these multiple resonance frequencies, high sound absorption occurs. To cope with their excessive length requirement for low-frequency application, their channel is stretched into labyrinth branches without affecting the resonance behavior (Fig. 3).

Theoretical background and numerical implementation

Labyrinth-type resonators are designed through analytical and numerical simulations for normal plane wave radiation excitation (PWR). The acoustic impedance of a labyrinth resonator (LR) is studied according to the analytical approach proposed by Magnani et Al. [3], where the labyrinth resonator is evaluated as a perforated plate followed by a QWT. The QWT of length L has an impedance equal to:

$$Z_{QWT} = -jZ_{eff}\cot\left(k_{eff}L_{eff}\right), \tag{2}$$

modelled through Low Reduced Frequency model (LRF), introduced for the first time by Zwikker and Kosten [4], which takes into account viscous and thermal dissipation changing the sound wave Helmholtz equation. $Z_{eff} = \rho_{eff}c_{eff}$ and $k_{eff} = \omega/c_{eff}$ are respectively the effective impedance and the effective wavenumber retrieved by *lossy Helmholtz equation*, and L_{eff} is the effective length of the labyrinth, which takes into account number of branches n and width of the channel d that are not considered in the QWT resonance frequency equation [5]:

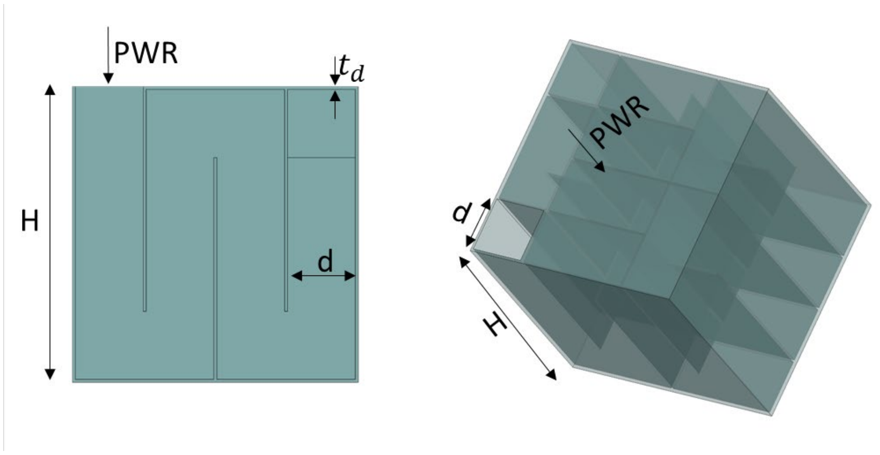

Figure 3: Labyrinth resonator excited by a plane wave radiation (PWR).

$$L_{eff} = L - (4 - \pi)\frac{d}{2}(n - 1). \quad (3)$$

The plate of thickness t_d with the square inlet hole of side-length d is studied through Johnson-Champoux-Allard (JCA) approach [6]. The impedance of the labyrinth resonator is:

$$Z_{LR} = \frac{1}{\phi_{inlet}}\left[Z_{dh_{JCA}}\frac{-jZ_{QWT}\cot\left(k_{dh_{JCA}}t_d\right) + Z_{dh_{JCA}}}{Z_{QWT} - jZ_{dh_{JCA}}\cot\left(k_{dh_{JCA}}t_d\right)}\right], \quad (4)$$

where $Z_{d_{JCA}} = \rho_{JCA}c_{JCA}$ and $k_{d_{JCA}} = \omega/c_{JCA}$ are respectively the impedance and the complex wavenumber of the perforated plate, with $c_{JCA} = \sqrt{K_{JCA}/\rho_{JCA}}$, ρ_{JCA} and K_{JCA} effective speed of sound, density and bulk modulus. $\phi_{inlet} = A_{hole}/A_{plate}$ is the perforatio ratio between the hole area and the plate area. The acoustic impedance is used for the evaluation of the sound absorption coefficient $\alpha = \Pi_{dissipated}/\Pi_{incident}$, which indicates the portion of the incident sound energy dissipated by the sample. The sound absorption of the labyrinth resonator will be calculated with:

$$\alpha_{LR} = \frac{4Re(Z_{LR}/Z_0)}{|Z_{LR}/Z_0|^2 + 2Re(Z_{LR}/Z_0) + 1}. \quad (5)$$

Several labyrinth resonators are modelled and analyzed through COMSOL Multiphysics, Pressure Acoustics Module, with first resonance peak at 60, 90, 120Hz (Figure 4a-c). Their height (thickness of the sample) is fixed at 100mm, to consider a competitive space for aeronautical application. The 60Hz labyrinth has lateral dimension of 97mm x 97mm, the 90Hz has lateral dimension of 145mm x 49mm and the 120Hz has lateral dimension of 73mm x 73mm. The numerical model is developed following the scheme of the equivalent experimental test with an impedance tube. A normal plane wave radiation excites the tube, and the sample is placed at the end of the tube backed by a rigid wall. Two probes with a relative distance s evaluate pressure in the tube, with P_2 at a distance x_2 respect to the sample, and P_1 at a distance $x_1 = x_2 + s$. The

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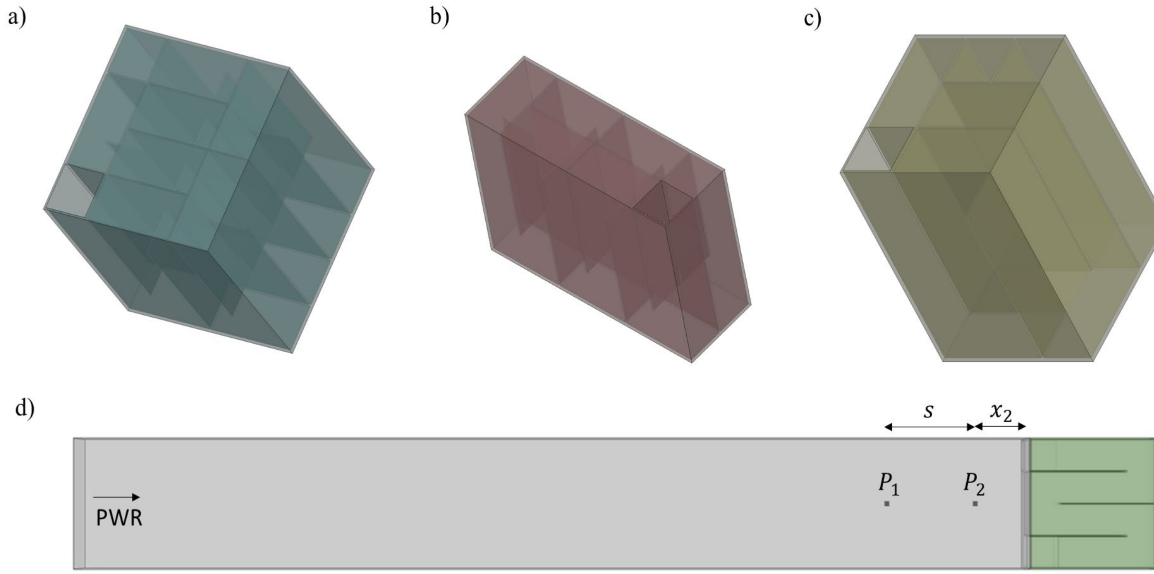

Figure 4: a) labyrinth model with first resonance peak at 60Hz; b) labyrinth model with first resonance peak at 90Hz; c) labyrinth model with first resonance peak at 120Hz; d) COMSOL model of the impedance tube for sound absorption measurements.

sound absorption coefficient is estimated according to the ISO 10534-2 1998 [7], with R reflection coefficient:

$$R = \frac{P_1/P_2 - e^{-jk_0 s}}{e^{jk_0 s} - P_1/P_2} e^{2jk_0 x_1}, \qquad \boldsymbol{\alpha = 1 - |R|^2}. \tag{6}$$

Results and discussion

Numerical simulations with analytical check are plotted for each labyrinth resonator (Fig. 5). The sound absorption estimated through numerical analyses consistently matched the analytical method. Each resonator has harmonic peaks, and their sound suppression is extremely interesting for low-frequency application on the engine nacelles, or to suppress tonal noise of diesel engines at low frequency for industrial application like naval and automotive. The amplitude of each peak depends on several parameter, but the most effective is the perforation ratio (the portion of the area of the inlet respect to the total area excited by the plane wave). The 120Hz labyrinth shows the worst first-peak among the three cases, but this can be easily solved by increasing its perforation ratio. A labyrinth-type metamaterial made with several samples of labyrinth resonator is studied to cover each resonance and take advantage of its harmonic behavior. The designed metamaterial is based on previous resonators, in particular with one 60Hz sample, two 90Hz sample and three 120Hz resonators (Fig. 6a). The multiple labyrinth resonator metamaterial keeps the absorption peak of each QWT in correspondence of its resonances, with an intuitive change of amplitude due to perforation ratio, affected by the number of repetitions per each labyrinth (Fig. 6b). For instance, the 60Hz labyrinth is just one, and its absorption is less effective than the case with just the 60Hz resonator. In the same way, the 120Hz effect is consistently enhanced. This result opens to several hybrid solutions which can embed multiple labyrinth resonators tuned at different frequencies, with the object to optimize their perforation ratio, finding a compromise between number of resonances and tonal behavior of the system. Indeed, a higher number of samples with different tuning frequency can lead to broadband sound absorption at low frequency, but the amplitude will be reasonably reduced; on the other hand, a combination of few labyrinths implies tonal sound suppression.

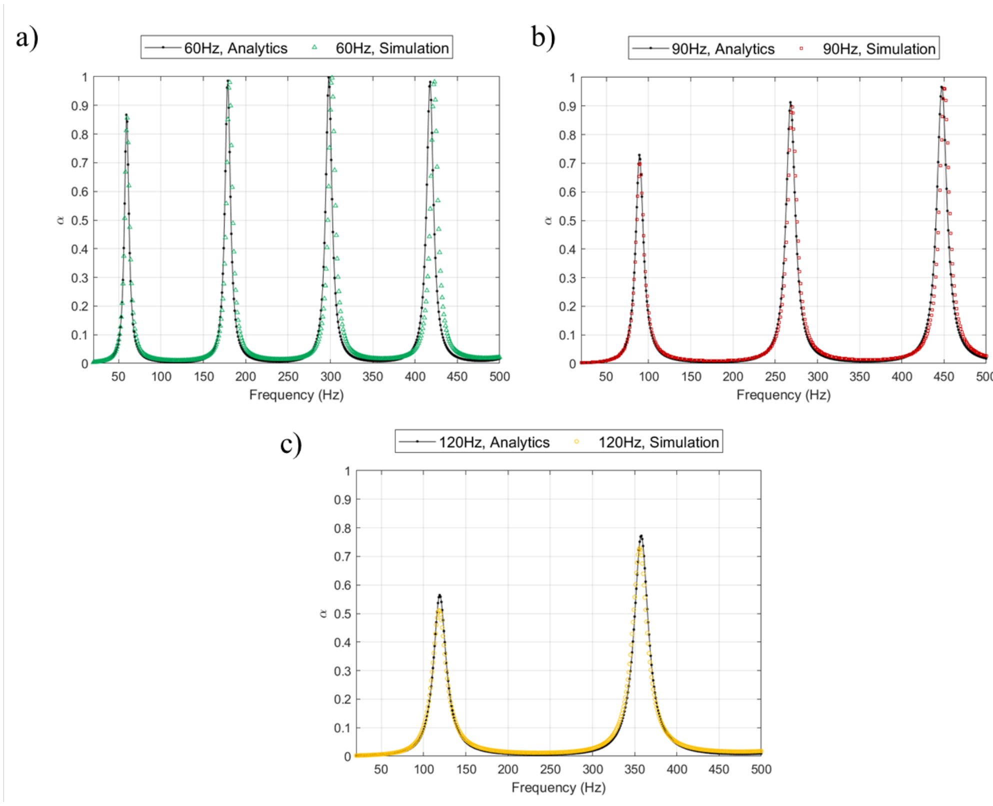

Figure 5: a) Numerical results with analytical comparison for a labyrinth resonator designed with first resonance at 60Hz; b) numerical and analytical results for 90Hz labyrinth resonator; c) numerical and analytical results for 120Hz resonator.

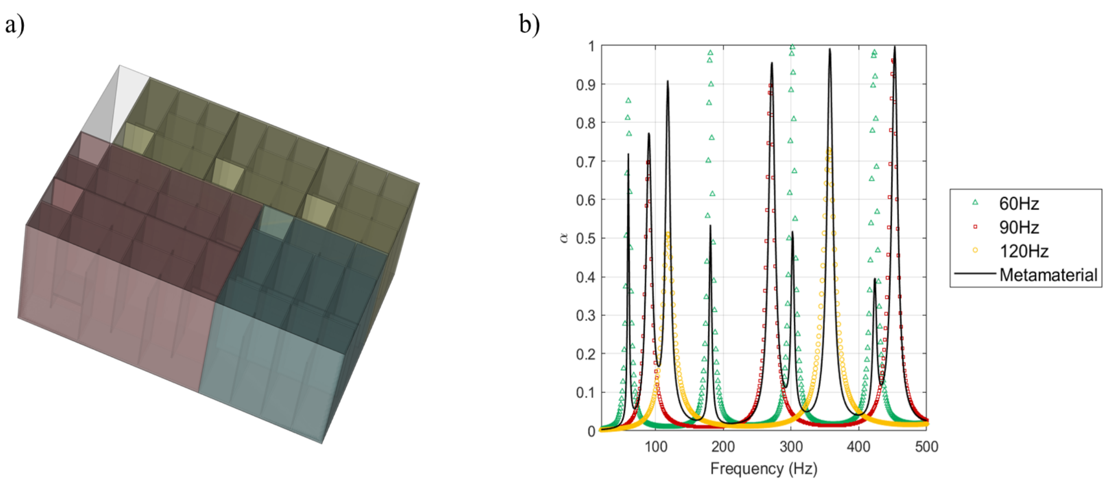

Figure 6: a) multiple labyrinth acoustic metamaterial; b) sound absorption plot of the proposed acoustic metamaterial.

Conclusions

Labyrinth resonators are presented as an innovative solution for the design of acoustic liners. Their competitive performance, flexibility and space requirements can be very attractive for an aeronautical application aiming to reduce engine noise. Numerical simulation represents a preliminary step; the sound absorption performance of the single labyrinth resonator and the complete acoustic metamaterial will be experimental tested inside impedance tube and under diffuse acoustic field to evaluate their performance under random excitation. The model will be 3D printed with several materials like PLA and resin. The final scope is to merge a comprehensive knowledge of models like this to design innovative acoustic liners that can improve low-frequency performance of pre-existing solution without affecting weight and space.

References

[1] L. Cao, Q. Fu, Y. Si, B. Ding, and J. Yu, "Porous materials for sound absorption," *Composites Communications*, vol. 10. Elsevier Ltd, pp. 25–35, Dec. 01, 2018. https://doi.org/10.1016/j.coco.2018.05.001.

[2] X. Q. Ma and Z. T. Su, "Development of acoustic liner in aero engine: a review," *Science China Technological Sciences*, vol. 63, no. 12. Springer Verlag, pp. 2491–2504, Dec. 01, 2020. https://doi.org/10.1007/s11431-019-1501-3.

[3] A. Magnani, C. Marescotti, and F. Pompoli, "Acoustic absorption modeling of single and multiple coiled-up resonators," *Applied Acoustics*, vol. 186, Jan. 2022. https://doi.org/10.1016/j.apacoust.2021.108504.

[4] C. Zwikker and C. W. Kosten, "Sound Absorbing Materials," *Elsevier Publishing company*, 1949.

[5] Giuseppe Catapane, Dario Magliacano, Giuseppe Petrone, Alessandro Casaburo, Francesco Franco, and Sergio De Rosa, "Labyrinth Resonator Design for Low-Frequency Acoustic Meta-Structures," in *Recent Trends in Wave Mechanics and Vibrations*, 2022, pp. 681–694. https://doi.org/10.1007/978-3-031-15758-5_70.

[6] N. Atalla and F. Sgard, "Modeling of perforated plates and screens using rigid frame porous models," *J Sound Vib*, vol. 303, no. 1–2, pp. 195–208, Jun. 2007. https://doi.org/10.1016/j.jsv.2007.01.012.

[7] "IS0 10534-2 1998: Acoustics-Determination of sound absorption coefficient and impedance in impedance tubes-Part 2: Transfer-function method," 1998.