DOI: 10.61782/fa.2025.0534

FORUM ACUSTICUM EURONOISE 2025

LOW-FREQUENCY ACOUSTIC AND VIBROACOUSTIC TREATMENTS TO REDUCE SOUND TRANSMISSION WITH DUCTS

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ABSTRACT

This study addresses the attenuation of low-frequency noise in ducts without modifying the cross-sectional geometry or introducing pressure losses. Conventional solutions, such as porous materials or reactive silencers, typically show limited effectiveness below 500 Hz and suffer from degradation under airflow. We propose two compact and robust alternatives: a mechanical elastic approach and an acoustic resonator-based approach. The elastic solution uses a soft viscoelastic material to create a mass–spring system that efficiently attenuates low frequencies through mechanical resonance. The acoustic solution is based on an array of quarter-wavelength resonators with a spatial gradient, designed to target a broader low-frequency band while minimizing flow-induced noise regeneration. Both silencers were manufactured and experimentally tested in laboratory conditions, including under airflow, to evaluate their acoustic performance and robustness. The results show significant transmission loss in the sub-500 Hz range without additional noise generation, confirming the relevance of resonance-based mechanisms for compact low-frequency silencers.

Keywords: *Metamaterial, duct, Experimental measurement, Silencer, flow*

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1. INTRODUCTION

Ventilation systems represent a significant source of noise pollution in both industrial and residential environments, necessitating the implementation of effective acoustic attenuation devices. Ventilation duct silencers have been extensively studied, but they still present major limitations, particularly concerning their size, low-frequency attenuation, and impact on airflow.

The most commonly used solution in the industry today is the parallel baffle. These consist of parallel sound-absorbing panels, typically made of mineral wool or fiberglass, covered with fabric or a perforated sheet. These devices provide effective attenuation at mid and high frequencies [1]. However, their limited performance in the low-frequency range (<500 Hz) is well known [2] and particularly problematic in many industrial applications, as they can induce significant aerodynamic pressure losses, which in turn increase the operating energy costs of ventilation systems [3-4]. Dissipative cylindrical silencers, used in circular ducts, are also widely employed in the industry and exhibit similar low-frequency limitations as parallel baffles [5]. To mitigate these issues, a larger-diameter casing can be used, with dissipative material applied to its inner walls. This design preserves the original duct cross-section, minimizing pressure losses. In any case, absorbing materials (such as mineral wool, foam, or fiberglass) are vulnerable to humidity and particulate contamination, reducing their durability, which can lead to delamination and potential health concerns when exposed to strong airflow. To address these issues and the low-frequency shortcomings of dissipative silencers, reactive silencers have been investigated as an alternative solution. By utilizing resonance phenomena, these silencers aim to improve attenuation in targeted frequency ranges. Resonator silencers, such as Helmholtz or quarter-wave types, provide targeted attenuation of specific frequencies [6-7]. Furthermore, flow-induced noise regeneration remains a key limitation for many existing solutions, requiring careful design to prevent unwanted acoustic emissions.

This study focuses on developing new proposals for dissipative-like silencers that are effective at low frequencies, particularly below 500 Hz, while maintaining performance even in the presence of airflow without generating additional noise. By leveraging resonance-based mechanisms, these treatments aim to enhance sound attenuation while maintaining compactness and robustness in demanding environments. Two different strategies are investigated: an elastic approach utilizing soft and flexible materials, and an acoustic approach based on resonance gradients, offering a practical solution to mitigate flow-induced noise regeneration.

2. USE CASE CONFIGURATION

All results presented in this paper will be experimental transmission losses shown for "dissipative-like silencer" configurations (i.e. where the internal guide cross section remains unchanged). Two examples are displayed and each example has been tested with a different setup for practical reasons (Fig.1): A square duct with a cross-section of 10 cm × 10 cm for the elastic solution (a) and a circular duct with a 16 cm diameter for the acoustic solution (b).

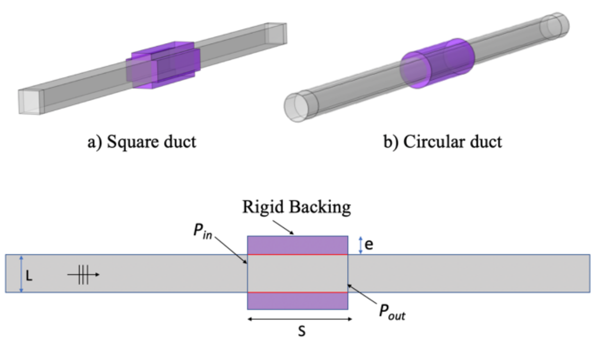

Figure 1. Experimental setups

A silencer is placed at the center of the duct, with the treatment thickness fixed at e = 3 cm in all cases to ensure compactness while addressing the target frequency ranges for attenuation. The transmission loss (TL) is determined by measuring the acoustic pressure upstream and downstream of the silencer using the microphone doublet method. In this configuration, the squared duct cutoff frequency is 1600 Hz, while the cutoff frequency of the circular duct is 1256 Hz. All configurations are first modeled and dimensioned numerically using the Finite Element Method (FEM) implemented in COMSOL Multiphysics. Once the numerical models are established, prototypes are fabricated and tested experimentally to validate the numerical predictions. In this paper, we will only present the experimental results.

3. MITIGATION STRATEGIES

3.1 Elastic Approach

In this approach, we aim to excite elastic phenomena to create, for example, a mass-spring system using a lightweight and flexible material, allowing us to control its resonance behavior. The objective is to fine-tune the system by either adjusting the mass (by adding elements to the flexible material) or modifying the stiffness (by softening the material). For practical reasons, we found no better compromise between mass and Young's modulus than using a porous material. Therefore, we utilize Melamine foam, but instead of exploiting its acoustic properties, we apply an impervious film to excite only its mechanical properties.

3.1.1 Simple case: soft elastic material

The film prevents acoustic propagation within the foam pores but allows mechanical deformation of the porous skeleton, effectively turning the foam + film system into a mass-spring resonator with a resonance frequency dependent on the Young's modulus of the foam and the mass of the system. With a Young's modulus of 100 kPa for Melamine foam, we estimate the resonance frequency to be 1200 Hz. However, this frequency is too high compared to our target of 500 Hz. To address this, we propose making the structure more flexible by introducing a periodic network of cylindrical holes filled with air, which allows local deformations of the foam and reduces the equivalent Young's modulus (Fig. 2). The experimental device consists of cylindrical air inclusions with a diameter of 12 mm and a periodicity of 3 cm.

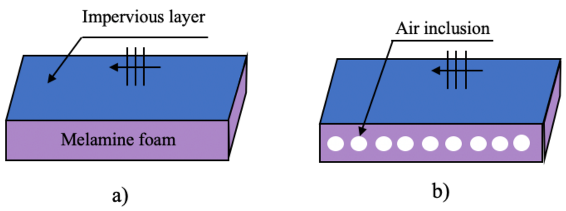

Figure 2. Liners constituting the dissipative-like silencer composed in both cases of 420x100x30mm melamine foam and 50 µm Mylar impervious layer.

Experimental results comparing these two configurations are shown in Fig. 3, where the mass-spring resonance of the homogeneous foam is clearly visible at 1150 Hz, achieving a dip with a maximum transmission loss of 30 dB. On the other hand, the TL of the sample with air inclusions shows multiple dips, achieving a significant TL enhancement over a large frequency range, particularly between 600 Hz and 1200 Hz.

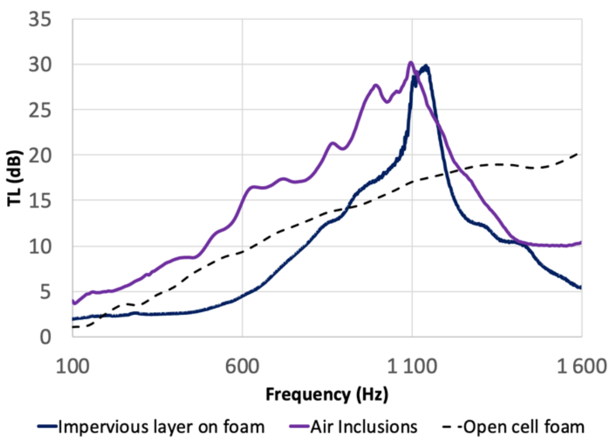

Figure 3. Experimental transmission loss comparison between the homogeneous liner and the air inclusion liner. Experimental TL of 3cm open cell foam is also plotted for information

Even though the TL is clearly enhanced, we did not achieve a sufficient improvement below 500 Hz with this solution, as we have already reached the manufacturing limit: Drilling larger holes can result in the destruction of the foam during the process. For this reason, we decided to change our approach by modifying the phenomenon involved and using local resonance instead of global deformation.

3.1.2 Elastic plate with locally resonant effects

By considering the foam with its impervious film as a soft elastic material it is relatively simple to create locally resonant phenomena by adding new elements within the plate thickness. This concept can be implemented using various types of inclusions, such as solid inclusions that act as local masses, with the matrix functioning as the spring, or flexural plates that bend and oscillate with the deformation of the soft material. By carefully tuning these inclusions, the system can be optimized to provide significant transmission loss at targeted low frequencies. In this study, we present results only for cylindrical aluminum inclusions with a diameter of 12 mm, embedded in the same foam as before, with a periodicity of 3 cm (Fig. 4). The thickness of the inclusions is 1 mm.

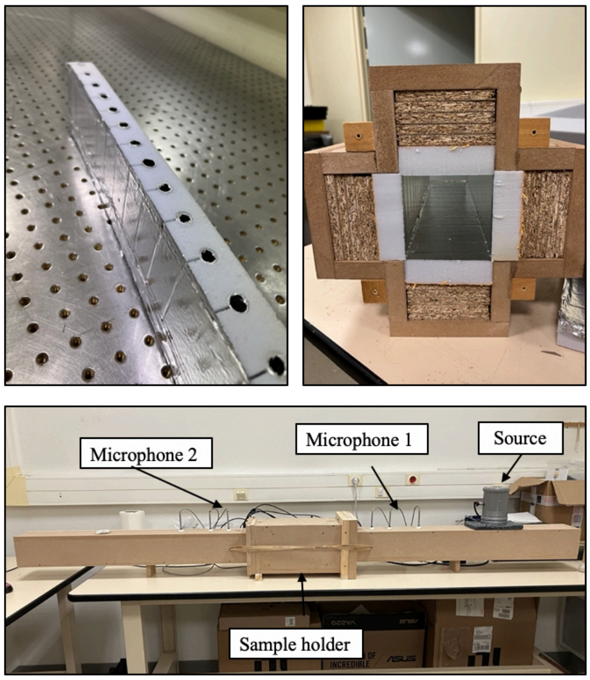

Figure 4. Pictures of the experimental setup for the elastic use case

Fig. 5 shows the experimental TL obtained with the homogeneous liner and with the sample containing aluminum inclusions. The effect of the inclusions is clearly visible between 200 and 500 Hz, with a TL of around 10 dB. As a result, beyond this frequency band, the system is no longer effective. It is therefore not suitable as a standalone solution, but it can serve as the low-frequency component of a hybrid silencer, incorporating an additional section to address mid- and high-frequency noise, while maintaining a compact form factor and avoiding pressure drop or flow-induced noise regeneration. In parallel, we also investigated another way to reach the same target, but using an acoustic approach.

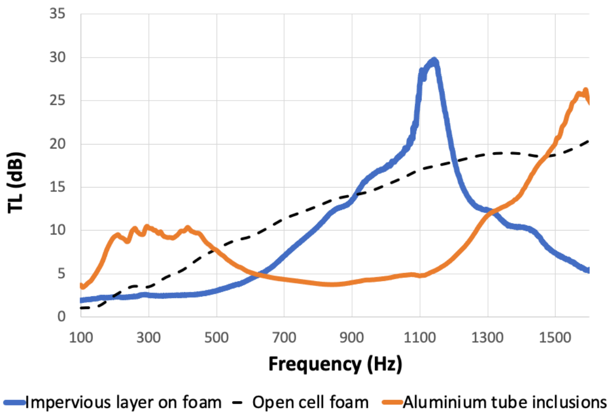

Figure 5. Experimental transmission loss comparison between the homogenous impervious foam liner and the rigid inclusion liner. Experimental TL of 3cm open cell foam liner is also plotted for information (dashed line).

3.2 Acoustic Approach

In many industrial applications, traditional porous materials cannot be used due to high temperatures, harsh environments (e.g., humidity, gas exposure, abrasion, or dust), or the need for high-pressure cleaning. Therefore, alternative transmission loss mechanisms based on reactive devices with resonator gradients are worth to investigate. In this study, we explore the potential of quarter-wavelength resonators. Unlike Helmholtz resonators, which require precise dimensional tuning due to the critical coupling of losses and sensitivity to aspect ratio, quarter-wavelength resonators are primarily controlled by the length of the duct. Although achieving low-frequency attenuation requires relatively long ducts, these can be coiled to fit within the available space. For this use case, we designed a 3 cm thick, 25 cm long silencer aimed at achieving a 10 dB transmission loss in the [250–450] Hz range (Fig. 6). The main challenge with this approach is maintaining performance in the presence of airflow. The addition of cavities directly connected to the duct walls increases local surface roughness and pressure losses, potentially inducing turbulence and noise regeneration at resonance frequencies. To address this issue, we covered the entire silencer surface with a micro-perforated mesh (25% perforation rate).

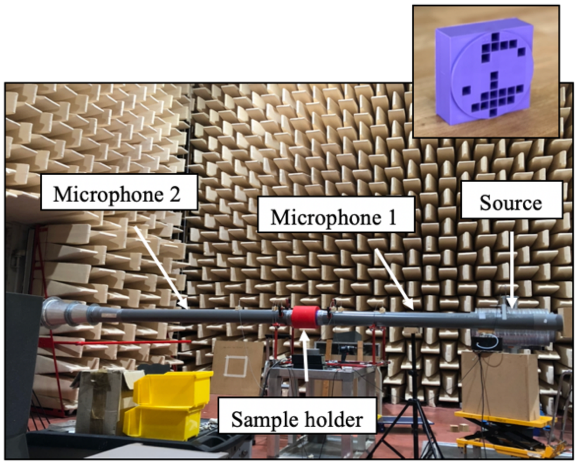

Figure 6. Experimental setup for the graded 1/4 wavelength resonator silencer with flow. Top picture depicts the unit cell sample used and wrapped to obtain the final circular silencer

The resulting transmission loss curve shows that at Mach 0.1, the device maintains 10 dB attenuation over the targeted frequency range (Fig. 7).

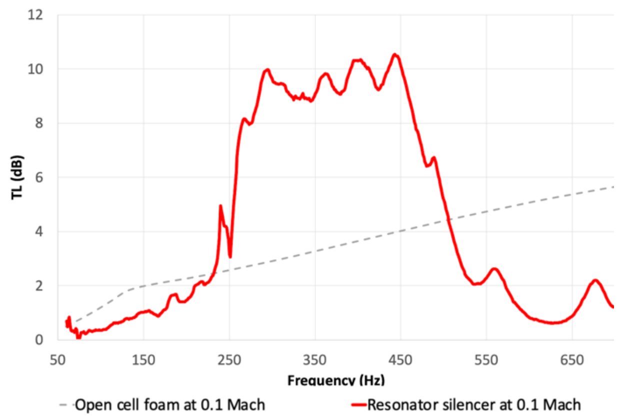

Figure 7. Experimental TL obtained for graded resonator device covered with 25% micro-perforated plate and measured with 0.1 Mach flow. Open cell foam TL for 0 and 0.1 Mach are also plotted for information.

Furthermore, we performed noise regeneration measurements and confirmed that with the micro-perforated mesh, the regenerated noise level is as low as that observed when the experimental setup is tested without a silencer. As previously mentioned, resonator-based silencers are not effective beyond their frequency range of interest and must be combined with a mid- to high-frequency system to achieve broadband transmission loss. However, they can be highly valuable in meeting industrial constraints particularly in terms of compactness.

4. CONCLUSION

In this study, we have explored two alternative silencing strategies tailored for low-frequency noise attenuation while maintaining a constant duct cross-section. The elastic approach, based on a flexible material forming a mass-spring system, demonstrated its effectiveness in leveraging mechanical properties for improved low-frequency attenuation. The acoustic approach, using quarter-wavelength resonators, provided an alternative solution suitable for harsh industrial environments where porous materials are not viable. Both silencers were designed and tested in controlled laboratory conditions, ensuring a realistic evaluation by incorporating airflow considerations. The results confirm that these solutions achieve significant transmission loss in the targeted low-frequency range without introducing additional noise due to flow effects.

Looking forward, future work will aim to enhance the robustness and efficiency of these silencers under real operating conditions. This includes manufacturing, material choice, long-term performance assessments in the presence of humidity, dust, and temperature variations, as well as their integration into complex duct systems. Optimization strategies could be employed to fine-tune the geometric and material parameters for targeted industrial use cases. Additionally, hybrid designs combining both elastic and acoustic mechanisms may open new avenues for compact, broadband, and flow-resistant silencers, meeting the increasingly stringent acoustic and environmental requirements in ventilation and process industries.

Finaly, this paper has focused on the experimental validation of these concepts, providing key insights into their feasibility and limitations. Further details, including advanced numerical optimizations and potential industrial applications, will be discussed in our oral presentation.

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