DOI: 10.61782/fa.2025.0948

FORUM ACUSTICUM EURONOISE 2025

VALIDATING THE USE OF ACOUSTIC METAMATERIALS IN INDUSTRIAL APPLICATIONS FOR LOW-FREQUENCY NOISE REDUCTION

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ABSTRACT

Vibroacoustic and acoustic metamaterials are promising technologies for noise and vibration reduction. However, their adoption in the industry is limited due to several factors, including a complex design process, industrialization challenges, and costly solutions that constrain their cost-benefit in real applications.
The present work focuses on the design and experimental validation of two types of metamaterials designed to address specific acoustic challenges in train interior noise. The first solution is a vibroacoustic metamaterial (VAMM) based on local resonance effect, designed to reduce the transmission of vibrations on a train panel around 160 Hz. The second solution is a ventilated acoustic metamaterial (AMM) for rectangular open ducts, conceived to reduce airborne noise at frequencies around 170 Hz without reducing the airflow. For both cases, a numerical model was developed and a prototype was built using additive manufacturing technologies.
Experimental validations showed vibration reductions greater than 30 dB in narrow-band and 17 dB in 1/3rd octave bands at the frequencies of interest for the VAMM. In addition, sound pressure level reductions up to 6 dB in narrow-band and 3 dB in 1/3rd octave bands were achieved for the AMM. These results demonstrate the potential of metamaterials for industrial and railways applications.

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Keywords: *acoustic metamaterial, ventilated, additive manufacturing, railways.*

1. INTRODUCTION

Developing low frequency and broadband sound insulation solutions has always been a significant challenge in noise control engineering. In many sectors like aircraft and railways, solutions based on porous materials for low-frequency sound absorption are limited to the available space for their installation, as these require a significant thickness to be efficient. This challenge becomes even more critical when low frequency airborne sound attenuation is needed with minimal reduction of the air flow. To address this, acoustic metamaterials (AMMs) offer promising solutions.
AMMs are engineered materials that have unique properties, such as negative mass or negative bulk modulus, which arise from their periodic structure. The study of AMMs originated with research on phononic crystals in 1993. In recent decades, its use has expanded significantly, driven by advancements in additive manufacturing technologies that enable the fabrication complex geometries. One of the most compelling aspects of AMMs is their ability to manipulate sound, enabling the creation of barriers that selectively attenuate specific frequencies [1].
Recently considerable effort has been dedicated to developing AMM for low frequency broadband insulation. Some proposed solutions include the use of periodically aligned acoustic black holes [2], honeycomb sandwich structures with attached membranes [3]. Additionally, significant advances have been made to enhance the broadband attenuation capabilities of vibracoustic metamaterials (VAMM) [4] and ventilated acoustic

metamaterials [5], offering solutions that are both effective and easy to manufacture. In the railways sector, innovative solutions for interior noise reduction in trains, including AMMs, were explored in the TRANSIT project with promising results from simulation point of view [6] [7].

2. RESEARCH CONTEXT AND OBJECTIVES

The aim of this work is to propose innovative solutions, based on metamaterials, for potential application cases in railways and industry. Noise reduction based on conventional solutions faces limitations related to weight and space, particularly when dealing with low frequency. Train interior noise is a combination of airborne and structure-borne noise. The structure-borne part is low frequency, and it is transmitted from the main noise sources such as the bogie and auxiliary equipment through the train carbody to the interior. Vibroacoustic metamaterials can help to reduce vibration and thus the structure-borne noise contribution in this frequency range. In this context, a VAMM based on local resonance effect to cancel bending waves in a plate structure is proposed.
Besides, there are several acoustic sources related to ventilation systems, such as cooler fans of auxiliary equipment, or the HVAC supply fan. The latter might be a relevant noise source for train interior noise, especially at train low speeds and for certain passenger positions. The duct's system has often limitations in terms of space, so solutions based on AMM can be a smart alternative to reduce the fan's blade passing frequency. In this context a ventilated AMM is proposed, tuned at a typical frequency for this kind of fan.
The objective of this research is, based on previous works found on literature as a starting point, to adapt specific designs to the above-mentioned applications.
The VAMM solution and its validation are described in chapter 3. The ventilated AMM solution and its validation are described in chapter 4.

3. CASE STUDY 1: VIBROACOUSTIC METAMATERIAL

3.1 Proposed solution

The first solution proposed in this study is a resonator, based on the VAMM approach proposed in [4] but redesigned to achieve its eigenmode at lower frequencies (around 150 Hz). Additionally, the requirements for the solution included ease of manufacturing, the ability to be mounted vertically and the affordability of use in terms of cost. For this reason, a beam-like resonator made with polypropylene with a metallic tip mass was designed and simulated.
The resonator was attached to a 3mm thick aluminum 2024 T3 plate, which served as the base structure. A 3.6 g steel tip mass, representing 26% of the bare plate's mass, was used. According to the framework described in [4], this configuration is expected to produce a bandgap width of 15 Hz. COMSOL Multiphysics was used to fine-tune the resonator's geometry in order to achieve the desired eigenfrequency of around 160 Hz (Figure 1). The chosen material, Innovatefil© polypropylene used has a very low young modulus (390 MPa), making it suitable for this application. The VAMM was manufactured using Bambu X1 Carbon 3D printing machine and glued directly to the aluminum plate. To facilitate the placement of the samples, a 0.8 mm thick tape was also printed

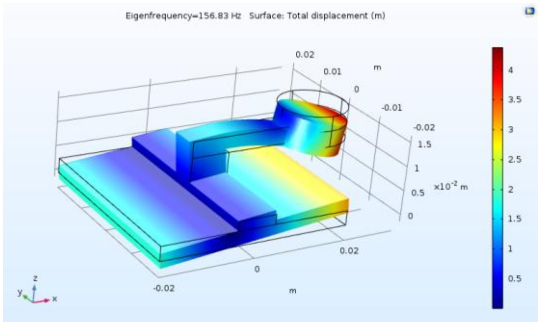

Figure 1. Modal analysis simulation of the beam-type VAMM resonator.

3.2 Experimental validation

The validation of the VAMM material performance was done by measuring averaged frequency response functions through impact testing. Results have been compared between 2 cases:

- The reference plate (bare plate)
- The reference plate + add-on VAMM

Validation has been done for two different configurations: a case where the VAMM has been installed over the whole plate area and a case where it has been installed only in the central part of the plate, occupying 22% of the total area.
Acceleration frequency response functions have been measured by averaging 5 impacts, performed at the lower edge of the plate. The response was measured at 4 different positions, at the upper edge of the plate. The impacts were performed with an instrumented hammer (PCB, model

086D05) with a nylon tip, and a set of piezoelectric accelerometers of 100mV/g.
The experiment performed with the solution added on the whole surface was done in free boundary conditions, by suspending the plates on an elastic rope, and in supported condition, with the plates supported on a table by means of foam pads (Figure 2). The evaluation of the partially applied solution has only been done in the supported condition.

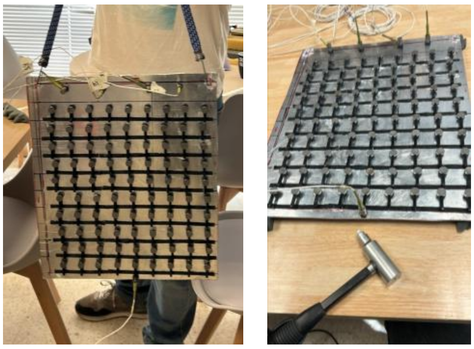

Figure 2. Experimental validation of the beam-like VAMM in free and supported boundary conditions.

3.3 Results

The comparison of the averaged frequency response functions of the bare plate and the bare plate with the VAMM are shown in Figure 3 and Figure 4 for free and supported boundary conditions respectively.

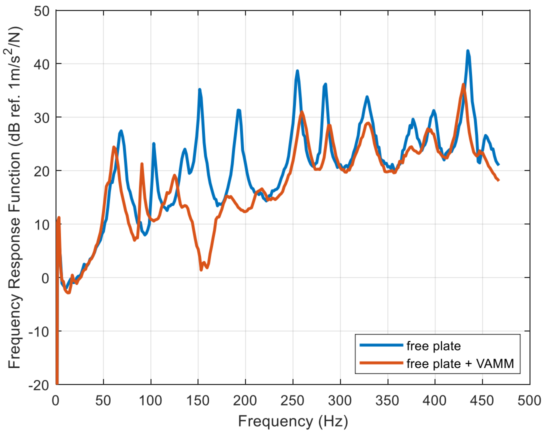

Figure 3. Magnitude of the averaged acceleration frequency response function with the VAMM solution applied in the whole plate surface (free boundary conditions).

Some differences are observed in the magnitude of the peaks between the free and supported cases. Despite the different boundary conditions, the same stop band is observed in both cases, in the range between 130 and 180 Hz, with a strong dip at 155 Hz (33 dB of reduction). Furthermore, a suppression of the peaks is observed up to 210 Hz. Besides, probably due to a significant amount of damping, peaks above 210 Hz are partially damped.

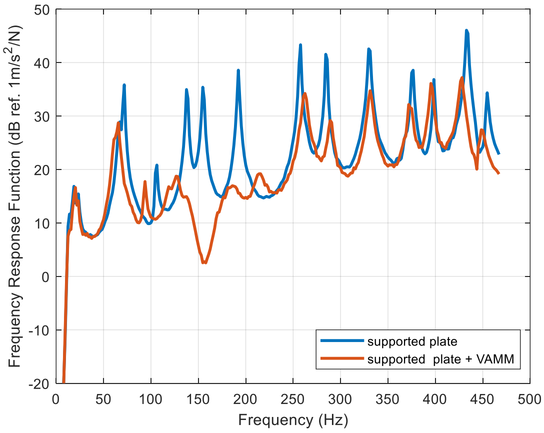

Figure 4. Magnitude of the averaged acceleration frequency response function with the VAMM solution applied in the whole plate surface (supported boundary conditions).

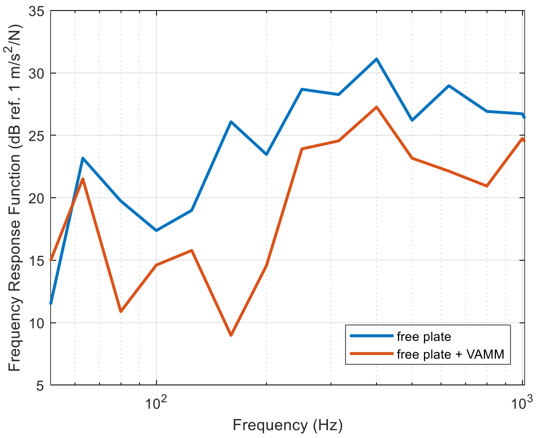

Figure 5. Averaged acceleration frequency response function in 1/3rd octave bands with the VAMM solution applied in the whole surface.

It is worth reading these results in one-third octave bands, as they are commonly used in noise control in industry. Reductions of 17 dB at 160 Hz band, and 9 dB at 200 Hz are achieved (Figure 5).

Results for the VAMM installed in 22% of the surface are shown in Figure 6. The stop-band behaviour is not observed in this case. A reduction in the amplitude of the peaks is achieved between 140 and 200 Hz. Above this frequency, only a very slight reduction in the amplitude of the peaks is observed. In one-third octave bands, the maximum reduction achieved is 11 dB at 160 Hz.

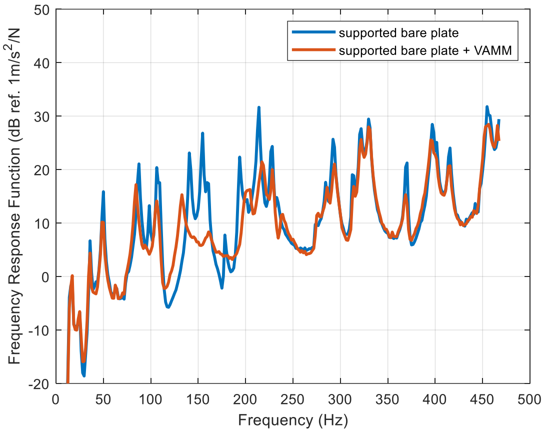

Figure 6. Magnitude of the averaged acceleration frequency response function with the VAMM solution applied in 22% of the plate surface.

4. CASE STUDY 2: VENTILATED ACOUSTIC METAMATERIAL

4.1 Proposed solution

The solution proposed to increase the absorption in an open-duct is a ventilated acoustic metamaterial, composed of multiple monopolar resonators arranged the same plane parallel to the section of the tube. The design features several Helmholtz resonators placed in a rectangular ring configuration. This design was based on the methodology proposed by Meng et al. [5], adapted to match the typical dimensions of a train's HVAC ducts (270 x 210 mm). A frequency domain analysis was performed using COMSOL Multiphysics to achieve an eigenfrequency at lower frequencies. The analysis involved creating a plane wave excitation in a Navier-Stokes linearized domain with perfect matching layers applied at the end of the ducts. The results show that the sound pressure levels (SPL) at Helmholtz resonator cavities are highest around 170 Hz (Figure 7).

The ventilated acoustic metamaterial was fabricated using PLA on a Prusa XL 3D printer. Due to the large sample size, the structure was subdivided into multiple sections and assembled using screws. To avoid the use of support materiel, the Helmholtz cavities were printed without the rear wall, which was glued in place after printing.

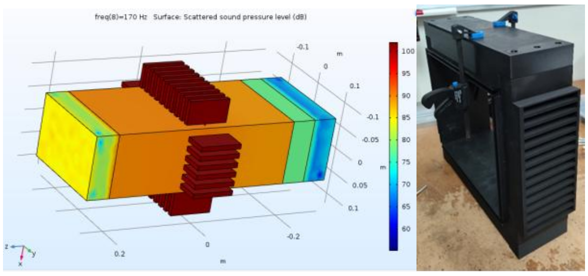

Figure 7. Scattered SPL obtained with finite element simulation of ventilated acoustic metamaterial (left), and process of assembling the metamaterial (right)

4.2 Experimental validation

Experimental validation has been done in a semi-anechoic chamber. A rectangular duct made of 4 mm thick PMMA material has been mounted and assembled, at one end, to a box containing a loudspeaker. To test the solution, the AMM has been assembled at the other end of the rectangular duct (Figure 8).

The validation has consisted in the comparison of the sound pressure level at a set of receiver positions between the case with the AMM installed and a reference case, where the duct has been assembled to a sample with the same dimensions than the ventilated AMM but without the Helmholtz resonators. Pink noise has been used as acoustic excitation.

The set of 15 receivers has been placed at 80 cm from the end of the sample, covering an area of 100 x 50 cm. Results have been calculated by averaging the sound pressure level at all positions.

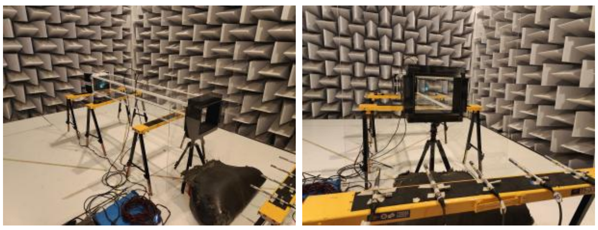

Figure 8. Images of the set-up in the semi-anechoic chamber.

4.3 Results

The comparison of the averaged sound pressure level results with and without the AMM solution is shown in Figure 9. In narrow band, a maximum reduction of 6 dB is found at 178 Hz and at 202 Hz. In one-third octave bands, this translates into a reduction of 3 dB at the band of 200 Hz and 1.4 dB at 160 Hz.

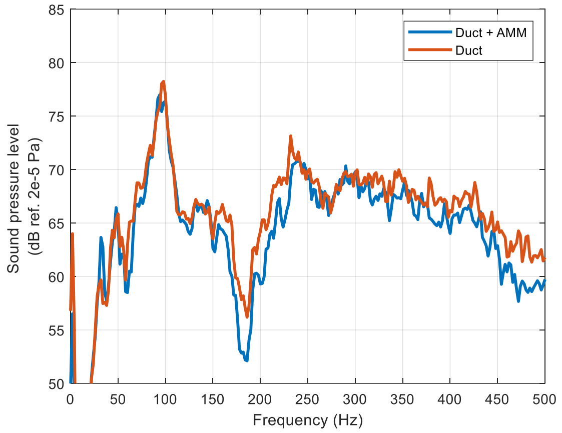

Figure 9. Comparison of the average sound pressure level results with and without the AMM solution installed.

5. CONCLUSIONS

In this work, two metamaterials have been designed, prototyped and experimentally evaluated for potential applications in the railway industry, based on the requirements and specifications of possible real-world cases. The proposed solutions are lightweight, easily manufacturable and easy to mount, with low production cost.

After the experimental evaluation of the beam-resonator based VAMM, a stop band has been clearly observed, with reductions up to 33 dB at 155 Hz. This corresponds to a reduction of 17 dB at 160 Hz one-third octave band. Thanks to these results, the solution appears promising. It has been observed that the total amount of resonators in the plate is relevant for the stop band performance. The next step to further develop this material would be, on the one hand, to move forward toward the industrialization phase. On the other hand, modifications could be explored to increase the stop-band frequency range without adding extra weight to the solution.

The results of the ventilated AMM solution have shown reductions of 6 dB in narrow band at frequencies near the target frequency, 170 Hz, which leads to a reduction of 3 dB at 200 Hz third-octave band. Discrepancies with the results of the literature may arise from defects in the design of the AMM, which is not completely optimized, or issues related to the assembly of its components. Further research is needed to improve the performance of the proposed solution.

6. ACKNOWLEDGMENTS

This work was funded by the European Union – Next Generation UE and the Recovery, Transformation, and Resilience Plan (PADIH); and supported by the Spanish Ministry of Industry and Tourism and EOI.

7. REFERENCES

[1] Aydın, G., & San, S. E. (2024). Breaking the limits of acoustic science: A review of acoustic metamaterials. Materials Science and Engineering: B, 305(April). https://doi.org/10.1016/j.mseb.2024.117384

[2] Li, L., Hu, H., & Wu, X. (2023). Ultra-Low-Frequency Acoustic Black Hole Radial Elastic Metamaterials. Applied Sciences, 13(20), 11542. https://doi.org/10.3390/app132011542

[3] Sui, N., Yan, X., Huang, T. Y., Xu, J., Yuan, F. G., & Jing, Y. (2015). A lightweight yet sound-proof honeycomb acoustic metamaterial. Applied Physics Letters, 106(17). https://doi.org/10.1063/1.4919235

[4] Atzrodt, H., Maniam, A., Droste, M., Rieß, S., & Hülsebrock, M. (2023). A Power-Based Framework for Quantifying Parameter Uncertainties in Finite Vibroacoustic Metamaterial Plates. Materials, 16(14). https://doi.org/10.3390/ma16145139

[5] Meng, Y., Romero-García, V., Gabard, G., Groby, J. P., Bricault, C., & Goudé, S. (2023). Subwavelength Broadband Perfect Absorption for Unidimensional Open-Duct Problems. Advanced Materials Technologies, 8(12). https://doi.org/10.1002/admt.202201909.

[6] I. Lopez, M. Abom, E. Cierco, FX. Magrans, R. Serra. Feasibility study of new concepts and approaches, TRANSIT Deliverable D4.1, December 2020

[7] E. Cierco, FX. Magrans, I. Lopez, A. Aulitto, D. Passato, M. Abom. Acoustic performance characterization of baseline and new design variants, TRANSIT Deliverable D4.2, June 2022.