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MetaVENT

Executive summary

The MetaVENT project addresses the pressing challenge of reducing low-frequency noise generated by Heating, Ventilation and Air Conditioning (HVAC) systems in modern vehicles. In conventional cars, engine noise partially masks the sound of HVAC units; however, in electric vehicles this masking effect is absent, making HVAC noise a more dominant and disturbing contributor to the acoustic environment of the cabin. Traditional noise control solutions, such as foams and liners, become ineffective below 1000 Hz unless significant thicknesses (often greater than 50 mm) are used, which are incompatible with the limited space available in automotive ducts.

To overcome these constraints, the project aimed to design, model, and test innovative **acoustic metamaterials** capable of achieving significant low-frequency attenuation (100–1000 Hz) within a thickness of less than 20 mm. Drivers of innovation included the rising demand for quiet and comfortable electric vehicles, stricter noise regulations in urban areas and the industrial push for lightweight, manufacturable solutions. In partnership with **DENSO Thermal Systems**, the project explored Helmholtz resonators, small cavity-neck systems that attenuate sound at a specific frequency through resonance, and labyrinthine geometries, which provide broadband performance by extending the acoustic soundwave path in compact volumes. Both were simulated using a multiphysics software capable of coupling fluid dynamics, structural vibration, and acoustics in a single model, and fabricated using additive manufacturing techniques.

The expected results included a set of validated simulation methodologies, 3D printed prototypes, impedance tube testing data and design guidelines for future industrial scalability. Experimental results confirmed the simulation predictions:

- attenuation peaks of up to **28 dB at target frequencies** for Helmholtz-based designs;
- broadband reduction of **3–10 dB in the 500–1000 Hz range** using labyrinthine structures.

These results demonstrate that compact acoustic metamaterials can provide real, scalable benefits in automotive HVAC applications, enabling significant low-frequency noise reduction within severe space constraints.

Key words:

Acoustic Metamaterials, Low-Frequency Noise, Automotive HVAC, Helmholtz Resonators, Labyrinthine Structures

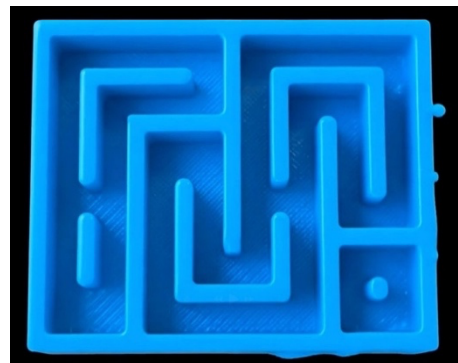
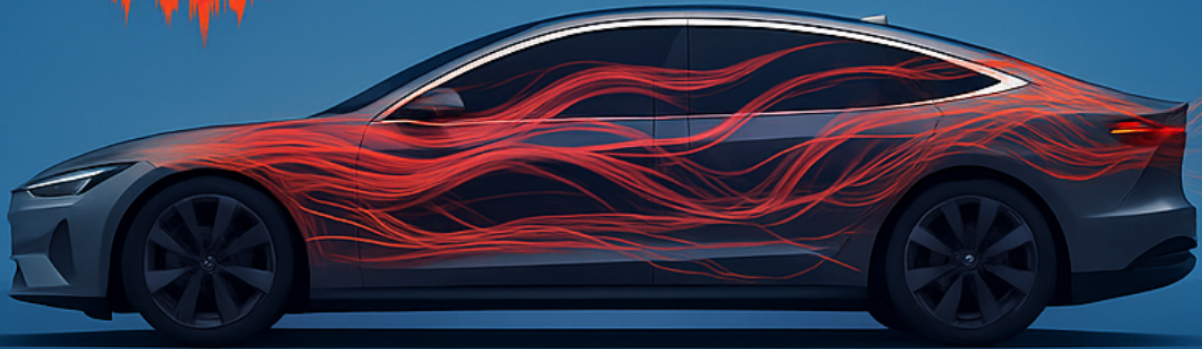
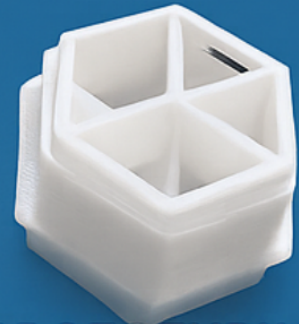
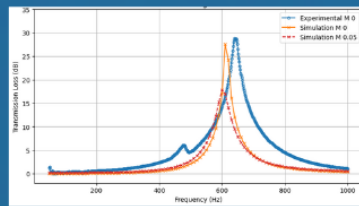
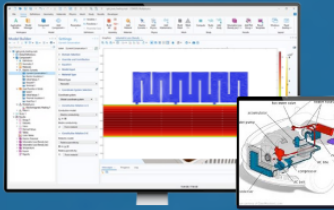


Figure 1. Representative labyrinthine structure of an acoustic metamaterial, illustrating the complex pathways used to attenuate noise.



MetaVENT



SIMULATIONS

VALIDATION

PROTOTYPING



Project description written by the Principal Academic Tutor

This project explored the use of metamaterials, engineered structures with unit cells designed to manipulate acoustic waves, for the control of low-frequency noise in HVAC systems. Unlike conventional absorbers, which require bulky dimensions, metamaterials can achieve attenuation in compact, lightweight forms. However, systematic design criteria are still lacking, especially when acoustic waves interact with turbulent flows such as those generated inside ducts or engines.

The objective was therefore twofold: to develop numerical optimization procedures capable of tailoring metamaterial geometries to strict space and frequency requirements, and to translate the best-performing concepts into fabricated prototypes using additive manufacturing. The workflow followed a progressive structure: the project began with literature review, case studies, and site visits at the industrial partner's headquarters, supported by seminars and onboarding activities to establish a shared baseline. Early design evaluations guided by tutors provided initial benchmarks and a detailed roadmap, including cost considerations and project gateways. From there, the team advanced to the design and simulation of preliminary structures, coupling acoustic and elastic properties with CFD analyses to capture flow-induced effects. Optimization algorithms were subsequently employed to refine geometrical and structural parameters, ensuring enhanced noise attenuation and robustness under realistic operating conditions.

In the following stages, fabrication trials using advanced manufacturing technologies, particularly 3D printing, were carried out in collaboration with academic laboratories and the industrial partner. These prototypes were then characterized experimentally: acoustic properties were measured with impedance tube testing. Iterative design-fabrication-testing cycles enabled progressive refinement, ultimately yielding optimized resonant and labyrinthine structures for low-frequency applications.

The expected results included not only working prototypes but also an optimization framework and validated design guidelines for future industrial scalability. This industry-oriented project highlights the innovation potential of metamaterials in tackling noise, vibration, and comfort challenges in next-generation vehicles, while fostering multidisciplinary collaboration across fluid dynamics, acoustics, materials science, and computational engineering.

Team description by skill

The MetaVENT project was carried out by a multidisciplinary team of master's students, each contributing expertise from their academic background:

- **Aerospace Engineering:** Applied knowledge of fluid dynamics, aerodynamics of ducts and acoustic modeling for flow-sound interactions.
- **Mathematical Engineering:** Expertise in optimization algorithms, parametric studies and numerical analysis of simulation data.
- **Data Science Engineering:** Automation of workflows, data management and statistical evaluation of parametric sweeps.
- **Computer Engineering:** CAD modeling, computational pipeline integration and scripting of simulation processes.

Together, the team shared responsibilities for **3D printing, prototyping and impedance tube testing**, ensuring that both simulation and experimental validation phases were covered despite the absence of a specialized experimental acoustics background. This collaborative approach guaranteed that every stage of the project, from modeling to fabrication and testing, was successfully addressed.

Goal

The primary goal of the MetaVENT project was to design, simulate, fabricate and experimentally validate **compact acoustic metamaterials** capable of attenuating low-frequency noise (100–1000 Hz) generated by HVAC systems in vehicles. Unlike conventional porous absorbers, which are bulky and inefficient at these frequencies, the proposed solutions needed to fit within the **strict dimensional limit of less than 20 mm in thickness**, while also ensuring minimal impact on airflow performance.

The project set out to demonstrate that **Helmholtz resonators and labyrinthine structures** could be engineered, optimized, and prototyped to achieve measurable attenuation in real-world conditions. Beyond achieving technical performance targets, the project also aimed to establish **scalable design criteria**, identify manufacturing methods compatible with industrial processes, and create a **validated workflow** that integrates simulation, optimization, and experimental testing.

Ultimately, the project's goal was not only to deliver working prototypes, but also to provide the automotive industry with guidelines and methodologies for integrating metamaterials into HVAC ducts, thereby contributing to quieter and more comfortable vehicles.

Understanding the problem

HVAC noise in vehicles is primarily tonal and occurs at low frequencies, where human perception is particularly sensitive. While traditional porous absorbers are effective in the mid-to-high frequency range, their performance degrades significantly at low frequencies without thick geometries. This limitation is critical in automotive duct applications, where any noise-control treatment can occupy a maximum installation depth of only about 20 mm per wall. Furthermore, pressure drop must be minimized to avoid compromising the efficiency of the HVAC system.

In electric vehicles, the absence of an internal combustion engine removes natural masking effects, making HVAC noise more noticeable. This has heightened consumer expectations for acoustic comfort and motivated the automotive industry to explore new materials and geometries. The project therefore defined the problem as one of **low-frequency attenuation in confined geometrical constraints**, requiring innovative solutions beyond conventional materials.

Exploring the opportunities

The exploration phase involved a systematic review of promising acoustic metamaterial geometries. Among these, Helmholtz resonators were identified for their sharp resonant attenuation peaks, which could be tuned by adjusting neck and cavity dimensions. Labyrinthine structures were also selected for their broadband attenuation capabilities, achieved by creating long acoustic paths within compact volumes, a similar feature shared with coiled resonators, that were explored as well. Additive manufacturing (3D printing techniques) offered the possibility to create these complex geometries with high precision and repeatability, a feature that traditional manufacturing processes could not guarantee.

At the same time, market trends reinforced the relevance of these developments. The global acoustic metamaterials sector, valued at USD 338.6 million in 2023, is projected to expand at a CAGR of 35.1% between 2024 and 2032, largely driven by the demand for quieter vehicle cabins and innovation in automotive HVAC noise control. In particular, the pursuit of enhanced acoustic comfort in electric vehicles, the push for sustainability-driven innovation and the recognition of acoustic performance as a competitive differentiator in premium segments further reinforced the relevance of these technologies. This phase therefore established not only the technical feasibility but also the industrial and commercial potential of acoustic metamaterials, identifying them as strong candidates for detailed simulation and prototyping.

Generating a solution

The solution generation phase combined numerical simulations, rapid prototyping, and experimental validation. Numerical analyses were performed in COMSOL Multiphysics, a simulation platform particularly suited for modeling the coupled interactions of fluid dynamics and acoustics in sound-damping structures. A dedicated workflow was established to predict the transmission loss of candidate geometries, and parametric sweeps were carried out to assess the influence of key design parameters. These simulations guided the optimization of both Helmholtz and labyrinthine configurations.

Prototypes were fabricated using 3D printing. Fused Deposition Modeling (FDM) enabled rapid and low-cost iterations, while Stereolithography (SLA) provided high-precision models suitable for acoustic testing. All samples were carefully sealed to ensure acoustic integrity and subsequently characterized in an impedance tube.

The impedance tube, a standardized device for measuring transmission loss and sound absorption, was employed to assess the acoustic properties of the printed geometries and to validate their effectiveness. Experimental results confirmed the numerical predictions: Helmholtz resonators achieved attenuation peaks of up to 28 dB at their tuned frequencies, while labyrinthine structures delivered broadband reductions of 3–10 dB in the 500–1000 Hz range.

The project concluded with design guidelines for industrial applications, including considerations of manufacturability, airflow resistance and noise reduction effectiveness.

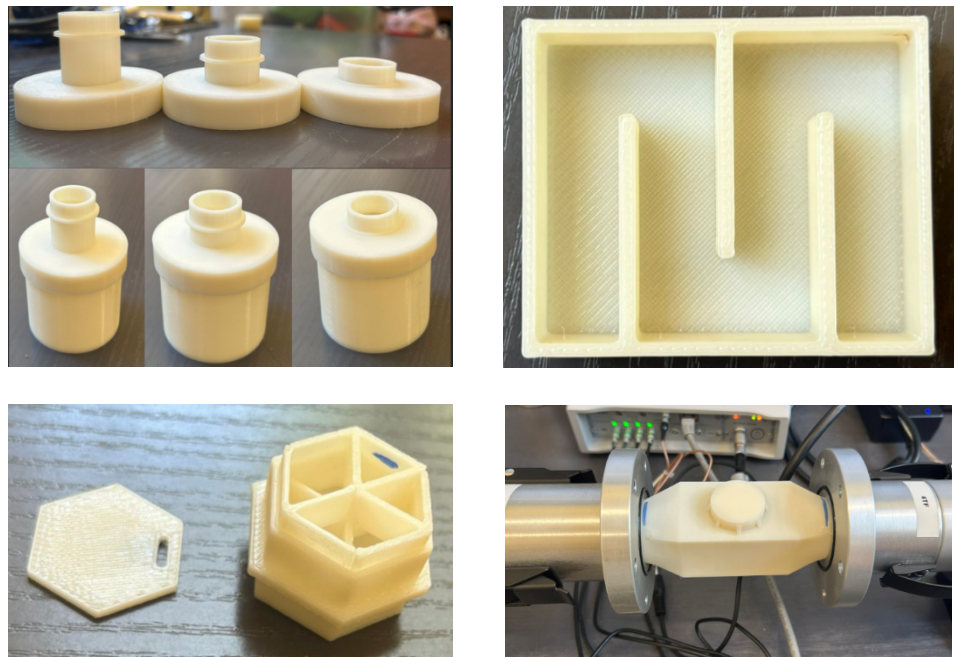


Figure 2. From top to bottom, left to right: Helmholtz resonators with different neck lengths; M-shaped labyrinth structure; hexagonal labyrinthine prism; experimental set-up with impedance tube.

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