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# Active reduction of noise transmitted into and from enclosures through encapsulated structures.

Marie Skłodowska-Curie Actions

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## Milestone 9

Review and results validation on integration of active cabin noise control systems with passive/metamaterials

WP2 – Noise reduction in vehicle and aircraft cabins

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## Introduction

In modern transportation, lightweight design has become essential for improving fuel efficiency and reducing emissions. However, this shift often compromises noise insulation, leading to increased cabin noise, affecting passenger comfort and, ultimately, health. Traditional noise control methods often require the addition of mass and/or volume, making them less suitable for lightweight applications. To address this challenge, locally resonant metamaterials (LRMs) have emerged as a promising alternative, offering targeted noise and vibration reduction without significant mass penalties. This review explores the potential of LRMs for cabin noise control, highlighting recent advancements and challenges.

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## 1. Cabin Noise: relevance and challenges

In recent decades, strict environmental regulations and economical requirements have led to a strong push towards the use of lightweight designs, especially in the transportation sector [1], [2]. However, the use of lightweight yet stiff materials typically result in a reduced noise insulation performance [3]. In modern transportation systems, cabin noise significantly impacts passenger comfort, safety and overall user experience. As vehicles and aircraft continue to evolve toward more efficient, lightweight, and sustainable designs, addressing cabin noise becomes therefore increasingly challenging. Simultaneously, awareness of the detrimental effect of noise on health is growing, indeed excessive noise exposure has been linked to fatigue, reduced speech intelligibility and long-term health effects such as chronic stress and cardiovascular diseases [4].

Cabin noise primarily originates from structure-borne and airborne sound transmission mechanisms. In automobiles, road-tyre interaction, aerodynamic effects and powertrain vibrations contribute to the noise environment [5], while in aircraft, noise and vibrations from the engines and turbulent boundary layers propagate into the cabin through the fuselage [6]. The shift toward electric vehicles (EVs) and hybrid-electric propulsion in aircraft has further altered the noise landscape by reducing engine noise and making other sources, such as aerodynamic turbulence and tire-road interactions, more prominent and perceptible to passengers [7].

Conventional noise, vibration, and harshness (NVH) control solutions, such as passive insulation materials (e.g. absorptive foams, fibrous materials), damping treatments (e.g. viscoelastic polymers, rubber layers) and structural modifications (e.g. reinforcements, heavy layers, tuned vibration absorbers) are widely used to mitigate cabin noise. However, these approaches primarily rely on the addition of volume or mass, which conflicts with the increasing demand for lightweight designs. This conflict is particularly problematic for low-frequency noise control (typically below 500 Hz), which generally dominates in automobile cabins [5], where effective sound absorption requires substantial material thickness.

In the transportation sector, where weight reduction is crucial for fuel efficiency and CO2 emission reduction [1], excessive reliance on these traditional solutions increasingly hinders compliance with economic requirements and stringent environmental regulations. These challenges necessitate innovative noise control strategies that provide effective attenuation, particularly in the low-frequency range, while maintaining lightweight and compact designs. In this context, metamaterials - engineered structures designed to manipulate wave propagation in unconventional ways - have emerged as a promising solution for next-generation cabin noise control. By leveraging locally resonant mechanisms, metamaterials show potential to achieve excellent noise and vibration reduction at targeted frequencies without the mass or volume trade-off associated with traditional solutions.

## 2. Locally resonant metamaterials

### 2.1. Passive solutions

Locally resonant metamaterials (LRMs) have emerged as a novel potential solution for effective, lightweight and targeted noise and vibration control. These structures rely on the addition of resonant elements onto a flexible host structure on a sub-wavelength scale, i.e. on a scale smaller than the targeted structural wavelength, to achieve a structural stop band [8], [9]. In the stop band, free wave propagation is prohibited, therefore resulting in a frequency band of strong vibration reduction and hence reduction in acoustic radiation and sound transmission [10], [11]. The primary mechanism governing LRMs is a Fano-type interference, resulting from interactions between the host structure and the resonators, leading to localized vibrational energy trapping in a frequency range in and around the stop band [12]. Since the creation of a stop band is a resonance-based effect that can be tuned by design of the resonators, the frequency in which they are effective is not linked to the mass or volume addition, making them particularly suitable for applications requiring a lightweight and compact noise and vibration control solution, especially in the hard-to-address low-frequency range [13].

In recent years, LRMs have been explored for reducing structure-borne and airborne noise in vehicle and aircraft cabins. In [14], waterjet cutting was used to create resonant elements into the cover of the power electronics module of an electric powertrain. By leveraging upon the stop band effect, a strong noise reduction was achieved in the one-third octave bands from 315 Hz to 1000 Hz while achieving a weight saving of 3 % (Figure 1).

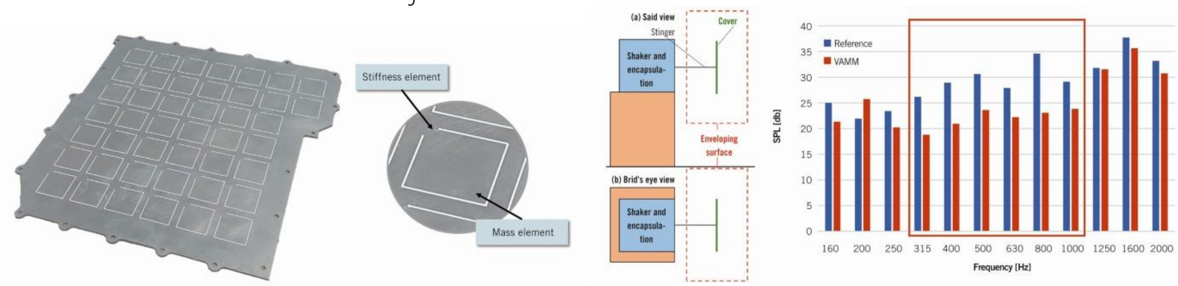


*Figure 1: Cover of power electronics with integrated resonators (left) and averaged sound pressure level measured with a sound intensity probe around the LRM cover (=VAMM) (right) [14].*

Other works have focused on integrating LRMs in vehicle doors [15], shock towers [16] and in tyres [17]. In [16], a conventional tuned vibration absorber placed on the rear shock towers was interchanged with a novel LRM solution. By designing the resonant elements to have an in-plane and out-of-plane mode in a frequency range around 190 Hz, a range where tyre/road noise typically has a significant acoustic contribution [5], a similar and/or better noise reduction was achieved, with only 48 % of the mass of the traditional tuned vibration absorber (Figure 2, left). In [17], rubber dual-mode resonators were glued into the tyre of a car, targeting the frequency range of acoustic tyre resonances and hence reduce the transmission of vibrations and radiation noise into the car cabin. Although a vibro-acoustic attenuation was achieved, more research is required on the effects of rolling speed as it lead to a varying degree of attenuation (Figure 2, right).

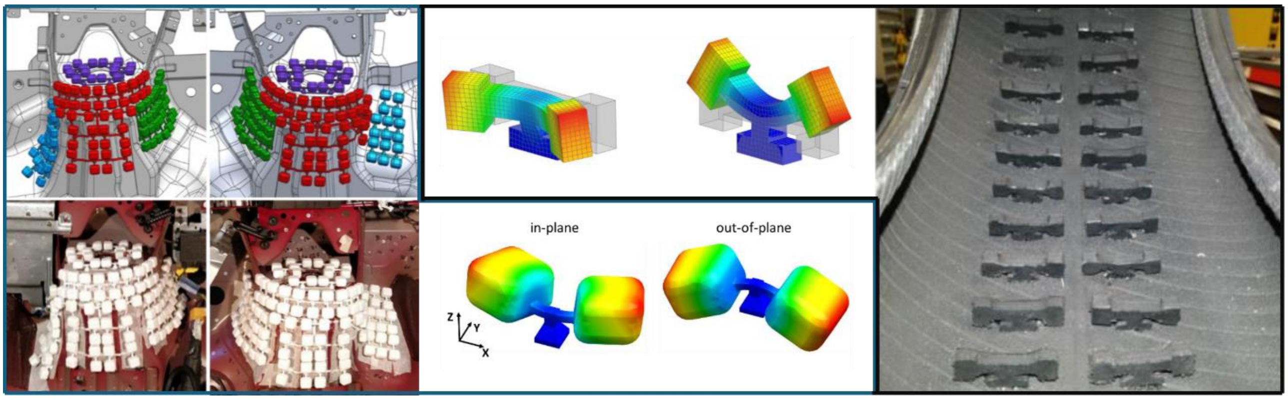


*Figure 2: (left, blue) Application of LRMs to the rear shock towers of a vehicle [16] and (right, black) in a tyre [17].*

The application of LRMs has also been investigated to improve aircraft's cabin noise insulation [18], [19], [20]. In [19], the use of membrane-type resonators was investigated to create fuselage noise shields, where a 3 dB improvement in noise radiation was reported (Figure 3). In [20], the acoustic insulation performance at ring frequency of an aircraft fuselage panel was improved by roughly 10 dB by adding 3D-printed resonators.

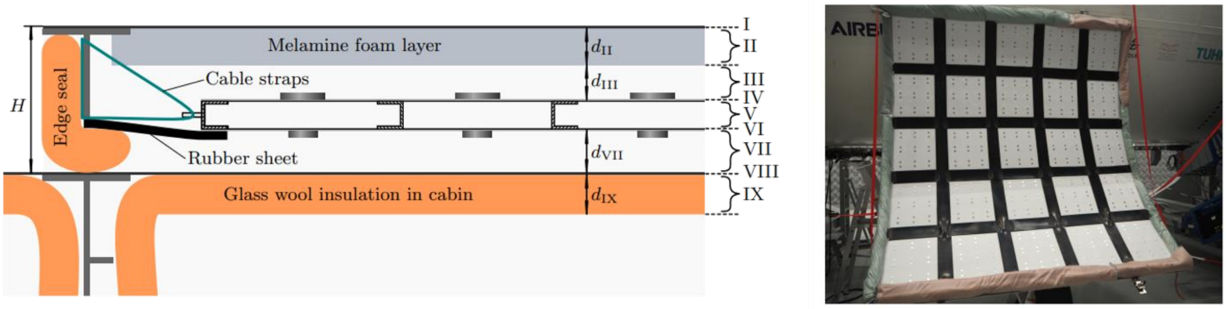


*Figure 3: Membrane-type resonators added in between foam and glass wool insulation in the fuselage of an aircraft [19].*

## 2.2. Active solutions

Besides novel passive LRM concepts, research efforts have also been directed toward active noise and vibration control. One subcategory is active noise control (ANC), where the basic concept (Figure 4) is to send a secondary audio signal into the cabin that cancels the noise generated by the noise sources, typically based on feedforward/feedback control systems to minimize their residual error [21]. Challenges in this field include the often random and time-varying nature of noise in vehicle cabins, cost constraints, system stability issues, noncausality and limited spatial coverage [5].

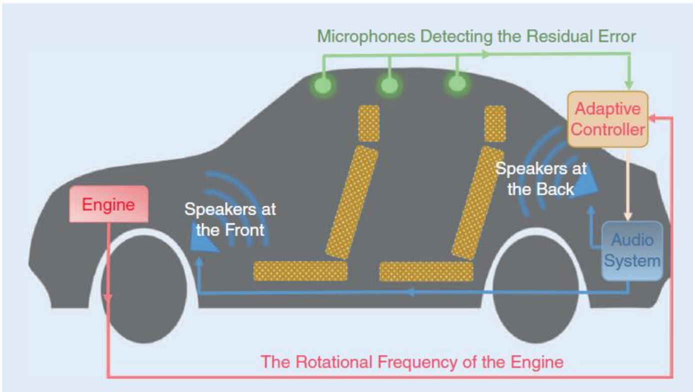


*Figure 4: Illustration of the ANC principle [5].*

Also, structural (semi-) active LRMs have gained significant research interest over the past decades, however they have been less applied to the mitigation of cabin noise. Shunted piezoelectric patches, a type of electromechanical resonator, have been studied for their ability to create tunable or adaptive structural stop bands [22], [23]. By modifying the electrical impedance of the shunts, the resonance frequencies of the piezoelectric elements can be shifted, thereby shifting the operational frequency range of the LRM solution. Works with self-controllability and/or tunability have been investigated [24], [25]. This capability is particularly useful for addressing structure-borne noise in vehicle and aircraft cabins, where excitation frequencies can vary significantly. Additionally, stop band broadening has been investigated by modifying the shunt circuit, e.g. by incorporating negative capacitance circuits [26], [27]. While active LRMs address a key limitation of their passive counterparts, i.e. a tunable stop band, they introduce added complexity by often requiring (real-time) control mechanisms, electronics and/or requiring an external energy supply.

## 3. Conclusion

Despite their promising characteristics, these passive/active LRMs still face many challenges to be addressed.

Since in passive LRMs the stop band is linked to an eigenfrequency of the designed resonators, precise and scalable manufacturing is required. Current realizations often rely on lasercutting, 3D printing and gluing, while active research is also dedicated to exploring more scalable manufacturing methods like thermoforming [28] and injection moulding [29].

Additionally, LRMs typically exhibit strong attenuation only within a narrow frequency band. To address this limitation, research efforts have focused on optimization strategies such as multimodal resonators and distributed resonance tuning to extend their effective bandwidth.

Another key challenge is the interaction of LRMs with real-world industrial environments, where factors such as boundary conditions, temperature variations, partial treatments and acoustic surroundings can affect their performance, sometimes deviating from predictions made in controlled experimental or numerical studies. Future advancements are expected to focus on real-life application, improving broadband performance and integrating LRMs with hybrid noise control solutions, i.e. a combination of passive and (semi-) active LRMs, to enhance noise mitigation across a broader frequency spectrum.

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