Enhanced lightweight NVH solutions based on vibro-acoustic metamaterials

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Summary

The NVH performance of conventional panels and structures is mainly driven by their mass. Silence often requires heavy constructions, conflicting with the emerging trend towards lightweight design. To face the challenging and often conflicting task of merging NVH and lightweight requirements, novel low mass and compact volume NVH solutions are required. Vibro-acoustic metamaterials with stopband behavior emerge as a possible novel NVH solution, combining lightweight requirements with superior noise and vibration insulation in the currently hard to address lower frequency ranges. Through further industrial valorization, these vibro-acoustic metamaterials pave the way for a new class of light and compact NVH solutions with ample applications in automotive for low and mid frequency NVH mitigation.

1 Introduction

Over the past decades, increasingly stringent emission regulations have given rise to the introduction of lightweight materials and designs. The growing awareness of the health impact of noise and vibrations meanwhile leads to ever tightening noise and vibration exposure regulations. Apart from legal considerations, poor noise, vibration and harshness (NVH) behavior is also undesirable due to growing customer expectations. Since the NVH performance of conventional panels and structures is mainly driven by their mass, silence often requires heavy or bulky constructions, conflicting with the trend towards lightweight design. Novel low mass and compact volume NVH solutions are required to face the challenging and often conflicting task of combining both NVH and lightweight design requirements.

Recently, vibro-acoustic metamaterials have come to the fore as a possible novel NVH solution combining lightweight requirements with superior NVH attenuation performance, at least in some targeted and tunable frequency ranges, referred to as stop bands. This paper discusses the innovative vibro-acoustic metamaterial concepts that are being developed at KU Leuven and describes the further steps required for industrial valorization of the concept to bring these vibro-acoustic metamaterials closer to cost-effective, widely applicable lightweight and compact NVH solutions.

2 Vibro-acoustic metamaterials

Metamaterials are artificial structures engineered from conventional materials in order to exhibit some targeted performance that exceeds the performance of conventional materials. Considering vibro-acoustic metamaterials, this superior performance consists of resonance based stop bands, which are targeted and tunable frequency ranges in which superior vibro-acoustic attenuation performance is exhibited.

These metamaterials typically consist of (often periodic) assemblies of unit cells of non-homogeneous material composition and/or topology. More specifically, resonance based stop bands are obtained from resonant cells, exerting a non-zero net force, arranged on a scale smaller than the structural wavelengths to be influenced, and emerge from a Fano-type interference between incoming waves and the waves re-radiated by the resonant cells [1,2]. Since the stop band frequencies are determined by the resonance frequency of the resonant cells and thus not driven by the spacing between resonant structures, the possibility of low-frequency vibro-acoustic attenuation arises [3,4]. This brings within reach the operational frequencies of many practical noise control applications (typically 50-500-5000 Hz range), for which classic solutions are often too bulky or heavy.

At the KU Leuven the working principles and driving parameters of resonance based metamaterials have been investigated and a novel concept for metamaterials with resonance based stop bands is proposed [5]: the addition of resonant structures to an existing host structure. Since this technology depends on the combination of material and geometry, a wide range of materials and production processes are eligible. Furthermore, a large variety of designs can be proposed for the resonant structures, allowing the metamaterial to be optimized towards minimal weight, maximal attenuation or broadband attenuation.

3 Metamaterial demonstrators

Recent research at the KU Leuven has been focusing on demonstrating the potential of the metamaterial concept for a variety of NVH problems: acoustic transmission reduction and vibration attenuation.

To demonstrate the acoustic transmission reduction potential of the introduced metamaterial concept, inspiration is sought in the class of periodic lightweight structures. A honeycomb core enclosure is designed and manufactured using Selective Laser Sintering [5]. These periodic lightweight structures are gaining importance in transportation and machine design due to the combination of low mass with excellent mechanical properties. Resonant structures are embedded in the hollow cavities of the host structure, which offers a twofold advantage: (i) the host structure can be designed for optimal static stiffness or light weight while the resonant structures can be independently tuned for good vibro-acoustic behavior in a desired frequency range and (ii) the resonant structures can be covered for use in contaminated environments or when aesthetically desired.

A straightforward resonant structure design is considered, resembling a mass-spring system, with a thick mass portion and two thin legs providing the stiffness, which exhibits a clear low-frequent bending mode, introducing resonant behavior (Fig. 1).

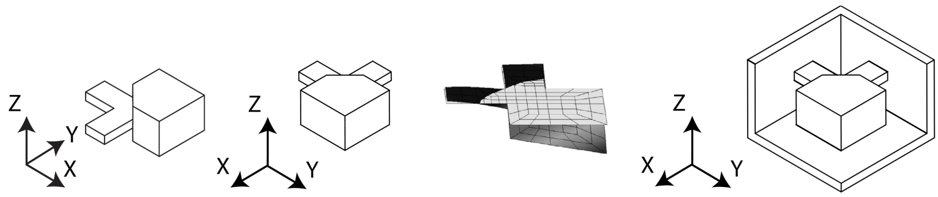

Fig. 1: Resonant structure of acoustic demonstrator, deformed FE model of resonant structure at resonance and unit cell of resulting metamaterial [5]

An FE model of the unit cell is used to predict wave propagation and thus stop band behavior in the metamaterial, which is explained in detail by the authors in [5]. The acoustic insertion loss measured for a 100x100x100 mm metamaterial enclosure, consisting of 8x8 cells on each face, is compared to a conventional, flat sided enclosure of the same outer dimensions, mass and material by encapsulating a small speaker. In Fig. 2, this comparison shows a clear zone of improved acoustic insulation performance between 700 and 1000 Hz, corresponding well to the designed stop band frequency range. The interested reader is referred to the following link (http://youtu.be/tOch_GsGaXg) to listen to the improvement.

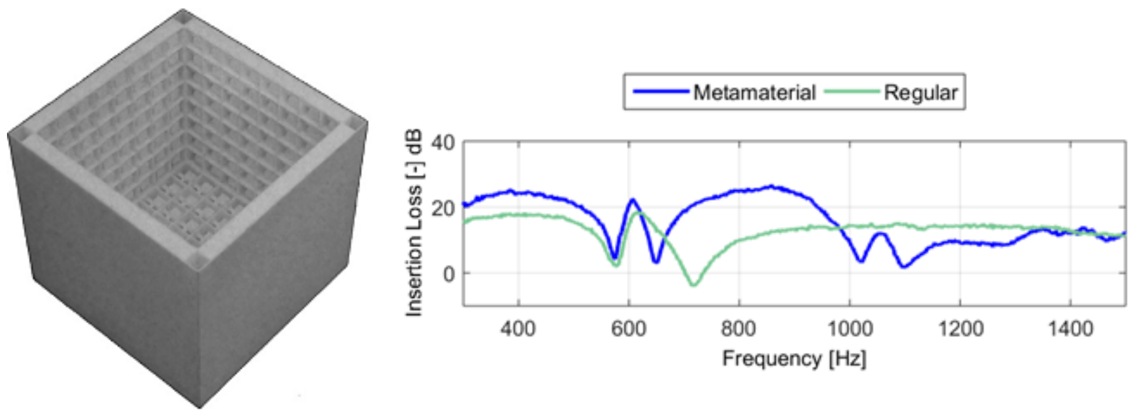

Fig. 2: Metamaterial enclosure for acoustic insulation and comparison of insertion loss measurements [5]

The potential of resonant metamaterials for vibration reduction along a transmission path is demonstrated by considering a 2 mm thick PVC duct host structure of outer dimensions 100x100x1000 mm and this time adding resonant structures to the outer faces of the duct [6]. Laser cut Plexiglas beam-like resonators of two resonance frequencies, named A (512 Hz) and B (577 Hz), are glued periodically on the duct (Fig. 3 and 4). Various patterns are considered to demonstrate the effect of metamaterials on wave propagation and to investigate the possibility of combining stop bands: only A, only B, half of the duct A, half of the duct B (sequential) and checkered A and B (mixed), each adding approximately 27% of mass to the bare host structure.

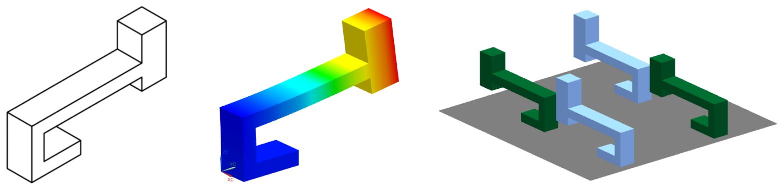

Fig. 3: Resonant structure of structural demonstrator, deformed FE model of resonant structure at resonance and unit cell for mixed configuration [6]

Comparing the out-of-plane RMS acceleration response around the circumference at the far end of the duct for an impact excitation at the near end, a clear vibration attenuation is obtained for all metamaterial configurations (Fig. 4). By combination of resonators in both sequential and mixed configurations, a combined broader frequency range of vibration attenuation is obtained along the transmission path.

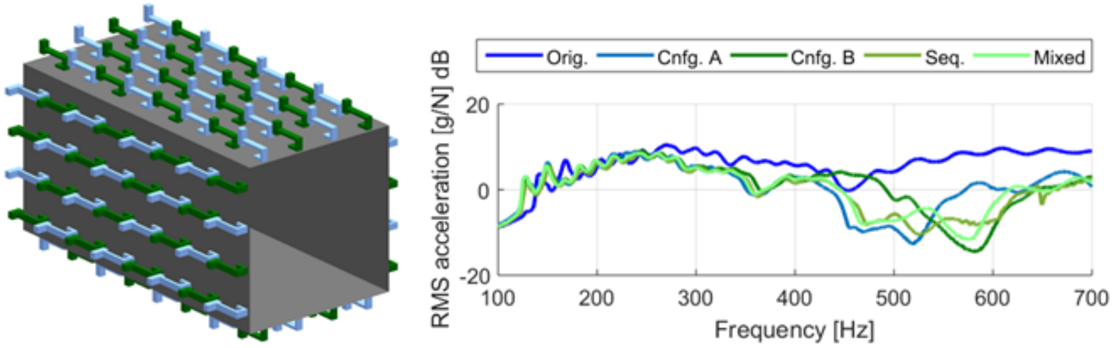

Fig. 4: Metamaterial for vibration attenuation along structural transmission path [6]

4 Towards industrial valorization

The presented demonstrators illustrate the huge potential of the vibro-acoustic metamaterial technology as lightweight NVH solution for the lower frequency ranges. With the established metamaterial design methods and knowledge, the current research at the KU Leuven aims at leveraging the metamaterial technology and knowledge towards industrial applications, focusing on three objectives: (i) assessing cost efficient manufacturing processes and design tools for metamaterials, (ii) investigating integration and interaction effects on the performance of metamaterial components in industrial environments and (iii) demonstrating the metamaterial performance on dedicated industrial use cases for vibration attenuation, acoustic radiation reduction and increased acoustic insertion loss in a.o. in-vehicle applications such as trim, body or engine shields.

5 Conclusion

This paper discusses vibro-acoustic metamaterials as a possible novel NVH solution, combining lightweight requirements with superior noise and vibration insulation performance. The potential is shown by means of designed and manufactured demonstrators for acoustic and vibration transmission reduction. The current research focuses on covering the entire value chain in designing, producing and integrating the metamaterial technology in products and processes, paving the way for a new class of light and compact NVH solutions with ample applications in automotive for low and mid frequency NVH mitigation.

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