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Lightweight NVH Solution Based on Vibro-Acoustic Metamaterials

Vibro-acoustic metamaterials with stopband behaviour are looked upon as a possible solution for combining NVH and lightweight requirements for engineering structures. This article discusses a metamaterial concept based on embedded resonant structures that exhibit vibro-acoustic stopband behaviour. This potential is shown through the design and validation of a demonstrator for increased acoustic insertion loss and a demonstrator for improved vibration attenuation.

INTRODUCTION

The Noise, Vibration and Harshness (NVH) behaviour of products is gaining importance due to increasing customer expectations and more stringent regulations. Ecological trends, however, increase the importance of lightweight design and reduce the applicability of classic (heavy) solutions. In view of this challenging and often conflicting task of merging NVH and lightweight requirements, novel solutions are required.

Vibro-acoustic metamaterials are candidates for superior lightweight NVH insulation, at least in targeted frequency ranges, referred to as stopbands. These

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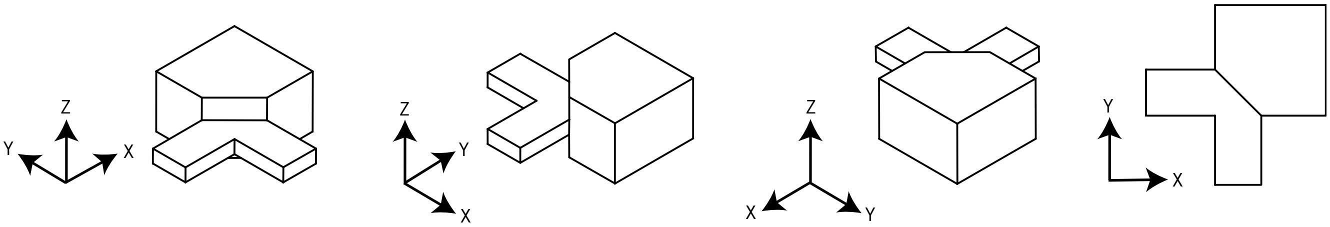

FIGURE 1 Resonant structure used in the acoustic demonstrator to introduce stopband behaviour (© Claeys | KU Leuven)

stopbands result from resonant cells arranged on a sub-wavelength scale [1-3]. [4, 5] explained the working principles, listed driving parameters and introduced a metamaterial concept based on embedding resonant structures. This article shows the potential for acoustic insulation and vibration reduction in a low-frequency zone.

METAMATERIALS BY INCLUSION OF RESONANT STRUCTURES

To obtain metamaterials with stopband behaviour, two conditions need to be met: (i) resonant cells have to be added to a host structure on a scale smaller than the structural wavelengths to be influenced [1] and (ii) the net sum of the forces on the hosting structure contributed by a resonant system should be non-zero [6].

The kinds of resonant systems which are eligible depend heavily on the structure to which the resonant systems are added. As a first example, periodic lightweight structures, such as honeycomb or rectangular core sandwich panels, are considered. The internal cavities of these periodic core sandwich panels allow inclusion of the resonant systems, while the combination of excellent mechanical properties and low mass can be preserved.

A huge number of designs can be proposed for the resonant structures, leaving room for optimisation towards, for example, minimal weight or maximal attenuation. For this article, a straightforward design that resembles a mass-spring system is chosen. Two thin legs are used to connect a heavy mass to a host structure **FIGURE 1**. The connection legs will determine the stiffness while the thick part of the resonator will determine the mass of this resonant structure.

To assess whether the addition of these resonant structures to the cavities of a periodic sandwich core will introduce a stopband, the wave propagation needs to be investigated. From literature, it is known that wave propagation through infinite periodic structures can be investigated through unit cell modelling [7, 8]. Based on an undamped Finite Element (FE) model of the unit cell and the application of periodicity boundary conditions, dispersion curves for freely propagating waves in an infinite periodic structure can be derived. Frequency zones for which no solutions are found correspond to frequency zones without free wave propagation and thus a stopband region. Thus, by building an FE model of the unit cell metamaterial, both the resonance frequency of the resonant structure and the dispersion curves can be calculated.

ACOUSTIC DEMONSTRATOR

To prove the potential of the introduced metamaterial concept to reduce acoustic transmission, acoustic enclosures with one open side are designed. These can be placed over a small speaker in such a way that the acoustic insertion loss can be determined by comparing sound radiation with and without the enclosure.

FIGURE 2 shows the demonstrator, which is made by Selective Laser Sintering. The inner volume is 100 x 100 x 100 mm, the ribs are hollow and each side consists of 8 x 8 unit cells.

FIGURE 3 compares the measured insertion loss of the metamaterial demonstrator to an enclosure with the same weight and produced in the same way but with flat sides with a thickness of 3.5 mm. Between 700 and 1000 Hz, the demonstrator enclosure clearly outperforms the regular enclosure. To see and hear this effect, the interested reader is referred to the following link: http://youtu.be/tOch_GsGaXg. The frequency zone of improved acoustic behaviour is somewhat wider than predicted by the stopband simulation (886 to 999 Hz), but this corresponds well with previous simulations by the authors [4].

VIBRATION REDUCTION DEMONSTRATOR

In order to prove the potential of metamaterials for vibration reduction along a transmission path, resonant structures are added to a PVC duct with the outer dimensions of 100 x 100 x 1000 mm and a thickness of 2 mm. The resonant structures are made by laser cutting a Plexiglas plate and are designed as cantilever beams with an end point mass and a supporting foot used to glue the structures to the duct. **FIGURE 4** shows the resonant structures and a section of the duct. Depending on the mass at the end of the structure, the resonance frequency of the resonant structure can be changed; for this design, the resonances are predicted at 512 and 577 Hz for type A and type B, respectively. More infor-

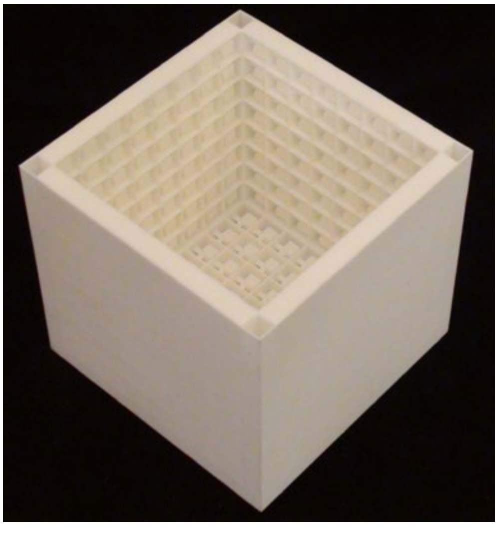

FIGURE 2 Picture of the acoustic demonstrator (© Claeys | KU Leuven)

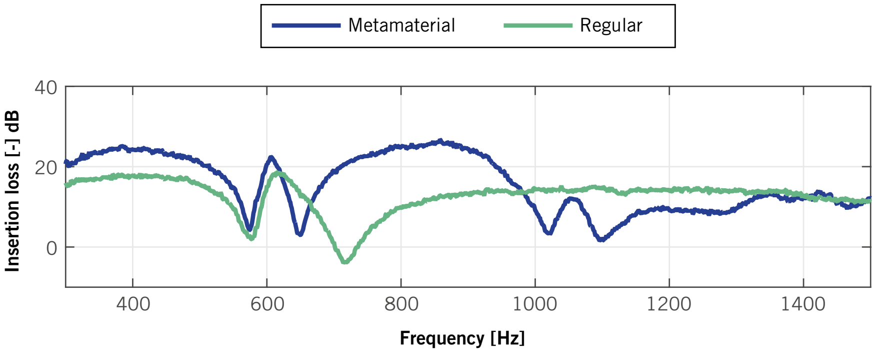

FIGURE 3 Comparison between the measured insertion loss for the metamaterial demonstrator and an equivalent mass enclosure with flat side panels and the same weight (© Claeys I KU Leuven)

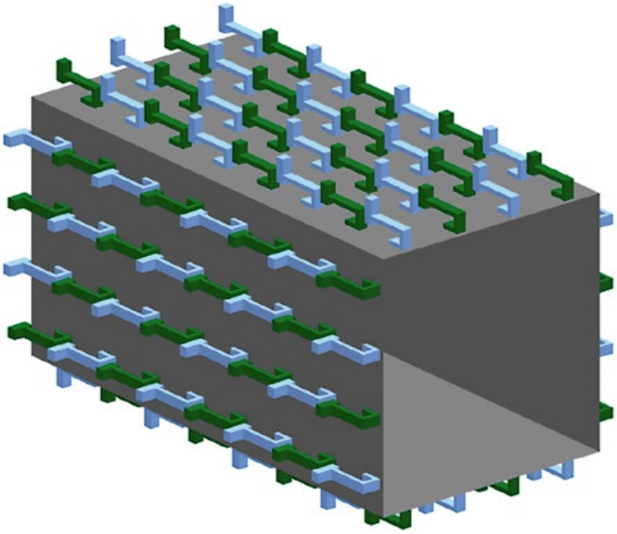

FIGURE 4 Visualisation of the resonant structure layout for the mixed configuration with green and blue resonant structures representing type A and type B, respectively (© Claeys I KU Leuven)

mation on this design and the measurements can be found in references [9, 10].

The demonstrators are used to show the effect of metamaterials on wave propagation and allow an investigation of the possibility to combine stopbands. Therefore, five different configurations will be considered, as listed in **TABLE 1**. The mixed configuration combines both resonant structure types in a chequered pattern, as illustrated in **FIGURE 4**, while the sequential configuration has only type A resonant structures on the first half of the duct and only type B on the second half.

To measure the wave propagation along the duct, response measurements are made on different sections along the duct. A section is analysed by measuring three equidistant points on every face of a section between two circumferential rows of resonant structures, resulting in 12 measurements for each section. With those 12 points per section, a RMS response is calculated. Since there are 40 circumferential rows along the duct, 41 sections – section 0 to section 40 – can be defined.

FIGURE 5 compares the attenuation from section 4 to section 36 for the different configurations. The sequential configuration clearly combines the effect of both stopbands, but the overall width is slightly narrower than in the A or B configuration, which is due to less resonant structures of each type being present on the duct. The results obtained for the mixed and sequential configuration are similar. However, the mixed case shows a better overlap between the two stopband regions.

The difference between the sequential and mixed configuration becomes apparent when exciting in the middle (section 20) and evaluating on the ends of the pipe (section 4 and section 36). **FIGURE 6** shows that, in the sequential case, only the low-frequency stopband is found when going from section 20 to 4 and the high-frequency stopband when going from section 20 to section 36. In the mixed case, however, both stopbands are always present, although less pronounced.

CONCLUSIONS

This paper introduces a novel method for creating resonant metamaterial-based NVH insulation: the addition of resonant structures to a host structure. Through the design of an acoustic demonstrator, it is shown that this results in a frequency zone of increased acoustic insertion loss compared to equivalent materials of the same weight. This potential can be seen and heard at the following link http://youtu.be/tOch_GsGaXg. A vibrational demonstrator showed that different stopbands can be combined in a metamaterial to achieve wider stopbands. This can be done by both a mixed or a sequential layout. The design of these metamaterials is aided by unit cell modelling. This tool allows a quick estimation of the location of the stopband frequencies and can be used to assess changes in resonant structure design.

Configuration	# Type A	# Type B	Mass addition	Stopband width [Hz]
original	0	0	0 %	/
A	640	0	27.4 %	488 to 538
B	0	640	26 %	549 to 603
sequential	320	320	26.7 %	488 to 538 & 549 to 603
mixed	320	320	26.7 %	494 to 513 & 558 to 588

TABLE 1 Metamaterial characteristics of the different configurations: amount of added resonant structures of each type, mass addition relative to the bare duct and predicted stopband width (© Claeys I KU Leuven)

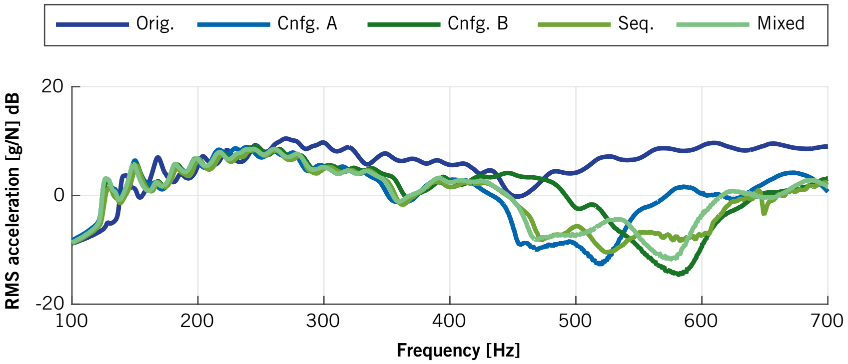

FIGURE 5 RMS acceleration for all configurations at section 36 for excitation in section 4 (© Claeys I KU Leuven)

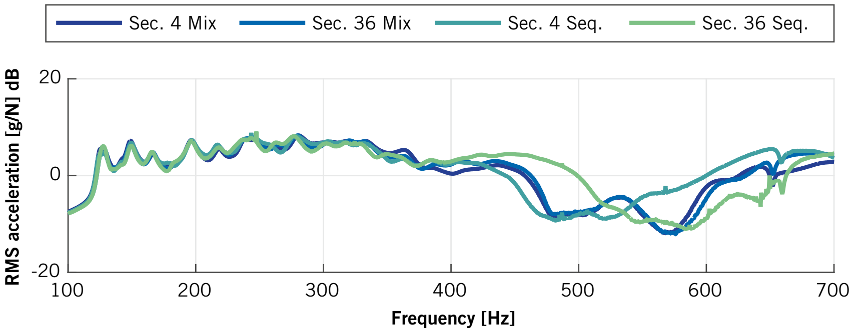

FIGURE 6 RMS acceleration for sequential (Seq.) and mixed (Mix) configurations at section 4 (Sec. 4) and 36 (Sec. 36) for excitation in section 20 (© Claeys I KU Leuven)

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THANKS

The authors would like to thank N. Rocha de Melo Filho, L. Van Belle and Elke Deckers. Furthermore, the European Commission for their support through the ENLIGHT and the KU Leuven Research Fund for their support through an IOF Leverage project. This research was partially funded by Flanders Make.