Design of a resonant metamaterial based acoustic enclosure

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Abstract
Periodic structures, such as honeycomb core panels, combine excellent mechanical properties with a low mass, making them attractive for application in transport and machine design. However, the high stiffness to mass ratio of these lightweight panels may result in unsatisfactory dynamic behaviour in that it may impair the panels’ ability to reduce noise and vibration levels. Liu et al. demonstrated that inclusions of high density spheres with a rubber coating in a matrix material result in low frequency sound isolation breaking the mass law [7]. These locally resonant metamaterials require a high density of local resonators throughout the matrix material, either spread randomly or periodically. In a previous paper by the authors, resonant structures were introduced into the cavities of a honeycomb structure with large cells (30 mm width), leading to a material with strong vibrational attenuation in a low frequency region [3]. In the present paper the potential for acoustic stop bands is shown through a demonstration on an industrial relevant test case: a periodic structure of cells with 10mm width and added local resonant structures. The existence of acoustic stopbands is experimentally proven, clearly showing that stopbands can improve the acoustic behaviour of lightweight panels.

1 Introduction

Increasing customer expectations and more restrictive legal requirements turn the acoustical behaviour of products into an important design criterion in the machine and transportation industry as well as in the construction and consumer goods sector. Ecological trends and the associated run for efficiency, however, increase the importance of lightweight design and reduce the applicability of classical (heavy) solutions to improve acoustic behaviour. In view of this challenging and often conflicting task of merging acoustical and lightweight requirements novel acoustic solutions are required. Ideally these novel solutions are easy to design and are characterised by a low mass and compact volume along with a high reliability at an affordable cost.

Vibro-acoustic metamaterials come to the fore as possible candidates for lightweight material systems with superior noise and vibration insulation, be it at least in some targeted and tuneable frequency ranges, referred to as stop bands. Contrary to phononic crystals, stop bands in metamaterials don’t rely on periodicity or Bragg scattering and work on spatial scales much smaller than the wavelength [8]. The stop bands induced in metamaterials result from resonant cells arranged on a subwavelength scale and can be described based on the Fano-type interference between incoming waves and the waves re-radiated by the resonant cells [4, 6]. Previous papers of the authors explain the working principles of stop bands based on resonant metamaterials and lists the driving parameters for stop band design [2].

This paper proposes the use of an innovative metamaterial concept to improve acoustic behaviour; resonant
structures are added to cavities of a periodic core sandwich structure to create stop band behaviour. The next section describes the rationale behind the proposed metamaterial concept, followed by a section describing the numerical prediction of the stop band behaviour of this concept. The following sections elaborate on the demonstrator design and the measurements on this demonstrator.

2 Inclusion of resonant structures

Metamaterials with stop band behaviour are obtained through the inclusion of resonant cells on a scale smaller than the structural wavelengths to be influenced [2]. Stop band behaviour can thus be achieved through the introduction of any system that introduces local resonant behaviour. In view of applications, the goal is to find resonant systems which do not jeopardise other requirements; structural integrity, light weight, use in contaminated environment, fire-resistance, ... . The kinds of resonant systems which are eligible heavily depend on the structure to which the resonant systems have to be added.

Inspiration for a high potential structure to introduce stop band behaviour is sought in the class of periodic lightweight structures, such as honeycomb core sandwich panels. They are becoming attractive for application in transport and machine design due to the combination of excellent mechanical properties with a low mass. Figure 1 shows examples of sandwich structures; a core acts as spacer to create distance between the skins such that a light structure with excellent stiffness properties in bending is obtained. The core has as main role to create distance between the skins as well as to resist forces perpendicular to the structure while the skin is designed to show a high in plane strength; given the different requirements for both, often the skin is made of a different material as the core. Different core layouts are possible and two typical layouts are hexagonal or rectangular cores.

Adding the resonant structures to the cavities of a periodic sandwich core (Fig. 3) will introduce a stop band, and thus improved acoustic behaviour, for frequencies in the vicinity of the resonance frequency of the resonant structures.
the resonant structure. Further analyses of how the resonant structures introduce stop band behaviour is the topic of next section.

### 3 Stop band prediction

From literature it is known that wave propagation through infinite periodic structures can be investigated through unit cell modelling [1, 5]. 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 stop band region.

Figure 4 shows the geometry of the unit cell which will be used to build a demonstrator. The resonant structure makes up 30% of the weight of the unit cell. Figure 5 depicts the FE model of this unit cell. Linear Quad4 elements are used to represent the resonant structure, core and skin. The resonator mass has a larger thickness than the connection legs; different properties are assigned to both element groups. The resonator mass element group is depicted in gray on the right side of Fig. 5.

![Figure 4: Dimensions in millimeter of the unit cell of the enclosure. The resonator leg thickness (L) equals 1 mm, the resonator mass (m) equals 4 mm.](image)

The material characteristics of the acoustic enclosures are given in table 1. The enclosures are made through Selective Laser Sintering (SLS) of Polyamide, the material and production characteristics are discussed in more detail in next section. Since the main goal of the simulations is to get an indication whether stop band behaviour is present rather than obtaining a detailed model, isotropy and linear behaviour of the material are assumed.

The resonant structure is designed to have a pronounced low frequent bending mode followed by subsequent modes higher in frequency. Figure 6 shows the first two modes of the free unit cell which can be related to modes of the resonant structure. Left the bending mode is shown which occurs at a frequency of 1272 Hz, the next mode, shown at the right, occurs at 5052 Hz; this large shift in frequency between the modes allows
Figure 5: FE model of the unit cell of the demonstrator. The gray elements in the top view (right) represent the resonator mass.

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus</td>
<td>$E$</td>
<td>1.65 MPa</td>
</tr>
<tr>
<td>Density</td>
<td>$\rho$</td>
<td>950 kg/m$^3$</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>$\nu$</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Table 1: Material characteristics of the material of the unit cell in the numerical simulations.

to correlate stop band behaviour with a certain resonance mode. Convergence of the model was validated against a refined unit cell model of 6766 nodes and 6576 elements. The used model with 198 nodes and 168 elements has an accuracy of 1% on the first mode and 1.5% on the second mode.

Figure 6: Undeformed mesh (light) and the deformation of the first modes (dark) of the resonant structures. Left: bending mode at 1272 Hz. Right: torsional mode at 5052 Hz.

The unit cell allows derivation of the dispersion curves of the demonstrator. Figure 7 shows the bending wave dispersion curves for the unit cell of the demonstrator in comparison to the dispersion curves of the host structure without resonant structures. The dispersion curves are similar except for a region around the resonance frequency of the resonant system for which no dispersion curves exists; a stop band opens up from 1065 Hz up to 1226 Hz. The shift with respect to the resonance frequency of the resonant structure (1272 Hz), is explained by the different boundary conditions of the unit cell during calculation of the resonance frequency.

4 Demonstrator example

To prove the potential of the introduced metamaterials concept to reduce acoustic transmission, an acoustic enclosure making use of resonant structures is designed. A variety of demonstrators can be thought of to determine the acoustic transmission characteristics of a material. In the choice for a suitable demonstrator, some determining factors are: unambiguous proof of concept, quantifiable effect and engineering relevance.

To obtain an unambiguous proof of concept it is crucial to have as less unknown effects in the design as possible. Connections between different components by bolts or combining parts together by gluing, is a likely source of uncertainty; it is preferred to have a demonstrator built in one part such that these unknowns are reduced.
To measure and quantify the effect of metamaterials on acoustic transmission loss different set-ups are possible. In view of an engineering demonstrator, it was chosen to design acoustic enclosures as boxes with one open side which can be placed over a small speaker. The acoustic transmission loss is then determined by comparing sound radiation with and without enclosure.

The metamaterial concept has a rather complex geometry and topology which is hard to produce with traditional manufacturing processes. Additive manufacturing is a production process which allows producing complex parts without the need of an expensive mould, making it a suitable production process for prototype design. Within the range of additive manufacturing processes, Selective Laser Sintering (SLS) is chosen to create the demonstrator. SLS is an additive manufacturing method where small powder particles are melted together by means of a laser. The melting of adjacent material particles is called sintering and by controlling the laser, a pattern can be sintered in a layer of material powder. Unlike other additive manufacturing methods, such as fused deposition modeling and stereolithography, the part being built is surrounded by unsintered powder at all times. This unsintered powder acts as a support for the next layers and facilitates building complex parts with jumps in geometry across the height of the part. This possibility of building complex parts is the main reason why SLS was chosen as production process.

Figure 8 shows a side and bottom view of the demonstrator design. One side of the enclosure contains 8 x 8 unit cells. It should be noted that the corners of the demonstrator are hollow and no resonators are added: no resonators are added since cavities have to be open due to the production process while fully filled corners would increase the weight of the enclosure. The size of the enclosure is a balance between obtaining a light
demonstrator and still being relevant; the enclosure is designed such that the inner dimensions make up a cube of 100 x 100 x 100 mm. Figure 9 shows a produced version of this demonstrator.

![Figure 9: Pictures of the demonstrator.](image)

5 Measurement results

The test set-up consists of a small loudspeaker placed on a wooden plate (Fig. 10). The wooden plate is placed on an iron support in the centre of a semi-anechoic chamber. Between the wooden plate and the loudspeaker, a small trim-like piece of fabric is placed; the trim covers the cable of the loudspeaker which runs in a small split in the plate. The sound power is evaluated on the surface of a surrounding box of 250 x 250 x 190 mm centred around the loudspeaker; the black dots on the wooden plate (Fig. 10) indicate the width and length of the surrounding box. The acoustic power is evaluated based on 5 intensity measurements, one on each side of the box, with a scanning intensity probe.

![Figure 10: Picture of the test set up (left) and an intenisty measurement of an acoustice metamaterial enclo- sure on the test set up (right).](image)

Figure 11 compares the measured insertion loss of the metamaterial demonstrator to the measured insertion loss of a regular enclosure with the same mass but build from flat panels of 3.5 mm thickness. Between 700 and 1000 Hz the demonstrator enclosure clearly outperforms the regular enclosure. The frequency zone of improved acoustic behaviour is a bit lower in frequency than the stop band predicted by the design of the resonant structures.
Further investigation of the produced demonstrator explain the shift in frequency; through optical measurements on a CNC Mitutoyo QuickVision Pro - 202 machine combined with QV Pak 4.4 software of dedicated test samples of the demonstrator unit cell it was shown that the average geometry of the resonant structure is smaller than the nominal geometry. The nominal values for both the connection leg and the resonator mass (Fig. 4) are never reached. This shift in geometry should be taken into account in the numerical model; the shift from the nominal 1 and 4 mm to the measured 0.83 and 3.85 mm thickness for the connecting leg and resonator mass respectively leads to a shift in stop band frequencies from 1065 - 1226 Hz to 861 - 986 Hz, corresponding well with the measures zone of increased acoustic insertion loss.

6 Conclusion

This paper introduces a novel method to create resonant metamaterials for acoustic insulation; the inclusion of resonant structures within the core of a sandwich structure. Through the design of a demonstrator it is shown that this results in a frequency zone of increased acoustic insertion loss with respect to equivalent materials of the same weight. Unit cell modelling allows a quick estimation of the location of the stop band frequencies and can be used as a tool to assess changes in resonant structure design. This metamaterial concepts allows the combination of light weight, compact mass and good acoustic behaviour along with other technological benefits such as integration in structural parts, use in harsh environments and easy designable beneficial frequency ranges. To see and hear this potential in a movie, the interested reader is referred to a movie which can be seen by clicking the following link (http://youtu.be/tOch_GsGaXg).

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References


