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A lightweight vibro-acoustic metamaterial demonstrator: Numerical and experimental investigation

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ABSTRACT

In recent years metamaterials gained a lot of attention due to their superior noise and vibration insulation properties, be it at least in some targeted and tuneable frequency ranges, referred to as stopbands. These are frequency zones for which free wave propagation is prevented throughout the metamaterial, resulting in frequency zones of pronounced wave attenuation. Metamaterials are achieved due to addition of an, often periodic, grid of resonant structures to a host material or structure. The interaction between resonant inclusions and host structure can lead to a performance which is superior to the ones of any of the constituent materials. A key element in this concept is that waves can be affected by incorporating structural resonant elements of sub-wavelength sizes, i.e. features that are actually smaller than the wavelength of the waves to be affected. This paves the way towards compact and light vibro-acoustic solutions in the lower frequency ranges. This paper discusses the numerical design and experimental validation of acoustic insulation based on the concept of metamaterials: a hollow core periodic sandwich structure with added local resonant structures. In order to investigate the sensitivity to specific parameters in the metamaterial design and the robustness of the design, a set of variations on the nominal design are investigated. The stop bands are numerically predicted through unit cell modelling after which a full vibro-acoustic finite element model is applied to predict the insertion loss of the demonstrator. The results of these analyses are compared with measurements; both indicate that this metamaterials concept can be applied to combine light weight, compact volume and good acoustic behaviour.

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 should be easy to design and are characterised by a low mass and compact volume along with a high reliability at an affordable cost.

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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 do not rely on periodicity or Bragg scattering and work on spatial scales much smaller than the wavelength [13]. 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 in the structure between incoming waves and the waves re-radiated by the resonant cells [8,11].

Previous papers of the authors study metamaterials through academic case studies; the driving parameters for vibrational stop bands are derived [5] and it is shown that vibrational stop bands can be extended to acoustic stop bands [4]. This paper focuses on translating the academic test cases to a set of practical demonstrators. Acoustic enclosures based on the concept of metamaterial with stop band behaviour are chosen as demonstrators. An innovative metamaterial concept is used to improve acoustic behaviour: resonant structures are added to cavities of a periodic core sandwich structure to create stop band behaviour. Different variations of the same demonstrator are designed in order to investigate robustness and sensitivity to design parameters. Numerical models are built in order to compare prediction of the stop band behaviour and insertion loss of these demonstrators with measurements.

The paper is outlined as follows. The first section introduces the concept of metamaterials through inclusion of resonant structures. The second section elaborates on the sensitivities which will be investigated through different demonstrators. Next the potential of this metamaterial concept is assessed through unit cell modelling of different demonstrators. The test set-up and a discussion of the modelling of this set-up and different enclosures are the topic of the next section. The derived models are used to provide a numerical validation which can be compared to the measurement results. First the nominal acoustic enclosure is discussed; next the variations of enclosures are compared. The main conclusions are given in the last section.

2. Metamaterial concept

To obtain metamaterials with stop band behaviour two conditions need to be met; resonant cells have to be added to a host structure on a scale smaller than the structural wavelengths to be influenced [5] and the net sum of the forces on the hosting structure contributed by a resonator should be non-zero [17]. Metamaterials with stop band behaviour are obtained through the inclusion of resonant cells on a scale smaller than the structural wavelengths to be influenced [5]. Stop band behaviour can thus be achieved through the introduction of any system that introduces local resonant behaviour: in the literature examples can be found of grids of mass–spring systems that act as a resonant system [5,12,18]. In view of engineering applications, the goal is to find resonant systems which do not conflict with other functional requirements such as structural integrity, low mass, use in contaminated environment, and fire-resistance. These kinds of resonant systems which are eligible heavily depend on the structure to which the resonant systems have to be added.

Lightweight periodic structures, such as honeycomb core sandwich panels, are becoming attractive for applications in transport and machine design due to the combination of excellent mechanical properties with a low mass. Fig. 1 shows examples of sandwich structures; the core acts as spacer to create distance between the skins such that a light structure with excellent bending stiffness properties 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 different requirements for both, often the skin is made of a different material than the core. Different core layouts are possible and two typical layouts are hexagonal and rectangular cores.

Since these sandwich panels have internal cavities, they provide potential to include resonant systems within these cavities. This has a double advantage: (i) inclusion of resonant systems within this host structure protects the resonant systems from environmental influences and (ii) these inclusions can be added without affecting the, often excellent, stiffness properties of the structure.

A resonant system is chosen which resembles a mass–spring system; two thin legs are used to connect a heavy mass to a structure, shown in Fig. 2. The connection legs determine the stiffness while the thick part of the resonator determines the mass of the resonator. Fig. 3 shows the addition of resonators to the cavities of a rectangular core, introducing stop band behaviour.

The design of the resonant structure as depicted in Fig. 2 has the following advantages:

- A clear low-frequent bending mode introduces localised resonant behaviour.
- The design which keeps an analogy to spring–mass systems allows straightforward control of the resonance frequency of the first bending mode.

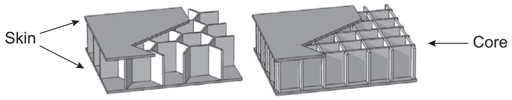

Fig. 1. Examples of sandwich structures; left a hexagonal core, right a rectangular core [16].