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Design and validation of metamaterials for multiple structural stop bands in waveguides

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ABSTRACT

Environmental and economic requirements lead to a constantly increasing application of lightweight designs. Fulfilling the conflicting goals of favorable noise and vibrational behavior and lightweight design is a challenging tasks, requiring novel low mass and compact volume solutions. Vibro-acoustic metamaterials come to the fore as possible lightweight solutions with superior noise and vibration insulation properties in targeted and tunable frequency ranges, referred to as stop bands. They typically consist of (often periodic) assemblies of unit cells of non-homogeneous material composition and/or topology, adding local resonant behavior to the host structure. Metamaterials targeting different stop bands can be combined to suppress vibrations over a larger frequency zone. This paper investigates various metamaterial layouts for reducing vibrations along a known transmission path, being a duct with a square section. The efficiency of the considered metamaterial designs for vibration attenuation are evaluated and compared both numerically and experimentally. Due to the typical periodic nature of this class of materials, the numerical prediction of the stop band behavior is modeled using unit cell models for the duct; both a one dimensional (1D) waveguide as well as a two dimensional (2D) infinite periodic structure. The efficiency and accuracy of both approaches are evaluated and compared to measurements. It is demonstrated that different resonant structures can be combined to merge stop bands, either using a mixed, checkered pattern, or a sequential pattern. Depending on the transmission path and the targeted frequency zone, either approach or a combination of both can be used. Furthermore it is shown that the 2D unit cell analyses gives an accurate prediction of the stop band locations.

1. Introduction

The last decades, ecological and environmental requirements combined with the run for efficiency have given rise to the need for lightweight materials and design [1]. Besides, due to more stringent legal regulations as well as customer expectations, the noise and vibration harshness (NVH) of products is evolving into an increasingly important design criterion [2]. However, lightweight design typically combines reduced weight and increased stiffness, leading to a deterioration of the noise and vibration attenuation performance. Consequently, merging lightweight and vibro-acoustic requirements results in a challenging and often conflicting task, for which novel low mass and compact volume solutions are sought.

Recently, vibro-acoustic metamaterials have emerged as possible candidates for lightweight materials with favorable noise and vibration attenuation behavior, at least in some targeted and tunable frequency ranges, referred to as stop bands [3,4]. Stop bands, i.e. zones with no free wave propagation in a certain frequency range of interest, are achieved mainly through two approaches [5]: Bragg scattering interference or resonance based interference. In a previous work, the authors concluded that resonance based stop bands are more promising to obtain low-frequency stop bands with strong vibrational attenuation [6].

Resonance based stop bands require, among other, the addition of cells with resonant behavior to the host structure on a scale smaller than the wavelength to be affected. A Fano-type interference between incoming waves and re-radiated waves by the resonant cells can then result in stop bands [6,7]. Although periodicity is not a requirement for achieving stop band behavior in these locally resonant metamaterials [3], the prediction of stop band behavior, or more general, wave propagation behavior is facilitated when using periodic structures. This periodicity allows a unit cell

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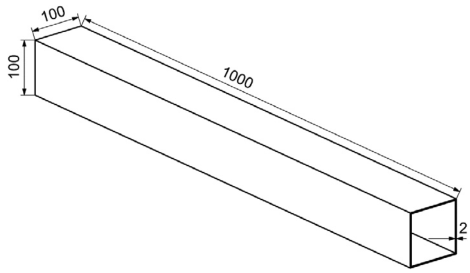

Fig. 1. Schematic representation of the square cross-section PVC duct used as a host structure. All lengths are given in [mm].

modeling approach based on the Bloch–Floquet theorem, considering infinite periodic structures [8,9]. This modeling approach gives rise to an eigenvalue problem in frequency and wave number to be solved, resulting in dispersion diagrams, giving information on the wave propagation characteristics of the structure at hand and as such allowing the identification of stop band frequency zones. The potential of these locally resonant metamaterials for noise and vibration control engineering and the design approach using unit cell models was demonstrated by the authors in previous publications [6,10], introducing a novel metamaterial concept based on the addition of resonant structures to a honeycomb-core host structure.

This paper studies the potential of locally resonant metamaterials for vibration insulation along known transmission paths in targeted frequency zones. The objective is to reduce out-of-plane bending since this often the most important wave type from a NVH point of view. As target frequency zone, the 500–600 Hz region is chosen: on the one hand classic damping materials are effective for higher frequencies and on the other hand metamaterials solutions are most effective in modal dense regions since they require interaction with the host structure.

Where acoustic transmission problems mostly consider sound propagation through two dimensional (2D) structures, for vibration insulation problems, the transmission path is often one-dimensional (1D) and the structure can be considered as a waveguide, as is the case for e.g. ducts, pipes, ... This characteristic creates the potential of combining different metamaterial layouts along the known transmission path, effectively combining different stop bands into broader frequency regions of vibration attenuation along the propagation direction of these waveguides. Multiple stop bands can be obtained by considering unit cells with multiple resonators as shown in [11–13] for structural vibration applications and as demonstrated by the authors in a vibro-acoustic setting [10].

The first experimental results on this idea were presented by the authors in [14]. This paper extends this work with additional measurements and continues the interpretation by comparing the measurements with unit cell models of varying complexity, with and without inclusion of damping. For the stop band design and analysis of the considered metamaterial waveguides, a unit cell modeling approach is adopted for infinite periodic, 1D structural waveguides based on the Finite Element (FE) method [15]. This procedure allows considering only a section of the structure at hand, greatly reducing the size of the model, while accurately representing the wave propagation throughout the waveguide, including the effect of damping. In view of computational effort and simplification of the wave propagation involved, a non-fluid loaded duct with square cross section is considered. Besides, considering a section of the waveguide, also a single resonant cell be considered as a further simplification, hereby adopting a unit cell modeling strategy for 2D infinite periodic structures [16]. In this study, both modeling approaches are adopted and compared with measurements.

This paper is organized as follows. The materials and properties of the host structure, the resonant structures and the different metamaterial layouts are discussed in Section 2. The unit cell models for both the 1D and 2D approach are presented in Section 3 and their results are the topic of Section 4. In Section 5, the experimental characterization method for measuring the stop band behavior is explained. Section 6 compares the measurements of the different realizations to the numerically predicted stop bands. The main conclusions of this work are summarized in Section 7.

2. Problem definition

This section describes the host structure and the resonant structures used to create stop band behavior: for both the geometry as the materials are discussed. The last part of this section discusses how the host structure and the resonant structures can be combined in different configuration to create metamaterials.

2.1. Host structure

In this study the application of locally resonant metamaterials is considered for obtaining structural vibration suppression along known transmission paths. Common examples are structured that behave like 1D waveguides such as beam like structures, ducts, pipes, rails.... In this work a commercially available non-fluid loaded duct with square cross section is chosen as host structure, illustrated in Fig. 1. The choice for a rectangular section is mainly driven by the possibility to allow 2D flat plate unit cell models.

2.1.1. Geometry

A rectangular PVC duct of outer dimension $100 \times 100 \times 1000$ mm and 2 mm thickness is chosen, as shown in Fig. 1. These circumferential dimensions are selected based on two conditions: (i) have modal behavior in the circumferential direction before the targeted frequency region of the stop band (ii) be large enough such that multiple resonant structure can be added on one side while still allowing production through laser-cutting. The length of the tube is chosen as a balance between a long length to ensure waveguide behavior and short enough to be manageable for experiments and amount of resonant structure required.

2.1.2. Material

The material properties of the duct are retrieved by model updating of a bare duct [17] and a weight measurement. The weight measurement in combination with the known geometry allows calculating the density while the correlation between the modeshapes retrieved with a Finite Element (FE) model and the experimentally measured modeshapes allows to update the Young's modulus and the Poisson's ratio of the PVC. For the modal updating procedure a FE model of the duct was built with 4000 linear shell elements. For the experimental test the duct was freely suspended and roving hammer excitation was used in combination with 4 lightweight accelerometers as references. The same equipment and measurement procedure was used as detailed in Section 5. The structural damping is estimated using the half power bandwidth method [18] on resonance peaks of structural response of the duct in the frequency range where the stop band will be effective, 500–600 Hz. In the model structural damping is taken into account as a complex Young's modulus: x% of structural damping leads to a Young's modulus $E(1+j\frac{x}{100})$ with j the imaginary unit $j=\sqrt{-1}$.

Table 1 lists the retrieved material parameters. During the updating procedure the average error on the frequency mismatch between measurements and model was below 1% when considering the 30 first correlated bending modes, being the modes below 300 Hz.