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The attenuation performance of locally resonant acoustic metamaterials based on generalised viscoelastic modelling

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ABSTRACT

Acoustic metamaterials are known as a promising class of materials interacting with acoustic and/or elastic waves. Band gap formation is one of the most spectacular phenomena that they exhibit. Different ways to broaden the attenuated frequency ranges are still being actively explored. It turns out that material damping through intrinsic viscoelastic material behaviour, if accurately tailored, may contribute to the enhancement of the performance of a properly designed acoustic metamaterial. In this study, a locally resonant acoustic metamaterial with periodic multicoated inclusions with viscoelastic layers is investigated. Multiple attenuation regimes obtained with the considered geometry are joined for a certain level of viscosity of the coating layer. The analysis is performed using a generalised Maxwell model, which allows for an accurate description of nonlinear frequency dependent elastic properties, and thus is widely used to model the behaviour of many polymeric materials in a realistic way. The study reveals that variation of the material parameters of the rubber coating with respect to frequency influences not only the position of the band gaps but also the effectiveness of the wave attenuation in the frequency ranges around the band gaps.

1. Introduction

Acoustic metamaterials are a novel class of materials possessing some unusual properties, uncommon or non-existent in nature. The mechanism of low-frequency wave attenuation based on the local resonance (Liu et al., 2000) attracts scientific attention due to various potential applications, e.g., noise insulation (Jiang et al., 2016) or energy harvesting (Li et al., 2016). Unlike phononic crystals (PCs), which is another class of materials capable of forming band gaps (frequency ranges where no wave propagation occurs), the design of locally resonant acoustic metamaterials (LRAMs) does not require periodicity and allows generating subwavelength band gaps (Krushynska et al., 2014). The number of occurring band gaps can be controlled through the microstructural design, for instance, by exploiting multicoated inclusions proposed by Larabi et al. (2007). Such a microstructure has been studied based on 1D model of dual-resonators in Huang and Sun (2010), and has been parametrically optimised in Tan et al. (2012) and Chen et al. (2016), leading to a reduced distance between band gaps.

However, the main limitation in terms of application of LRAMs is still the fact that the attenuated frequency ranges (even if they are multiple) are rather narrow. In the literature, a few solutions dealing with this limitation have been proposed, among which optimising the metamaterial topology (Matsuki et al., 2014), coupling of the effect of local resonance with Bragg scattering (Krushynska et al., 2016b; Yuan et al., 2013) and using resonators with distributed resonant frequencies (Huang and Sun, 2009; Krödel et al., 2015). More recently, also the potential influence of material losses on broadening attenuation regions, has started attracting researchers' attention (Krushynska et al., 2016a; Wang et al., 2015). Such a solution seems to be particularly promising considering the fact that material damping is an intrinsic feature of polymeric materials typically used in LRAMs.

Studies on damped periodic structures started with the works of Mead (e.g. Mead, 1973) in his analysis of a one dimensional periodic chain of masses with lossy springs, and by Mukherjee and Lee (1975) who have investigated transient effects in damped laminates. Until recently, available studies mainly focused on PCs. In a number of works investigating one- and two-dimensional PCs,

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broadening of band gap regions due to the presence of viscoelastic components has been observed (Frazier and Hussein, 2015; Zhao and Wei, 2009). It has been shown by Oh et al. (2013) that lossy PCs are more effective than homogeneous viscoelastic media in terms of energy dissipation. Moreover, in some cases where more advanced material models have been considered (e.g. generalised Maxwell), a shift of the attenuation regions, due to the frequency dependent storage modulus, has been reported Wei and Zhao (2010). These predictions have been confirmed by the experimental analysis conducted by Merheb et al. (2008). Currently, the studies of damped PCs are taken even further, for instance by including defect modes (Zhu et al., 2016).

The influence of damping on the periodic material's performance is not restricted to the band gap width and position. The entire band structure changes significantly, as reported in various studies (e.g. Laude et al., 2009; Moiseyenko and Laude, 2011). Based on the complex band structure representation, Moiseyenko and Laude (2011) have found that the losses in a phononic crystal have stronger impact on the real part than on the imaginary part of the wave number. However, as shown in Farzbod and Leamy (2011), high damping ratios can actually support the wave propagation within attenuation regions by decreasing the imaginary part of the wave number. In the work of Hussein and Frazier (2010), also the phenomena of branch overtaking and branch cut-off in the band structure have been observed and studied.

It turns out that the influence of material damping on the performance of LRAMs differs significantly from the case of PCs. First of all, not only the losses in the matrix material but also within the rubber-coated inclusions should be considered. Manimala and Sun (2014) have shown, considering three types of viscoelastic models (Kelvin-Voigt, Maxwell and Zener), that tailoring the damping within the resonators instead of relying on the dissipation in the matrix material might be beneficial for broadening the attenuation spectrum. This has also been confirmed in the works of Wang et al. (2015) and Krushynska et al. (2016a), using a locally resonant acoustic metamaterial with a single coated inclusion. The viscoelastic behaviour of the rubber coating has been shown to have a critical impact on the material performance in comparison with the damped matrix. Moreover, in case of a LRAM, the imaginary parts of wave numbers are predominantly influenced by the material losses and, as a result, the attenuation peaks related to the local resonances are smoothed. The dissipative effect that leads to this response has also attracted attention of researchers. As a consequence, the notion of metadamping has been introduced by Hussein and Frazier (2013) as an enhancement of material dissipation due to the presence of local resonance. Later studies (Frazier and Hussein, 2015) on both viscoelastic PCs and LRAMs have concluded that the effect of damping on the band gap size is actually more pronounced in case of PCs. However, the experimental and theoretical studies performed by Zhao et al. (2007; 2010) have shown a wide absorption range at low frequencies for a composite polymer slab with embedded local resonators, due to the dissipative mechanisms in the coating material.

So far, the analyses of viscoelastic LRAMs typically assume simple linear viscoelastic models, like the Kelvin-Voigt model, in order to describe the viscoelastic behaviour of the constituents (Wang et al., 2015; Zhao et al., 2007). With this model the material properties become complex, but the real part of the modulus (related to the elastic response) is still constant and only the imaginary part (associated with viscous behaviour) changes linearly with frequency. On the other hand, using the generalised Maxwell model, which has not been used extensively for locally resonant acoustic metamaterials, allows for a realistic variation of both terms with respect to frequency and as a consequence more realistically describes the material behaviour. This is important since most polymeric materials have properties that are known to be frequency dependent (Macosko, 1994).

In this paper, the multiple band gaps obtained with a particular microstructure with coaxial multicoated inclusions have been joined using viscoelasticity of the coatings. Such a concept has recently been introduced in Chen et al. (2016) and was studied based on a simple linear viscoelastic model in 1D (for longitudinal wave polarisation only). In the present study, an advanced viscoelastic model is used to describe the behaviour of the rubber coating, thus providing a more realistic insight into the influence of frequency-dependent material parameters on the locally resonant acoustic metamaterial performance. To this aim, a 2D analysis of a locally resonant acoustic metamaterial based on complex dispersion diagrams and power transmission spectra is conducted. The impact of viscoelastic material properties is studied in detail using the generalised Maxwell model for the coating layers in the inclusions. Furthermore, it turns out that a correct material model might be crucial if the focus is on exploiting viscoelasticity for joining band gaps. First, it is observed that due to the variation of elastic parameters with frequency, the band gap regions exhibit a shift. Depending on the elastic properties of the considered material, such a shift can be significant in some cases, which means that purely elastic predictions may not be sufficient to determine the band gap location. Therefore, while designing such a metamaterial, the dependence of the soft coating material behaviour on frequency should be verified. Secondly, if material damping is used for the purpose of joining band gaps, the target frequency range of wave attenuation (within the distance between the band gaps) needs to overlap with the region where the loss tangent level is sufficiently high. Otherwise the effect of bridging may not occur.

The paper is organised as follows, first, the modelling approach based on Bloch theory for obtaining complex dispersion diagrams and the finite element calculation of the power transmission spectra are described. Next, in Section 2.2, details on the considered geometry and material properties are given. Finally, in Section 3, the results of simulations are presented and discussed in Section 4. Section 5 summarises the main conclusions of the paper.

2. Modelling approach

The dynamic characteristics of a material can be obtained through the study of harmonic wave propagation, which is typically analysed based on its dispersion relation: the relationship between frequency ω and wave number $\mathbf{k}$. Some extraordinary properties of locally resonant acoustic metamaterials are depicted in such diagrams, already in the range of real wave numbers where the presence of band gaps may be captured (Krushynska et al., 2014; Liu et al., 2000). However, due to the continuity principle for the dispersion curves, branches within the band gap ranges are present in the domain of complex wave numbers, wherein the imaginary part of the wave number is often used as a measure of wave attenuation. Therefore, by considering complex band diagrams (real frequencies and complex wave numbers) information on spatial wave propagation as well as spatial attenuation of elastic waves is obtained. The analysis of the complex bands of dispersion diagrams may also contribute to a better understanding of band gap formation since tracing the evanescent Bloch waves becomes possible (Wang et al., 2015).

2.1. Complex dispersion diagram: formulation based on Bloch theory

The classical way for obtaining a dispersion relation is based on Bloch theory. The fundamental theorem for wave propagation in a periodic, infinite material states that the wave field in such a medium is also periodic (Brillouin, 2003; Deymier, 2013), and as a consequence, the analysis of such a structure can be restricted to