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On the impact of damping on the dispersion curves of a locally resonant metamaterial: Modelling and experimental validation

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ABSTRACT

Recently, locally resonant metamaterials have come to the fore in noise and vibration control engineering, showing great potential due to their superior noise and vibration attenuation performance in targeted and tunable frequency ranges, referred to as stop bands. Damping has an important influence on the performance of these materials, broadening the frequency range of attenuation at the expense of peak attenuation. As a result, understanding and including the effects of damping is necessary to more accurately predict the attenuation performance of these locally resonant metamaterials. Classically, these often periodic structures are analysed using a unit cell modelling approach to predict wave propagation and thus stop band behaviour, discarding damping. In this work, a unit cell method including damping is used to analyse the complex dispersion curves of a locally resonant metamaterial design. The wave solutions in and around the stop band frequency range are compared to those of the unit cell method discarding damping. The influence on the dispersion curves of damping in resonator and host structure is discussed and the obtained dispersion curves are validated through an experimental dispersion curve measurement based on an Extended Inhomogeneous Wave Correlation method using Scanning Laser Doppler Vibrometry for a metamaterial plate manufactured at a representative scale. Excellent agreement is obtained between the numerically predicted and experimentally retrieved dispersion curves.

1. Introduction

Over the past decades, tightening ecologic as well as economic requirements have given rise to the need for lightweight materials and designs [1]. Because of their increased stiffness over mass ratio, lightweight materials exhibit worse noise, vibration and harshness (NVH) behaviour. This conflicts with customer expectations and the increasingly stringent legal regulations regarding NVH exposure [2] for which current countermeasures are typically bulky or heavy. Novel low mass and compact volume NVH solutions are required to face the challenging task of merging both favourable NVH suppression performance and lightweight requirements.

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Among these novel NVH solutions, in recent years, innovative materials relying on stop band behaviour have been receiving increasingly more attention in noise and vibration engineering. Stop bands are frequency ranges in which no free wave propagation is possible [3], which allow these materials to exhibit superior NVH suppression performance. These stop band materials are generally subdivided into phononic crystals (PCs) and acoustic or locally resonant metamaterials (LRMs), for which the formation of stop bands relies on different mechanisms [4,5]. PCs are structured materials with periodic variations in properties. Their stop band behaviour relies on Bragg scattering, causing frequency zones of destructive interference between reflected and transmitted waves, linked to the length scale of periodicity [5–8]. The formation of stop bands in LRMs does not rely on periodicity or Bragg scattering, but emerges from the addition of local resonances to a host structure on a subwavelength scale, a spatial scale much smaller than the wavelength to be affected [5,9–11]. Stop band behaviour in LRMs is known to emerge from the Fano-type interference between incoming travelling waves and the waves re-radiated by these resonators around their resonance frequency [12,13]. Since LRMs do not require periodicity and are of subwavelength nature, they are more suitable to create targeted and tunable stop bands and thus superior NVH attenuation in the hard-to-address lower frequency range [13]. Therefore, in this work, LRMs are considered for further investigation.

LRMs have been widely investigated and their stop band effect has been established experimentally for a variety of realisations, ranging from one-dimensional beam-like structures to three-dimensional solid structures [6,10,14–20]. The analysis of LRMs, in order to numerically predict the attenuation performance, classically discards the presence of damping as the stop band mechanism causing attenuation does not rely on damping. However, as the materials used are often plastic or rubber-like, measured attenuation performances are often clearly affected by the presence of damping in these LRM constituents and are showing discrepancies with the numerical attenuation predictions. Only a limited number of works investigate the impact of damping on the LRM attenuation performance, often confined to mass-spring-damper lattices/resonant structures [13,21–24]. Effects of damping on more complex and practically realisable LRM structures are considered in [25–27], however, experimental validation is lacking. The main findings in these studies are in general that the presence of damping broadens the frequency range of attenuation with respect to the original stop band, at the cost of a decreased peak attenuation performance inside the original stop band. This work aims at (i) incorporating and analysing the presence of damping in the constituents (host structure, resonant structure and both combined) of a realisable two-dimensional plate type LRM design for the numerical attenuation performance prediction and (ii) validating the results with experimental measurements. By gaining insight in these effects, the presence of damping can then be exploited in future metamaterial designs to e.g. combine multiple stop band regions [20,28] or add specific damping treatments to or in between constituents [29], in order for these LRMs to be applicable for NVH suppression in a broader frequency range, while relying on trustworthy attenuation performance predictions.

The attenuation performance of stop band materials, in particular LRMs, is generally assessed by means of dispersion curve analysis, describing the wave propagation behaviour in the structure by representing the relation between the angular frequency ω or frequency f and the wavenumber k or propagation constant μ. To this end, the often, yet not strictly required, periodic nature of these metamaterials is exploited. Making use of infinite periodic structure theory and the Bloch-Floquet theorem allows the metamaterial structure to be represented by a single unit cell (UC), which results in an eigenvalue problem (EVP) in ω and k or μ. The solution of this EVP yields dispersion curves from which the wave propagation and thus stop band behaviour can be predicted [3,30]. The dispersion EVP is generally solved either for imposed freely propagating waves, thus real wavenumbers k or propagation constants μ, referred to as the "inverse", $\omega(k)$ or $\omega(\mu)$ method, or for imposed time harmonic motion, thus real frequencies ω, referred to as the "direct", $k(\omega)$ or $\mu(\omega)$ method [30–32]. In what follows, these methods will be referred to as the $\omega(\mu)$ and $\mu(\omega)$ approaches.

If no damping is considered in the UC, both $\omega(\mu)$ or $\mu(\omega)$ can be applied. Real, imaginary and complex wave solutions can be obtained, indicating freely propagating, evanescent and decaying waves respectively, in time or spatial domain. Classically, only the $\omega(\mu)$ method is applied and the dispersion curves are calculated for freely propagating, thus real μ along the edges of the irreducible Brillouin zone (IBZ) in the wave domain, referred to as the irreducible Brillouin contour (IBC) [3,33]. Stop bands emerge as frequency zones in which no freely propagating wave solutions are obtained for the dispersion curves along the entire IBC. If damping is considered in the UC model, the solutions of the EVP become complex and the $\omega(\mu)$ or $\mu(\omega)$ approach can be used to analyse the complex dispersion curves [31]. For the $\omega(\mu)$ approach, imposing freely propagating waves, thus real propagation constants μ, leads to complex frequency solutions ω corresponding to temporally decaying waves. The $\omega(\mu)$ approach has been developed and applied to analyse the effects of damping on dispersion relations for PCs in [32,34,35] and for LRMs in [21,36]. The $\mu(\omega)$ approach on the other hand imposes time harmonic wave motion, thus real frequencies ω, and solves the EVP for complex propagation constants μ, corresponding to spatially decaying waves. The effects of damping on the complex μ dispersion curves are analyzed for PCs in [32,37,38] and for LRMs [25,27]. In what follows, the main findings for each approach in the presence of damping are summarized.

Using the $\omega(\mu)$ approach, Hussein et al. [34] point out that, for a two-dimensional PC with Rayleigh damping, increasing damping shifts the dispersion curves down in frequency, while the band gap size can drop abruptly due to branch overtaking. For one-dimensional lumped mass-spring PCs, Hussein and Frazier [35] observe general viscous damping to cause branch overtaking and branch cut-off phenomena, which can result in sudden changes in the band gap size and formation of partial wavenumber band gaps. For two-dimensional PCs with proportional and general viscous damping, the dispersion curves are observed to shift down in frequency with damping. In [21] Hussein and Frazier report a metadamping phenomenon in one-dimensional viscously damped mass-in-mass chain LRMs, leading to considerable amplification of the