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Sound absorption by rubber coatings with periodic voids and hard inclusions

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ABSTRACT

Sound absorption by viscoelastic coatings for underwater applications comprising both periodically distributed voids and hard inclusions is presented. Using effective medium theory, each layer of gratings is approximated as a homogeneous medium with effective material and geometric properties, in which the monopole and dipole resonances of the inclusions are taken into account. A finite element model of the periodically distributed voided and hard inclusions in the host rubber medium is also developed. The different combinations of the layers are shown to have markedly different impacts on the acoustic performance, whereby the physical mechanisms governing sound absorption are strongly dependent on the Fabry-Pérot and dipole resonances associated with the presence of the inclusions. The effects of water backing or a steel backing plate are also shown to significantly affect the acoustic performance for the different layers of inclusions.

1. Introduction

Locally resonant phononic crystals are composite structures comprising sound scatterers in elastic media. Two main mechanisms governing the acoustic performance of phononic crystals are local resonance of the scatterers and destructive wave interference attributed to Bragg scattering due to periodicity of the scatterers [1,2]. For homogeneous materials, the density and elastic moduli are positive, whereas for materials with inclusions, the occurrence of local resonances lead to effective density or elastic moduli which are frequency dependent and can be zero or negative at some frequencies [3–8]. Resonant responses of the effective density and elastic moduli can be simultaneously achieved using phononic crystals that exhibit monopole, dipole and quadrupole resonances [8–11]. Utilising these phenomena, phononic crystals can be engineered to control air-borne or water-borne sound waves [3–5,12–15].

Inspired by phononic crystals with simultaneous resonant density and elastic moduli, the motivation of the current work is to investigate simple designs of phononic crystals for use as acoustic coatings that can be externally applied to marine vessels. These coatings play a dual role to minimise underwater noise pollution and absorb external acoustic waves for stealth purposes. To avoid reflection of sound waves, soft elastic media such as rubber with impedances close to the impedance of water are used. Further, soft elastic media embedded with inclusions facilitate the conversion of longitudinal waves into shear waves by inducing local resonances, thereby increasing sound dissipation. Acoustic coatings were initially designed using soft rubber containing periodic cavities [16,17], and later with heavy metallic inclusions [18]. A coating comprising heavy inclusions can be used in a deep sea environment as its sound absorption performance is less sensitive to the ambient fluid pressure compared to a coating comprising voids [19]. On the other hand, a coating comprising voids is lighter in weight compared to a coating comprising heavy inclusions. Further, compared to a coating comprising hard inclusions, a coating with voids is more efficient in blocking the transmission of noise from marine vessels [19–21]. A large number of analytical [16–18,21–26], numerical [24–41] and experimental [17,21,22,33–35] studies have been conducted to study the acoustic performance of coatings. Coatings with inclusions of different shapes such as cylindrical scatterers [16,17,24–27,35–38] and spherical scatterers [18,21–23,27–30], as well as different materials such as voided scatterers [16,17,21–25,27–31,35–40] and hard scatterers [18,26,28,32–34,39] have also been investigated.

To the best of the authors' knowledge, none of the aforementioned studies have considered the simultaneous inclusion of gratings comprising voided and hard scatterers, and their combined effect on sound absorption of an underwater acoustic coating. This

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paper analytically and numerically examines the acoustic performance of a soft elastic medium embedded with layers of periodically distributed voids and metallic inclusions for broadband absorption. In the analytical model, each layer of scatterers is modelled as a homogeneous medium with effective properties. A numerical model based on the finite element method is also developed for verification of the analytical model and to provide further physical insight into the mechanisms associated with sound absorption. Results for different combinations of layers of voided and hard inclusions obtained analytically and numerically show good agreement. It is found that the order of each layer of gratings in the direction of sound propagation has a large impact on sound absorption.

2. Phononic crystal models

To understand the individual and combined effects of layers of voids and hard inclusions embedded in a soft rubber medium, the following combinations of scatterers are considered:

(i) Two identical layers of periodically distributed cylindrical voids;
(ii) Two identical layers of periodically distributed hard cylinders;
(iii) A layer of cylindrical voids followed by a layer of hard cylinders in the direction of sound propagation;
(iv) A layer of hard cylinders followed by a layer of cylindrical voids in the direction of sound propagation.

Fig. 1 shows a schematic diagram of case (iv) comprising a layer of steel cylindrical scatterers followed by a layer of cylindrical voids embedded in rubber, in the direction of sound propagation. The host rubber medium has thickness t and is attached to a steel backing plate of thickness s. The radii of the hard and voided inclusions are denoted by a_h and a_v, respectively. The scatterers are arranged in a rectangular lattice. The distance between the two layers of scatterers is t_1. The scatterers are periodically distributed in the y-direction and the distance between the scatterers within a layer is d. The layer of scatterers closest to the steel backing plate is at a distance of t_2 from the plate. The cylinders are assumed to be of infinite height which allows modelling of the phononic crystal in two dimensions. For the steel backing case shown in Fig. 1, the fluid on the incidence side is water and the fluid on the transmission side is air. For a water-only backing case (not shown here), the steel plate is removed and the fluid on both the incidence and transmission sides is water. The phononic crystal is subject to acoustic plane wave excitation in the x-direction. Values for the geometric parameters were selected based on the authors' previous studies [25,26] in order to minimise the total thickness of the coating. The geometric and material parameters are listed in Section 4.

3. Methodology

3.1. Analytical model

Each layer of scatterers is modelled as a homogeneous medium with effective material and geometric properties as shown schematically in Fig. 2. The effective thickness of the layer made by homogenisation of voided and hard inclusions are respectively denoted by $l_{\mathrm{eff},v}$ and $l_{\mathrm{eff},h}$, where the subscript eff denotes an effective quantity, and the subscripts v and h denote voided and hard inclusions, respectively. The impedances of water and air are obtained by $Z_{w,a} = \rho_{w,a} c_{w,a}$, where ρ is the density, c is the speed of sound, and the subscripts w and a denote water and air, respectively. The speeds of sound in the rubber and steel are obtained using $c_{r,s} = \sqrt{\kappa_{r,s}/\rho_{r,s}}$, where κ is the longitudinal modulus and the subscripts r and s denote rubber and steel, respectively. The impedances of the host rubber medium and steel backing plate are obtained using $Z_{r,s} = \sqrt{\rho_{r,s}\kappa_{r,s}}$. The effective impedances of

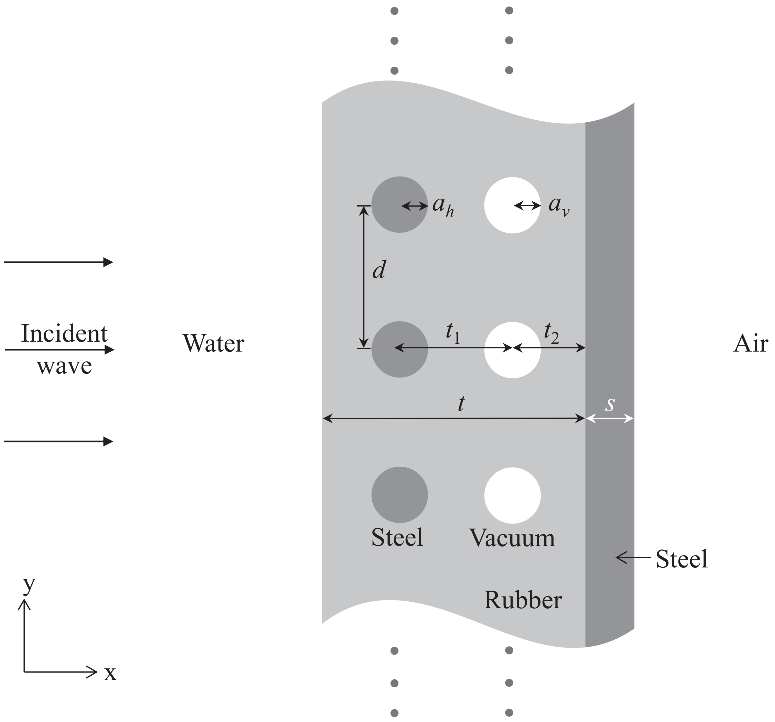

Fig. 1. Schematic diagram of a phononic crystal comprising two layers of periodic sound scatterers in rubber with a steel plate backing.