Acoustic metamaterials for maritime applications

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ABSTRACT

Acoustic metamaterials are rationally designed composites for which the effective material properties go beyond those of their bulk ingredients. A simple design of an acoustic metamaterial for maritime applications comprises a lattice of resonant scatterers embedded in a host elastic matrix. This composite design facilitates multiple scattering of waves and strong acoustic coupling between scatterers. Due to their extraordinary wave manipulation capabilities and the tremendous progress in fabrication technology, acoustic metamaterials are becoming immensely popular for noise control. However, the analytical and numerical treatment of acoustic metamaterials is still a challenging undertaking. The Maritime Division of the Defence Science and Technology and the School of Mechanical and Manufacturing Engineering at UNSW have developed a range of analytical and numerical tools to determine the acoustic performance of metamaterials for maritime applications. To this end, we have translated some well-known analytical results from electrostatics, fluid dynamics, diffusion kinetics, and solid-state physics to develop homogenisation and effective boundary approximation approaches. This paper provides an overview of our approaches for tailored designs of acoustic metamaterials.

1 INTRODUCTION

Acoustic metamaterials are engineered composite structures designed using distributions of resonant inclusions in a host material to exhibit favourable acoustic properties, for example, see Brunet et al. (2013), Cummer et al. (2016), Haberman and Norris (2016), Assouar et al. (2018) and references therein. Due to the tremendous progress in fabrication technology, acoustic metamaterials, often referred to as phononic crystals, can be manufactured as subtle morphological structures that can exhibit a rich variety of acoustic properties which go beyond those of their bulk ingredients. Due to the complexity of wave phenomena in acoustic metamaterials arising from multiple scattering, local resonances and resonance coupling, their analytical and numerical modelling is often a challenging undertaking. This necessities development of simplified models of acoustic metamaterials that are relatively easy to implement and computationally light to run.

One design of an acoustic metamaterial for maritime applications is a soft elastic medium embedded with a lattice of inclusions, employed as an external coating on marine vessels (Hladky-Hennion and Decarpigny, 1991; Ivansson, 2006, 2012; Meng et al., 2012a, 2012b; Méresse et al., 2015). The main mechanism for sound attenuation by the coating arises from enhanced wave scattering and the associated strain field amplification near the inclusions at frequencies around local resonance of the inclusions. This behaviour facilitates conversion of sound waves to shear waves, which are efficiently absorbed due to high damping capacity of shear waves in rubber-like materials. This work outlines the analytical and numerical capabilities developed by the authors and others to analyse the performance of acoustic coatings. A range of coating designs and physical mechanisms governing performance for the various designs are described.

2 METHODOLOGY

Several analytical and numerical approaches have been employed to investigate the acoustic performance of coating designs. These methods include (i) an effective medium approximation, (ii) an effective boundary condition, (iii) the finite element method, and (iv) the finite difference time domain method. A brief overview of each approach is described in what follows.

2.1 Layer homogenisation method

Effective medium approximation involves modelling an inhomogeneous composite material as a homogeneous medium defined by effective material and geometric parameters, for example, see Roux et al. (2020) and references therein. We have implemented effective medium approximation theory using layer homogenisation, in which a layer of resonant inclusions is modelled as a layer of a homogeneous material with effective material parameters sandwiched between two layers of the host rubber medium as shown in Fig. 1 (Sharma et al., 2017a, 2017b, 2018, 2019, 2020a). Our homogenisation technique is a two-step process. In the first step, global effective material properties of the entire coating are obtained. In the second step the effective properties of the homogenised layer encompassing the resonant inclusions are then calculated. Our approach takes into account multiple scattering of waves by the inclusions, the resonance frequency of the inclusions, and resonance coupling between inclusions in proximity.

2.2 Effective boundary method

In this approach, each layer of scatterers in the direction of sound propagation is approximated as an effective boundary, as shown in Fig. 2. We conceptually map the sound scattering by the lattice to scattering by an inclusions in the centre of a rigid duct with a cross section equal to the area of the unit cell (Skvortsov et al., 2019; Sharma et al., 2020b). We then calculate the blockage length of a scatterer in a duct, which is used to derive the reflection, transmission and absorption coefficients.

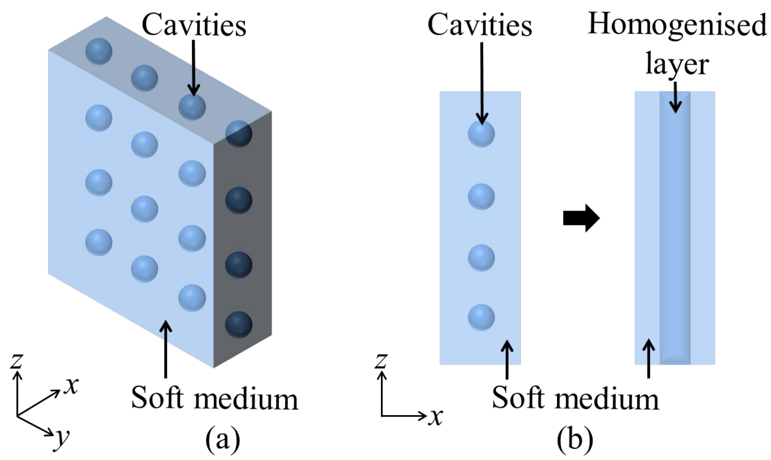

Figure 1: Schematic diagram showing (a) a layer of spherical cavities in a soft material and (b) the layer of cavities approximated as a homogenised layer with effective material and geometric properties. Figure reproduced from Sharma et al. (2020a).

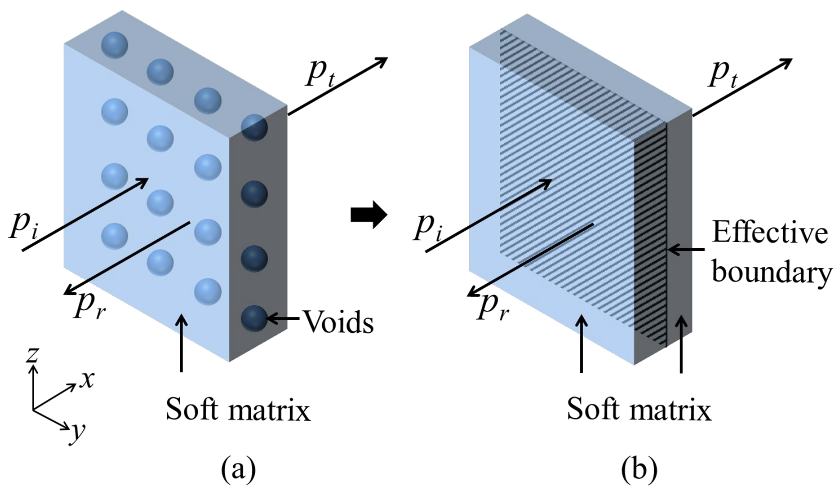

Figure 2: Schematic diagram showing (a) a lattice of spherical cavities in a soft material and (b) the layer of cavities approximated as an effective boundary. Figure reproduced from Skvortsov et al. (2019).

2.3 Finite element method

Finite element models of acoustic coatings have been extensively reported in the literature (for example, see Hladky-Hennion and Decarpigny 1991, Panigrahi et al. 2008, Wen et al. 2011, Meng et al. 2012a, 2012b, Zhao et al. 2014, Calvo et al. 2015, Ye et al. 2018, Zhong et al. 2019, Roux et al. 2020, Gao and Lu, 2020, Wang et al.

2020). Our finite element models are developed using COMSOL Multiphsyics (Sharma et al., 2017a, 2017b, 2018, 2019, 2020a, 2020b). Figure 3 shows a schematic diagram of a finite element model of a unit cell comprising a steel scatterer and a void embedded in a soft medium. The unit cell is subject to an incident plane wave from the fluid domain corresponding to water on the incidence side. The transmission side comprises a steel backing plate and air. The elastic media are modelled using the Solid Mechanics module and fluid media are modelled using the Pressure Acoustics module. Interactions between the solid and fluid domains are simulated by applying acoustic-structure boundary conditions at the interfaces. A free boundary condition is applied at the interface between the void and the elastic medium. A continuity boundary condition is applied at the interface between hard inclusion and the elastic medium. Anechoic termination of outgoing waves is simulated using a perfectly matched layer.

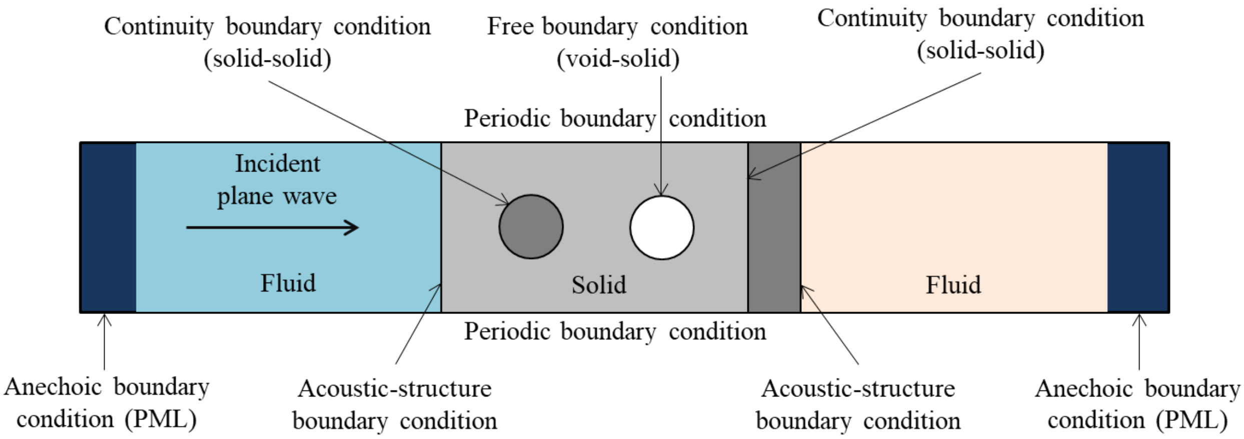

Figure 3: Schematic diagram of the finite element model of a unit cell comprising a steel inclusion and a void embedded in rubber attached to a steel backing plate. Figure reproduced from Sharma et al. (2018).

2.4 Finite difference time domain method

In addition to discretisation models based on the frequency domain, we have implemented the finite difference time domain method, which involves discretisation of the time dependent governing equations for wave propagation in a medium (Sharma et al., 2022). This is achieved using central-difference approximations to the space and time partial derivatives. The resulting finite difference equations are solved in a leapfrog manner using the propagation of velocities and stresses. A constitutive relation for the time domain method that accounts for damping in a lossy material is applied using an analogy between the fluid dynamics of viscous liquids and the elastodynamics of soft materials. The acoustic pressures and corresponding particle velocities obtained in the time domain are converted to the frequency domain using the Fast Fourier Transform to calculate the sound reflection, transmission and absorption coefficients.

3 RESULTS

3.1 Comparison between methods

To demonstrate the effectiveness of each method, the sound coefficients of a simple coating design obtained analytically and numerically are compared with experimental results from Leroy et al. (2015). The coating design is composed of a layer of cylindrical air-filled cavities embedded in polydimethylsiloxane (PDMS). The PDMS has steel backing on the transmission side and is submerged in water. The coating is subject to a normally incident plane acoustic wave. Figure 4 presents the transmission, reflection and absorption coefficients of the coating design obtained analytically using the layer homogenisation method and numerically using the frequency and time domain methods. Excellent agreement between the analytical and numerical results across a broad frequency range with experimental results from Leroy et al. (2015) can be observed. Multiple scattering of waves by the cavities results in conversion of sound waves into shear waves, which are efficiently dissipated in the PDMS due to high shear damping. The presence of the steel backing leads to high sound reflection due to impedance mismatch with the PDMS, which in turn results in low sound transmission (Fig. 4(a)). The reflection coefficient is observed to decrease with increasing frequency (Fig. 4(b)). Similarly, the absorption coefficient increases with increasing frequency, associated with an increasing effect of damping with increasing frequency (Fig. 4(c)).

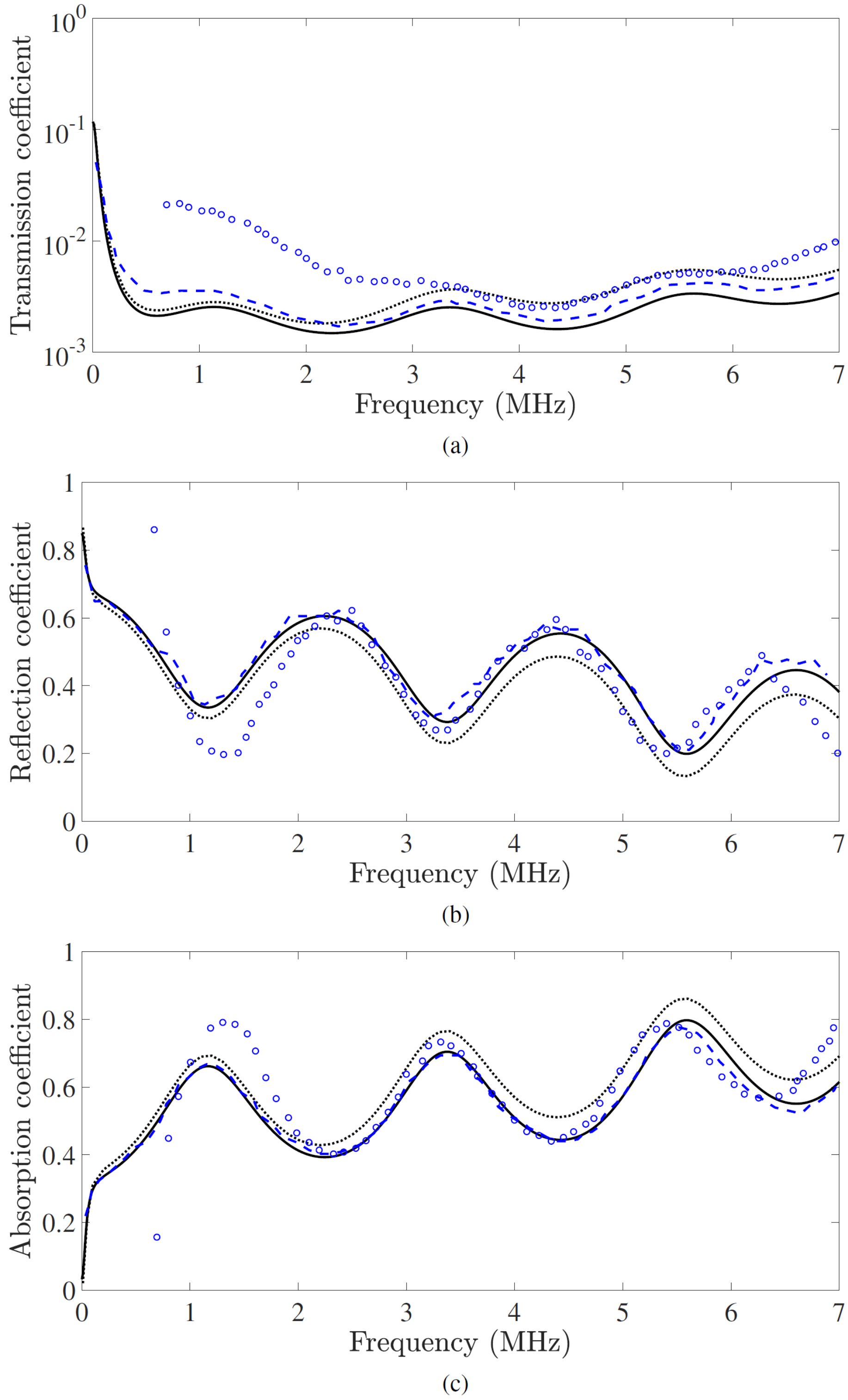

Figure 4: (a) Transmission coefficient, (b) reflection coefficient, (c) absorption coefficient of an acoustic coating comprising a layer of voids in a soft medium attached a rigid backing, obtained analytically using the layer homogenisation method (blue dashed lines), the finite element method (dotted black lines), the finite difference time domain method (solid black lines) and compared to experimental results (blue circles) from Leroy et al. (2015). Figure is reproduced from Sharma et al. (2022).

3.2 Inclusion material

We have investigated coating designs with inclusions of different material distribution. Figure 5 presents the transmission coefficient of a coating comprising a soft medium embedded with one or four layers of spherical cavities and submerged in water. The cavities are arranged in a square lattice within each layer. The first trough in the transmission coefficient is due to monopole resonance of the cavities. Figure 6 presents the absorption coefficient of a coating comprising a soft medium embedded with one, two and four layers of spherical steel inclusions and submerged in water. Multiple scattering of waves by the lattice of spheres enhances the effect of damping around the dipole resonance frequency, at which the incident sound waves are converted into shear waves and subsequently absorbed due to high shear damping. The frequency of dipole resonance of the spheres is not significantly affected with additional layers of scatterers. However, the sound absorption increases as the number of layers is increased arising from greater generation and dissipation of shear waves.

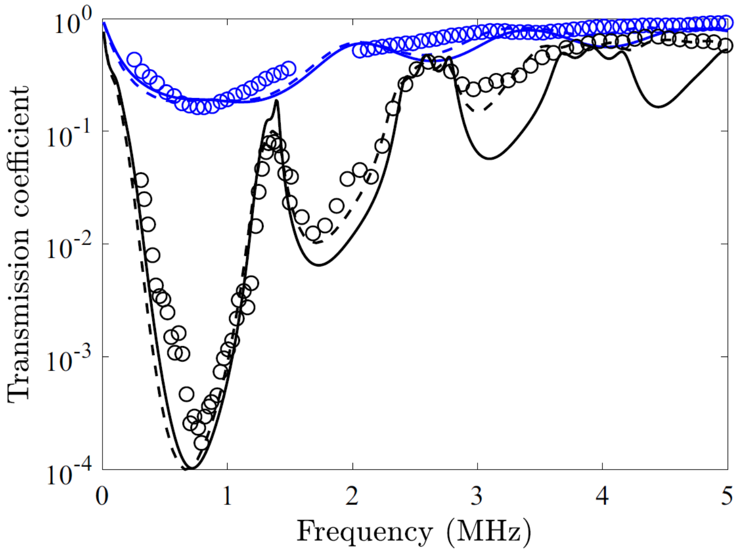

Figure 5: Transmission coefficient of one layer (blue lines) and four layers (black lines) of spherical cavities embedded in a soft medium submerged in water, obtained analytically using the effective boundary approach (solid lines), the finite element method (dashed lines). Our analytical and numerical results are compared to experimental results from Leroy et al. (2009) (circles). Figure is reproduced from Sharma et al. (2020a).

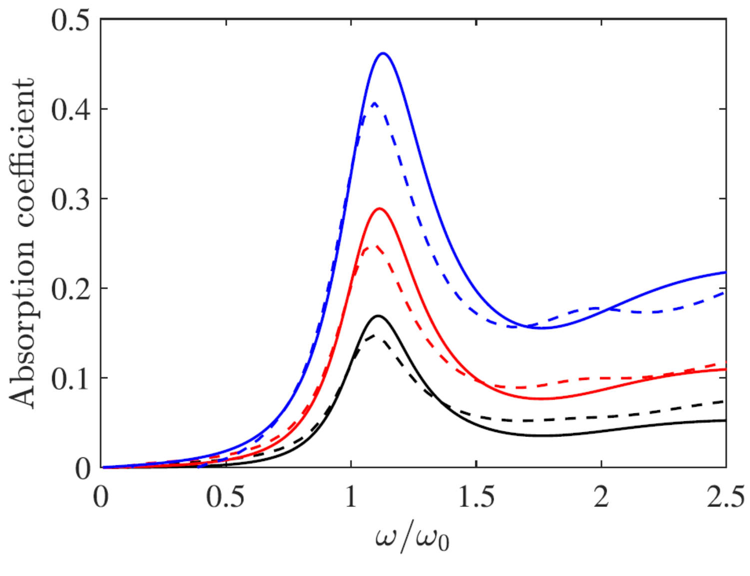

Figure 6: Absorption coefficient of one layer (black lines), two layers (red lines), and three layers (blue lines) of hard spheres in a soft medium as a function of non-dimensional frequency, obtained analytically using the layer homogenisation approach (solid lines) and numerically using the finite element method (dashed lines). Figure is reproduced from Skvortsov et al. (2021).

3.3 Coated cylindrical shell

We have extended our planar coating designs to consider a fluid-loaded cylindrical shell externally coated by a voided rubber coating, as shown in Fig. 7(a). The middle region of the coating encompassing the circumferential layer of voids is modelled as a homogenised layer with effective properties, as shown in Fig. 7(b). Our fully coupled model takes into account the vibrational response of the shell, the effects of local resonance of inclusions embedded in the coating, and the effect of heavy fluid loading from the surrounding water. Figure 8 presents the radiated acoustic pressure from an uncoated shell, the shell with a uniform rubber coating, and the shell with a voided rubber coating. Sound radiation from the shell with a uniform compliant coating increases with increasing frequency compared to the uncoated shell, attributed to an increase in coupling between the shell and water. In contrast, the coating with voids decouples the shell and water and reduces the structure-borne sound in a broad frequency range. The frequency of the first peak in the radiated pressure around 75 Hz corresponds to a spring-mass resonance, where the homogenised layer acts as the spring and the mass is provided by the steel shell. Beyond the first peak due to the spring-mass resonance, subsequent peaks in the radiated pressure correspond to circumferential orders of the shell. A significant reduction in radiated sound is achieved in a broad frequency range around monopole resonance of the voids. Wave scattering by the voids converts sound waves to shear waves, which are efficiently dissipated in the soft medium. At frequencies around and after the monopole resonance frequency, the homogenised layer of voids acts a reflecting boundary and blocks sound transmission through the coating. Results predicted using the analytical model presented here are in excellent agreement with numerical simulations using the finite element method.

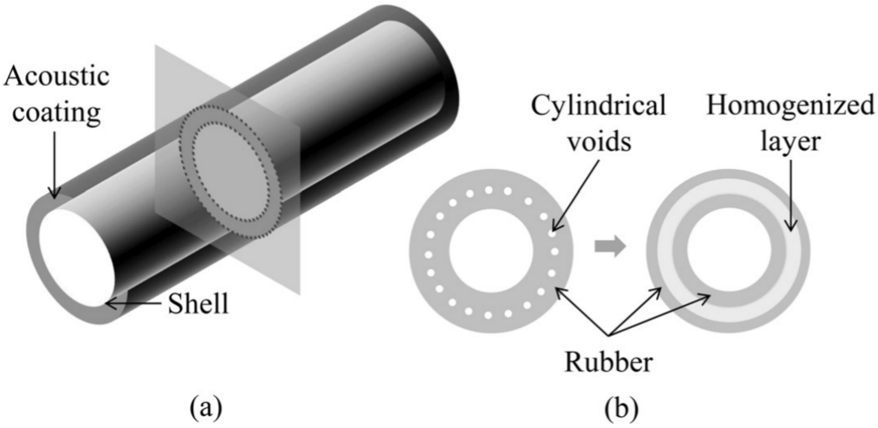

Figure 7: Schematic diagram of a cylindrical shell with a metamaterial coating comprising periodic cylindrical voids in rubber. (b) The layer of voids is modelled as a homogenised layer with effective properties. Figure reproduced from Sharma et al. (2021).

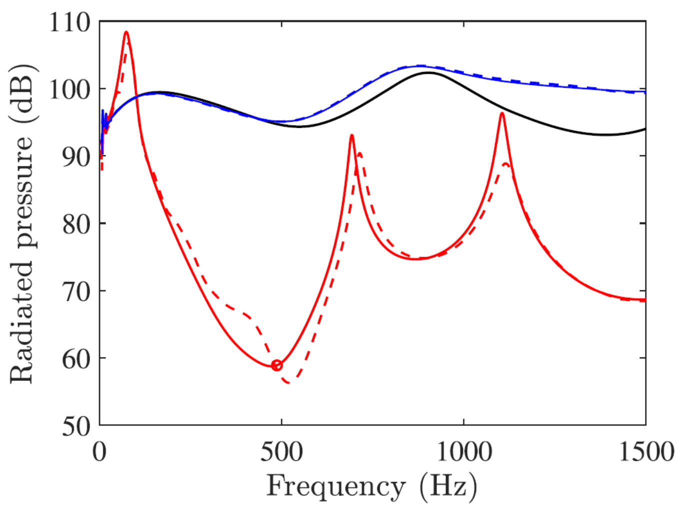

Figure 8: Radiated acoustic pressure (dB ref 1 μPa) from an uncoated shell (black lines), a shell with a uniform rubber coating (blue lines), and voided rubber coated shell (red lines), obtained analytically (solid lines) and numerically (dashed lines). The monopole resonance of the voids is indicated using a red circle. Figure reproduced from Sharma et al. (2021).

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