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The design of Helmholtz resonator based acoustic lenses by using the symmetric Multi-Level Wave Based Method and genetic algorithms

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ABSTRACT

Sonic crystals can be used as acoustic lenses in certain frequencies and the design of such systems by creating vacancies and using genetic algorithms has been proven to be an effective method. So far, rigid cylinders have been used to create such acoustic lens designs. On the other hand, it has been proven that Helmholtz resonators can be used to construct acoustic lenses with higher refraction index as compared to rigid cylinders, especially in low frequencies by utilizing their local resonances. In this paper, these two concepts are combined to design acoustic lenses that are based on Helmholtz resonators. The Multi-Level Wave Based Method is used as the prediction method. The benefits of the method in the context of design procedure are demonstrated. In addition, symmetric boundary conditions are derived for more efficient calculations. The acoustic lens designs that use Helmholtz resonators are compared with the acoustic lens designs that use rigid cylinders. It is shown that using Helmholtz resonator based sonic crystals leads to better acoustic lens designs, especially at the low frequencies where the local resonances are pronounced.

1. Introduction

Sonic crystals (SCs) are defined as periodically distributed scatterers in a fluid. For over a decade, the use of SCs as acoustic metamaterials has been an attractive topic. This is because they can exhibit properties which are impossible to have by using conventional materials. Initially, the focus was on blocking the sound [1–6]. Later, the characteristics of SCs to focus sound have been realized as well, which showed that they can be used as acoustic lenses. There are various ways to focus sound using SCs. At low frequencies, below the first Bragg scattering band gap, the SCs can act as homogeneous materials with lower speed of sound as compared to the hosting fluid's. As such the sound can be focused with lenticular topologies by using an effective positive refraction index [7,8]. It is also possible to focus sound by changing the local density within the SCs and tunnel the waves to focus. Such lenses are called gradient index lenses [9–11]. Another possibility is to use local resonances to create negative refraction index lenses above the first band gap [12–16].

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In addition to the aforementioned ways to create acoustic lenses, Håkansson et al. [17,18] proposed an alternative way by using an inverse design procedure. These devices are referred to as scattering acoustical elements (SAE) [19] or quasiordered structures [6] and are the focus of this paper. The main idea is to create vacancies on predefined SC grids, such that the resulting topology would focus sound on the desired receiver point. Genetic algorithms (GA) are used for the optimization procedure, as it suits very well to represent the existence of the scatterers in the design. In this way, a very high number of possible configurations can be searched efficiently with a rather low number of function evaluations. An advantage of SAE type lenses is that they can focus an incoming Gaussian beam or plane wave to a desired focal point. On the other hand, it is not clear how negative refraction index lenses can tackle such problems [19]. Moreover, the fact that negative refraction is observed for narrow frequency bands limits their practical use [19].

While the initial studies on SCs were based on rigid cylinders, the use of Helmholtz resonators as the unit scatterers has been investigated as well. It has been shown that the SCs with Helmholtz resonators can focus the sound better than their rigid cylinder counterparts [20]. This is true especially for the low frequencies, where the local resonances are the reasons behind the focusing effect.

Although it has been demonstrated that the refraction index of acoustic lenses made up of Helmholtz resonators is higher than the rigid cylinder ones, they have never been used in the design procedure proposed by Håkansson et al. [17]. This paper investigates the design of acoustic lenses made up of Helmholtz resonators and compares them with the acoustic lenses made up of rigid cylinders.

The modeling of such acoustic lenses is not trivial, especially when they are based on Helmholtz resonators. This is mainly because of the high number of scatterers and the resulting large system of equations. The main trend in modeling SCs is to use multiple scattering theory, yet this is only possible if the scatterer shapes allow analytical solutions. For more complex shapes, the Finite Element Method in frequency domain or the Finite Difference Method in time domain have been used. However, both of them need special boundary conditions to be able to solve unbounded problems. Moreover, in the context of a design procedure, creating vacancies on the predefined topologies needs re-meshing of the domain for every iteration of the optimization since both are domain discretization methods. Considering that thousands of function evaluations are needed in such cases, these methods become impractical. A better option might be to use the Boundary Element Method [21] because of its inherent ability to solve unbounded problems and that it is a boundary discretization method. On the other hand, it can be still very expensive to solve because of the high number of scatterers.

The Multi-Level Wave Based Method (ML-WBM) [22], which has been developed as an alternative to the element based methods, suits very well for the considered multiple scattering problem. It is an extension to the Wave Based Method [23–25], which is based on an indirect Trefftz approach [26] and uses the exact solutions of the governing equations to approximate the field variables. It is more efficient as compared to the Boundary Element Method for multiple scattering problems with moderately complex scatterers [22]. It also inherently satisfies the Sommerfeld radiation condition. In the context of a design procedure, the ML-WBM becomes even more attractive. Building up a model which has vacancies on predefined SC grids only needs a subset of the full grid model. In other words, constructing the system of equations is not needed for every iteration. This property of the ML-WBM brings a huge performance boost in the optimization concept, both because there is no time lost for constructing the system of equations and because the number of unknowns are rather low compared to element based methods [23].

In addition, symmetric boundary conditions are derived for the ML-WBM such that the inherent advantages of the ML-WBM for modeling SCs are even more pronounced in this paper. It is shown by Håkansson et al. [17] that using the symmetric boundary conditions in acoustic lens designs brings a big performance boost while the end result is only slightly affected. The same principle is followed here.

In short, this paper aims at demonstrating the advantages of using Helmholtz resonators in the context of acoustic lens designs. Furthermore, the benefits of using the ML-WBM for this problem are emphasized, while symmetric boundary conditions are derived for the method. Therefore, the paper is organized following the two mentioned points. After the problem definition in Section 2, a review of the ML-WBM is presented in Section 3. The derivation of the symmetric boundary conditions is presented thereafter in Section 4. In Section 5, the design procedure is explained. The optimization results that compare acoustic lenses made up of Helmholtz resonators and rigid cylinders are presented in Section 6, and finally, the paper is concluded with Section 7.

2. Problem definition

The problem under consideration, illustrated in Fig. 1, is a steady-state acoustic problem which is governed by the inhomogeneous Helmholtz equation [27]:

$$\nabla^2 p(\mathbf{r}) + k^2 p(\mathbf{r}) = -\mathrm{j}\rho_0 \omega \delta(\mathbf{r}, \mathbf{r}_q) q, \tag{1}$$

with k being the acoustic wavenumber, δ the Dirac-delta function, ρ_0 the fluid density, ω the angular frequency and q a volume velocity source strength.

The problem boundary Γ is defined by two parts: the finite part of the boundary, Γ_b, and the boundary at infinity, Γ_∞. Based on the three types of commonly applied acoustic boundary conditions, the finite boundary can be divided into three