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LEVEL SET-BASED TOPOLOGY OPTIMIZATION OF ACOUSTIC METAMATERIALS

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Abstract

Acoustic metamaterials are artificially engineered materials that are designed to have extraordinary acoustic properties, such as a negative effective bulk modulus and negative effective mass density. Several novel applications using such acoustic metamaterials have been proposed, such as sound isolation devices, acoustic cloaking [1], acoustic super lenses [2], and others. Most metamaterials consist of periodic structures of unit cells that are sufficiently small compared to the wavelength of the target frequency. While the constituent materials themselves do not exhibit extraordinary properties, the overall array of periodic structures can be considered as an effectively homogeneous acoustic material and such materials exhibit extraordinary properties globally, such as negative effective properties.

For the design of acoustic metamaterials, Liu et al. [3] first experimentally demonstrated that composite materials composed of lead balls coated with silicone rubber and epoxy resin show a negative bulk modulus. Subsequently, research concerning the realization of acoustic metamaterials that exhibit negative bulk modulus and negative mass density has been reported. However, the performance of such acoustic metamaterials is very sensitive to their unit cell design, and appropriate unit cell designs that exhibit desirable properties are usually difficult or time-consuming to find using trial and error methods. Therefore, there is a need for a systematic design approach, such as topology optimization, that can be applied to the development of efficient unit cell designs.

This paper presents a level set-based topology optimization method for the design of negative bulk modulus acoustic metamaterials. The purpose of the optimization problem here is to find optimized configurations of acoustic metamaterials composed of rubber and epoxy that achieve a negative effective bulk modulus at a prescribed frequency. In the design of acoustic metamaterials, the presence of grayscale areas in an optimal configuration significantly affects its performance. Therefore, in this study, we applied a level set-based topology optimization method [4], to avoid grayscale areas in the optimized configurations. To compute the effective bulk modulus of the acoustic metamaterials, we utilize an effective property retrieving method [5] that computes the effective acoustic properties based on reflection and transmission coefficients, which is an extension of a method originally proposed for computing the effective properties of electromagnetic metamaterials based on S parameters [6]. The optimization problem is formulated to minimize the effective bulk modulus to obtain acoustic metamaterial designs that exhibit negative bulk modulus. The optimization algorithm uses the adjoint variable method (AVM) for the sensitivity analysis and the finite element method (FEM) for solving the acoustic wave propagation problem, the adjoint problem, and the reaction diffusion equation used when updating the level set function. Finally, several numerical examples for two- and three-dimensional effective bulk modulus minimization problems are provided to confirm the utility and validity of the proposed method. The optimization results show that the obtained configurations behave as structures that have a negative bulk modulus at the prescribed operating frequency.

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