Modelling theory of functional element design for metamaterials with arbitrary negative Poisson's ratio

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ARTICLE INFO

Keywords:
- Modelling theory
- Metamaterials
- Negative Poisson’s ratio
- Functional element
- Topology optimization
- Vibration reduction

ABSTRACT

Metamaterials with arbitrary negative Poisson's ratio (NPR) can be designed by functional element topology optimization method, but modelling theory of this method is not investigated thoroughly, including functional element, volume fraction ration, the definition of objective functions and NPR constraints. In this paper, functional element with different shapes (triangle and rectangle), method of evaluating macroscopic NPR value, and three categories of objective functions: maximum compliance, minimum mass, minimum compliance, are conducted. A series of metamaterials structures with arbitrary NPR (the ratio range is $-0.3$ to $-6.0$) are designed, and the NPR values of these metamaterials structures are verified. Static analysis shows that the Poisson’s ratio between single functional element and macroscopic metamaterials structure are consistent with each other (error rate is 3.3%). Dynamic analysis to explore the vibration reduction performance of the metamaterials structure. All our works provide a method and theory for the design of novel metamaterials structure with arbitrary specified NPR.

1. Introduction

Conventional materials present a positive Poisson’s ratio and their cross-sections become larger under compression and smaller under tension, in contrast, some special materials will occur laterally in cross-sections become larger under compression and smaller under tension. NPR materials and structures are termed by Evans et al. [1] as auxetics or auxetic cellular materials, and auxetic materials and structures exhibit the interesting properties by virtue of the auxetic behavior [2]. And possessing the features of lightweight, shock absorbing and vibration reduction, the study of auxetic cellular materials have attracted increasing attention of scholars for several decades [3,4]. With the improvement of design [5] and manufacturing ability [6,7], the development of auxetic materials and structures have made remarkable progress, more and more auxetic materials and structures are being used to replace traditional materials, and satisfactory results have been achieved in the automotive, marine engineering, aerospace and other industrial fields [2].

In terms of dynamic performance, auxetic cellular materials show excellent impact resistance performance compared to the conventional materials [8], and it has been found that the size of the cell configuration can significantly affect the impact resistance of the auxetic materials [9]. Zhang et al. [10] studied the effect of auxetic honeycomb materials on the dynamics performance of vibration isolator, and the effect of cellular configuration parameters on the vibration and impact resistance of the structure were analyzed [11]. Nguyen and Pham [12] presented a nonlinear dynamic analysis and vibration of sandwich plates with NPR in auxetic honeycomb. In reference [13,14], the influence of parameters such as wall thickness, angle and cell numbers on the vibration reduction performance of the honeycomb materials were studied by using size optimization. These above references mainly studied the influence of cell configuration parameters on the properties of auxetic cellular materials, and most of these conclusions were based on deterministic configurations.

On the contrary, it is not convenient to design a novel cell configuration based on a specified given NPR. Most of the existing studies of auxetic cellular materials were conducted for common cell configurations [4], and the designing of novel cell configuration is still lack of systematic theories and methods. For the realization of innovative topology configuration design, topology optimization method seeks to find the optimal layout of materials that satisfies the required set of design demands. In the following sections, topology optimization design of the metamaterials structure will be summarized as two aspects: (a) microscopic material and (b) macroscopic structure. Fig. 1(a) illustrates a microscopic materials topology optimization method, which focuses on the design of the microscopic layout of the materials, instead of paying attention to the distribution of materials on the macroscopic
Fig. 1. Cellular materials design method based on different size scales: (a) Microscopic topology optimization; (b) Micro-Macro Concurrent scale topology optimization; (c) Macroscopic (functional element scale) topology optimization.

path. Fig. 1(a) is a design method based on the microscopic scale, and the optimized structure does not show the form of holes at the macroscopic scale, but the materials constituting the structures are arranged in the form of microscopic holes on the microscopic scale. Fig. 1(b) represents a concurrent scale of micro-macro materials topology optimization, this method is described as a combination of optimizing macroscopic structure distribution and optimizing microscopic material layout of hole-type cell configuration. Fig. 1(b) is a method for collaborative design at the microscopic and macroscopic scales. At the macroscopic scales, by optimizing the structural distribution to form a macroscopic topological shape, and the materials make up these the macroscopic structures are composed of cellular materials that are obtained by microscopic scales design. Therefore, this collaborative design method is a two-scale topology optimization design method with both macroscopic scale and microscopic scale.

Topology optimization method in microstructure material design can trace back to 1988, when Bendsoe and Kikuchi [15] used the homogenization method to design cellular materials and configurations. Since then, the topology optimization method has been applied to the design of metamaterials, and many scholars competed to carry out extensive and in-depth studies. In order to establish the mathematical relationship between the topology shape of the microscopic cellular materials and the equivalent performance of the macroscopic structural materials, Sigmund [16,17] proposed the transformation of optimal cell microstructure design into the topology optimization design of cells, and then the same microstructure cells were periodically arranged to form macroscopic material structures. Cheng [18] studied the multi-objective concurrent topology optimization for designing homogeneous cellular materials. Similarly, Niu [19] and Wang [20] studied the two-scale design variables of optimization method to realize the macrostructures and microstructures of cellular materials. In addition to these above researches, other scholars have done some in-depth researches on the topology optimization of cellular materials and the improvement of performance [21–24].

The performance in the metamaterials structure is determined by special designing and periodic arrangement of the substrate structures, indeed, the internal layout of the metamaterials plays a decisive role in the extraordinary properties of metamaterials structure. In this work, we consider a nonparallel approach by selecting (spatial) uniform macro design domain and optimizing this domain topologies, thus a Functional Element Topology Optimization Method is proposed for designing macroscopic metamaterials structures, the general idea of functional element topology optimization method can be depicted in Fig. 1(c): The configuration of the functional element is optimized by topology optimization method, and then the metamaterials structure is comprised of periodically arranged optimal functional elements. (Where, the definition of this functional element is detailed in Section 2.3). In Fig. 1(c), this proposed method is a macroscopic scales method, which focuses only on the structural configurations at the macroscopic scales, and does not involve the microscopic design of the constituent materials of the structure, that is, the material constituting the macrostructure is a common materials. The advantage of this method is that only need to optimize for a single functional element, and it can effectively improve the computational efficiency. On the basis of the method, this paper will conduct an in-depth study, and a systematic modelling theory of topology optimization will be proposed for designing metamaterials structures with arbitrary NPR.

2. Functional element design by topology optimization

In the field of materials science, metamaterials are also referred to as superstructure materials: Novel metamaterials structures are constructed by functional element configuration design and its periodic arrangement. In this paper, topology optimization theories are used to design the optimal material layout of functional elements, which will be discussed in detail below.

2.1. Theory of topology optimization

The structural topology optimization problem is actually a series of elements in the presence or absence, through the iterative optimization calculation to retain the structural elements that are advantageous for the structural force path and to delete the elements that have little effect on the configuration of the force path. Common topology optimization methods include: Homogenization Method [25], Variable Density Method [17], Evolutionary Structural Optimization (ESO) [22], Level Set Method [26], and so on.

These above methods and theories have advantages and disadvantages for the aspects of completeness, the difficulty of algorithm implementation, calculation accuracy and computational efficiency. Among them, Variable Density Method is an interpolation method which has a wide range of engineering applications. The general idea of Variable Density Method is to introduce a hypothetical density variables materials to form the physical relationship between physical parameters of the materials, such as elastic modulus and allowable stress, and the density of the materials. The density values of discrete mesh elements in design domain are taken as a column design variable vector, and by deleting elements whose density are less than the threshold determined by a certain criterion, the materials distribution path is achieved. SIMP (Solid isotropic materials with penalization) is an alternative approach to topology optimization among Variable Density Method [27], especially for the optimization of complex structures, therefore, SIMP is used to establish the topology optimization model in this paper.

2.3. Functional Element Topology Optimization Method

In this paper, we will conduct an in-depth study of topology optimization in this paper.
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