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Concurrent topology optimization of macrostructures and material microstructures for natural frequency

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ABSTRACT

Based on the bi-direction evolutionary structural optimization (BESO) method, a concurrent two-scale topology optimization algorithm is proposed for maximizing natural frequency of structures. The macro-scale structure is assumed to be constructed with a composite material, whose microstructure is represented by periodic unit cells (PUC). This optimization scheme aims to obtain the optimal topologies of the structure at the macro-scale level and microstructure of its material at the micro scale simultaneously, so that the resulting structure with a given weight has maximum natural frequency. The effective properties of a composite material with representative PUC are homogenized and integrated into the frequency analysis of the macrostructure. To implement topology optimization at both scales, the design variables are assigned for both the macrostructure and microstructure of its material. The sensitivity analysis with regard to the variation of design variables is conducted for iteratively updating the topologies at both scales synchronously. Numerical 2D and 3D examples are presented to demonstrate the validity of the proposed concurrent optimization algorithm for frequency optimization problems.

1. Introduction

Structural optimization is becoming an important engineering technique due to the limited material resources, technological competition and environmental compacts. With the rapid development of computer technology and practical algorithms implementation over the last several decades, structural optimization technology has been transferred from academic research to the current usage stage. Engineers and designers have had benefits from experiencing the optimization techniques. Topology optimization of continuum structures seeks the optimized material layout in the design domain while satisfying the various design constraints such as a given amount of material. Compared with size and shape optimizations, topology optimization of continuum structures allows designers to create more novel and efficient conceptual designs for various structures via providing more design freedoms [1], but at the same time it is most challenging.

In recent decades, starting from the landmark paper on topology optimization using the homogenization method [2], various optimization methods, e.g. Solid isotropic material with penalization (SIMP) [3–5], Evolutionary structural optimization (ESO) [6,7] and Level-set method [8,9], etc. have been invented and applied to solving many engineering design problems. Most of the current topology optimization methods are based on finite element analysis (FEA) which the design domain is discretized into finite elements, and the optimized topology is represented by elemental design variables such as solid or void.

The ESO method was first proposed by Xie and Steven [6], which gradually removes inefficient materials from the design domain and the remaining structure evolves to an optimum. The bi-directional evolutionary structural optimization (BESO) method is the later version of ESO which not only allows inefficient materials to be removed but also adds efficient materials simultaneously [10,11]. The current BESO method was proposed by Huang and Xie [12] which has been demonstrated to be capable of generating reliable and practical topologies for various types of structures [1,13].

Topology optimization techniques are mainly used to solve one-scale design problems, either at the macro-scale level to improve the structural performances or at the micro-scale level to invent new material microstructures for the prescribed or extreme properties [14–18]. At macro-scale level, topology optimization aims to seek the best layout of the given materials so that the resulting structure has the optimal performance. While the material design at the micro-scale level focused on prescribed or extreme effective properties of the material disregard of its service conditions. In material design, the material microstructure is represented by the periodical unit cell (PUC), which also makes it possible to combine the properties of each constituent into a new composite material. The homogenization method is used to calculate the macroscopic effective properties of the heterogeneous material and then the inverse homogenization method is used for topology optimization of material microstructures [19]. The material design by topology optimization for various objectives has been investigated by many researchers. For

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example, Neves et al. [20] extended the material design to maximize the total strain density. De Kruijf et al. [21] designed material microstructures for maximizing thermal conductivity and stiffness. Based on the BESO method, the optimal microstructures of cellular materials with maximum bulk or shear modulus [18], and composites with extreme electromagnetic permeability and permittivity [22] have been investigated.

The microstructure designs of cellular material and composites may not be efficient when they are used to construct macrostructures, since the performance of a macrostructure depends on not only the effective properties of its materials, but also its service conditions. Huang et al. [23] studied the optimal design of material microstructures in order to maximize the stiffness of macrostructures under the given conditions. However, the ideal design of a continuum structure is essentially a two-scale topology optimization problem which should consider the optimal macroscopic topology of the structure as well as optimal microstructures of its materials [24]. Rodrigures et al. [25] put forward a hierarchical computation approach inspired by the biological system, which designs the macrostructure by integrating with a series of material microstructures. This approach has also been extended to 3D cases [26]. To solving the two-scale optimal design problems Liu et al. [27] proposed a hierarchical topology optimization of structures and material microstructures but with two volume constraints at the macro-scale level and micro-scale level separately. Yan et al. [28] developed the concurrent topology optimization for minimizing the compliance of thermoelastic structures under the total weight constraint. Yan et al. [24] integrated a concurrent topology optimization on minimizing the mean compliance of structures. With the same concept, the concurrent topology optimization of structures constructed with thermal insulation materials was carried out [29].

Frequency optimization has great significance in engineering fields, especially for aeronautical and automotive industries. The topology optimization techniques have been applied to the frequency problems, e.g. homogenization method [30,31] and SIMP method [32,33], etc. and applications in industry could be found, e.g. a topology optimization on automotive component proposed by Boonpan and Bureerat [34]. Due to the artificial localized modes which are likely appeared when solving the eigen-frequency optimization using the original SIMP method, a modified SIMP scheme with a discontinuous function has been implemented successfully [32,33]. Frequency optimizations by ESO/BESO method also can be found in several publications [35–38]. Huang and Xie [39,40] pointed out that it is not sufficient to directly eliminate the elements which acting as the design variables from the design domain unless the soft elements are completely equivalent to void elements under certain conditions. For the frequency optimization of continuum structures, a new BESO algorithm with discrete design variables, 1 and $x_{\min}$ (e.g. 10^{-3}) was developed by utilizing the material interpolation scheme [39,40].

Considering the effect of material microstructures, Niu et al. [41] developed a two-scale frequency optimization for designing the structure with ultra-light cellular material. Zuo et al. [42] proposed a two-scale BESO optimization for design macrostructures with cellular or composite materials, where the two separate volume constraints were assigned at the macro-scale level and the micro-scale level separately in the above frequency optimizations. However, such factitious volume constraints artificially allocated the total weight to the structure and its material, which greatly hinders the interaction between the macro- and micro-scale levels. As a result, the optimized designs for the macrostructures and microstructures of materials may be far away from an optimum if inappropriate volume fractions are used for the structure and material. Therefore, it is necessary to develop a genuine concurrent topology optimization algorithm for natural frequency under a total weight constraint, which should calculate automatically the volume fractions of macrostructures and material microstructures.

This paper addresses this challenge and will develop a new topology optimization algorithm based on BESO for optimally designing macrostructures and material microstructures concurrently, so as to achieve the resulting structure to have the maximum natural frequency. The layout of this paper is as follows. Section 2 establishes the topology optimization formulations and the material interpolation scheme. Section 3 presents the homogenization theory, which obtains the effective properties of materials, the two-scale finite element analysis and sensitivity analysis. Section 4 illustrates the numerical implementation of the proposed concurrent BESO procedure. Section 5 demonstrates several 2D and 3D numerical examples to verify the effectiveness of the proposed method. Section 6 draws some concluding remarks.

2. Topology optimization

2.1. Topology optimization problem

It is assumed that a continuum structure with the prescribed boundary condition as shown in Fig. 1(a) is composed of a uniform composite material. Using the finite element analysis, the dynamic behaviour of the macrostructure can be expressed by

$$(\mathbf{K}-\omega_k^2\mathbf{M})\mathbf{u}_k = 0 \tag{1}$$

where **K** and **M** are the global stiffness matrix and mass matrix respectively, which will be computed through the effective properties of the PUC in the next section. ω_k represents the k th natural frequency and $\mathbf{u}_k$ is the eigenvector corresponding to ω_k, which based on the Rayleigh quotient

$$\omega_k^2 = \frac{\mathbf{u}_k^T\mathbf{K}\mathbf{u}_k}{\mathbf{u}_k^T\mathbf{M}\mathbf{u}_k} \tag{2}$$

Meanwhile, the macro-structural material is composed of two base materials with the uniform microstructure as shown in Fig. 1(b)

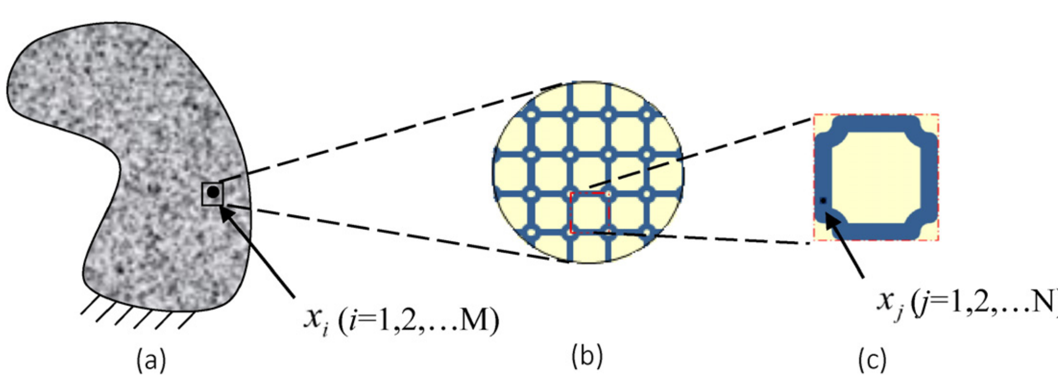

Fig. 1. Two-scale model of a macrostructure and its material microstructure: (a) macrostructure; (b) microstructure; (c) periodic unit cell (PUC).