Composite Structures 128 (2015) 221–233

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Concurrent design of composite macrostructure and multi-phase material microstructure for minimum dynamic compliance

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ARTICLE INFO

Article history:
Available online 25 March 2015

Keywords:
Topology optimization
Concurrent design
Dynamic compliance
Multi-phase materials
BESO method

ABSTRACT

A method for the concurrent topology optimization of composite macrostructure and periodic microstructure with multi-phase materials is proposed, where the objective is to minimize the dynamic compliance of the macro structure under harmonic excitation force. Based on a material interpolation scheme with multiple materials, the sensitivity of the dynamic compliance with respect to the design variables on the two scales is analyzed. The concurrent topology optimization model of composite macrostructure and multi-phase periodic microstructure is built, where constraints are imposed on the material volumes. Correspondingly, a numerical technique and an optimization procedure based on the bi-directional evolutionary structural optimization (BESO) method are presented. Results of numerical examples show that the proposed method is effective for the concurrent design of composite macrostructure and material microstructure for minimum dynamic compliance.

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1. Introduction

The optimal design can be categorized into size optimization, shape optimization and topology optimization for composite materials and structures in general. Fare et al. [1] took the layer thickness and the orientation angle of the material fibers as design variables with the aim to minimizing the dynamic response of anisotropic symmetric or anti-symmetric composite laminated rectangular plates with various boundary conditions. Furthermore, they [2] optimized composite laminated doubly curved shell with constraints on the thickness and control energy. Sandeep et al. [3] used fiber orientation, material and thickness in each lamina as well as the number of lamina in the laminate as design variables to obtain optimum laminate in terms of minimizing the cost, weight or both cost and weight. Saravanos et al. [4] improved the dynamic performance of composite structures by the design of micromechanics, laminate and structural shape parameters. Liu et al. [5] developed a fixed grid evolutionary structural optimization method to explore shape optimization of multiple cutouts in composite structures. Hansel et al. [6] optimized laminate structures by removing the material in low stress area based on an inverted form of growth strategy. Hansel et al. [7] presented a heuristic and a genetic algorithm for the topology optimization of the individual laminate plies so as to minimize the weight of the laminate structures. Blasques [8] simultaneously optimized topology and material of laminated composite beams with eigenfrequency constraints.

Topology optimization has now become an important design tool in civil and mechanical engineering fields for improving the performance of structures and materials, including every aspect of static and dynamic characteristics. The existing research works can be divided into two classes, i.e., the topology optimization of the macrostructure and that of the material microstructure. As to the former, there is a large amount of literature available since the emergence of the concepts and techniques of the structural topology optimization. The next is to design the microstructure of the material in order to obtain desired properties. Sigmund [9] designed the periodic microstructure of a material to obtain prescribed constitutive properties. Neves et al. [10] also discussed the optimal design of the periodic microstructure of cellular materials for optimal elastic properties. Yi et al. [11] improved stiffness/damping characteristics by the optimal design of microstructures of viscoelastic composites. Radman et al. [12] studied the design of isotropic periodic microstructure of cellular materials using the bi-directional evolutionary structural optimization (BESO) technique. Chen et al. [13] presented a topology optimization method to design the microstructure of the viscoelastic damping materials so as to obtain a prescribed shear modulus. Andreassen et al. [14] carried out the design of periodic composites with dissipative materials for maximizing the loss/attenuation of

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http://dx.doi.org/10.1016/j.compstruct.2015.03.057
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propagating waves. Andreassen et al. [15] focused on the design of elastic three-dimensional materials with periodic microstructures that are manufacturable. Recently, these methods have also been extended to the optimization of thermal [16], acoustic [17], magnetic [18,19] and photonic performance [20] and combinations thereof [21–24]. However, in the afore-mention research only single scale is considered in the topology optimization. Several techniques have been developed for the concurrent topology optimization problem dealing with both macro-structure and micro-structure [25–31]. However, most of these studies are confined to the optimization on static characteristics or that with one material. Little attention has been devoted to the concurrent design of macrostructure and periodic microstructure under the dynamic loading.

The rest of this paper is organized as follows. In Section 2, based on a material interpolation scheme for multi-phase materials, the sensitivity analysis of the dynamic compliance of the macrostructure under harmonic excitation force with respect to the design variables on the two scales, i.e., macro- and micro-scales, is presented. The concurrent topology optimization of composite macrostructure and material microstructure is built in Section 3. In Section 4, the corresponding numerical technique and optimization procedure based on the BESO method is developed. In Section 5, three numerical examples are presented to demonstrate the effectiveness of the proposed method. Finally, conclusions are drawn in Section 6.

2. Dynamic compliance and sensitivity analysis

The equation of motion of the structure under harmonic excitation force can be written as

$$\mathbf{M}\ddot{\mathbf{X}} + \mathbf{C}\dot{\mathbf{X}} + \mathbf{K}\mathbf{X} = \mathbf{F}e^{i\omega t} \tag{1}$$

where $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ denote the system mass, damping and stiffness matrices, respectively. ω is a circular frequency of the external excitation. $\ddot{\mathbf{X}}, \dot{\mathbf{X}}$ and $\mathbf{X}$ denote the system acceleration, velocity and displacement vectors, respectively. $\mathbf{F}$ is the amplitude of the external force vector. i is the imaginary unit. The system mass and stiffness matrices can be obtained by the assembly of the element mass and stiffness matrices, respectively

$$\mathbf{M} = \sum_{j=1}^{N_e} \mathbf{M}_j = \sum_{j=1}^{N_e} \int_{\Omega_j} \mathbf{N}^T \rho_j^E \mathbf{N} d\Omega \tag{2}$$

$$\mathbf{K} = \sum_{j=1}^{N_e} \mathbf{K}_j = \sum_{j=1}^{N_e} \int_{\Omega_j} \mathbf{B}^T \mathbf{D}_j^E \mathbf{B} d\Omega \tag{3}$$

where $\mathbf{M}_j$ and $\mathbf{K}_j$ are the mass matrix and the stiffness matrix associated with element j, respectively. $\mathbf{N}$ denotes the shape function on the macro-scale level. $\mathbf{B}$ is the strain/displacement matrix. N_e is the number of macrostructure elements. ρ_j^E and $\mathbf{D}_j^E$ are the mass density and the elastic matrix associated with element j, respectively. Ω_j is the area or the volume associated with element j. The superscript E indicates that the corresponding parameters are obtained by SIMP (solid isotropic material with penalization) method.

Assuming that the adopted damping model is the proportional damping model, the system damping matrix can be expressed as

$$\begin{aligned}\mathbf{C} &= \beta_1 \mathbf{M} + \beta_2 \mathbf{K} \\ &= \beta_1 \left(\sum_{j=1}^{N_e} \int_{\Omega_j} \mathbf{N}^T \rho_j^E \mathbf{N} d\Omega \right) + \beta_2 \left(\sum_{j=1}^{N_e} \int_{\Omega_j} \mathbf{B}^T \mathbf{D}_j^E \mathbf{B} d\Omega \right)\end{aligned} \tag{4}$$

where β_1 and β_2 are proportional damping coefficients.

For the topology optimization of the structure with multi-phase materials, there are many models to express the mass density and the elastic matrix for each element by the material interpolation scheme based on SIMP method or other methods [32–35]. In the SIMP method, the overall mechanical properties of a multi-phase material (with "void" as one phase) are generally formulated according to a "rule of mixtures". The material interpolation scheme based on SIMP is adopted in this paper due to the twofold reasons. One is that the number of the materials used in topology optimization is limited and small. Another is that the model is easily integrated in BESO method. Then the mass density and the elastic matrix associated with macro structural element j can be described as follows

$$\begin{aligned}\mathbf{D}_j^E &= \sum_{q=1}^{n-1} \left[\left(\alpha_{j1}^s\right)^{\eta_1} \cdots \left(\alpha_{jq}^s\right)^{\eta_q} \left(1 - \alpha_{j(q+1)}^s\right)^{\eta_{(q+1)}} \mathbf{D}_q^H \right] \\ &\quad + \left(\alpha_{j1}^s\right)^{\eta_1} \left(\alpha_{j2}^s\right)^{\eta_2} \cdots \left(\alpha_{jn}^s\right)^{\eta_n} \mathbf{D}_n^H\end{aligned} \tag{5}$$

$$\begin{aligned}\rho_j^E &= \sum_{q=1}^{n-1} \left[\left(\alpha_{j1}^s\right)^{\lambda_1} \cdots \left(\alpha_{jq}^s\right)^{\lambda_q} \left(1 - \alpha_{j(q+1)}^s\right)^{\lambda_{(q+1)}} \rho_q^H \right] \\ &\quad + \left(\alpha_{j1}^s\right)^{\lambda_1} \left(\alpha_{j2}^s\right)^{\lambda_2} \cdots \left(\alpha_{jn}^s\right)^{\lambda_n} \rho_n^H\end{aligned} \tag{6}$$

where $\mathbf{D}_q^H$ and ρ_q^H are the equivalent elastic matrix and the equivalent mass density of the qth phase material on macro scale and can be calculated based on homogenization method, respectively. η_q and λ_q are respectively the exponent parameters associated with the elastic matrix and the mass density, $q = 1, 2, \ldots, n$. The superscript s in the design variables indicates that the corresponding parameters belong to the macro structure. The construction of the design variables on macro scale are illustrated in Fig. 1 and

$$\mathbf{D}_q^H = \frac{1}{|Y_q|} \int_{Y_q} \mathbf{D}_q (\mathbf{I} - \mathbf{bu}) dY \tag{7}$$

$$\begin{aligned}\rho_q^H &= \frac{1}{\left|Y_q^{mic}\right|} \sum_{p=1}^{n_e} \left[\left(\alpha_{p1}^{m,q}\right)^{\theta_1} \left(1 - \alpha_{p2}^{m,q}\right)^{\theta_2} \rho_{q1} \right. \\ &\quad \left. + \left(\alpha_{p1}^{m,q}\right)^{\theta_1} \left(\alpha_{p2}^{m,q}\right)^{\theta_2} \left(1 - \alpha_{p3}^{m,q}\right)^{\theta_3} \rho_{q2} \cdots \right] |Y_{qp}|\end{aligned} \tag{8}$$

$$\begin{aligned}\mathbf{D}_q &= \sum_{k=1}^{N-1} \left[\left(\alpha_{p1}^m\right)^{n_1} \cdots \left(\alpha_{pk}^m\right)^{n_k} \left(1 - \alpha_{p(k+1)}^s\right)^{n_{(k+1)}} \mathbf{D}_{qk} \right] \\ &\quad + \left(\alpha_{p1}^m\right)^{n_1} \left(\alpha_{p2}^m\right)^{n_2} \cdots \left(\alpha_{PN}^m\right)^{n_N} \mathbf{D}_{qN}\end{aligned} \tag{9}$$

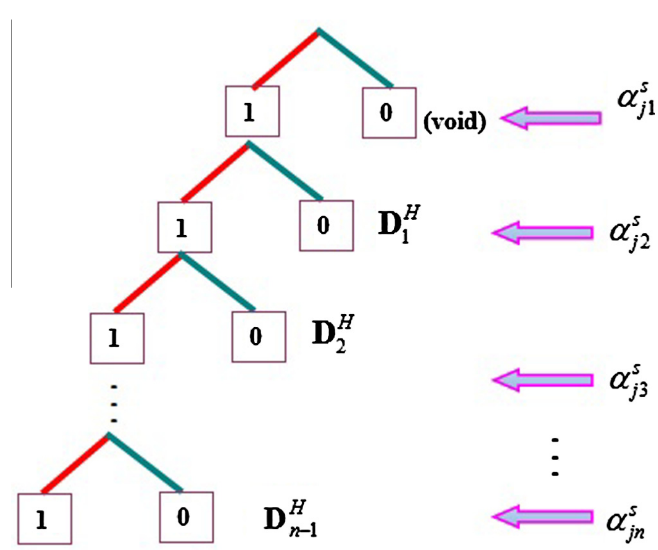

Fig. 1. Sketch figure of the design variable on the macro-scale level.

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