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Concurrent topology optimization for minimizing frequency responses of two-level hierarchical structures

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Abstract

This paper presents a concurrent topology optimization methodology for minimizing the frequency responses of multiscale systems composed of macro and micro phases. Although there is existing research on the topology optimization of structures and optimization of the materials for frequency responses, topology optimization approaches considering both scales simultaneously are relatively limited. The methodology proposed here aims to apply the bi-directional evolutionary structural optimization (BESO) method to find the optimum layout on both macro and micro scales of the structure, with the objective of minimizing the frequency response in the macro structure. For this coupled system, it is assumed that the macro structure is composed of a periodic material whose effective properties are obtained using the homogenization theory. The designs of the macro and micro structures are conducted simultaneously. The homogenized elasticity matrix used in the finite element analysis of the macro structure is obtained from considering the layout of the micro structure. A series of numerical examples are presented to validate the optimization procedure and to demonstrate the effectiveness and the efficiency of the proposed method.

Keywords: Topology optimization; Concurrent design; Frequency response function; Homogenization; BESO

1. Introduction

The reduction of frequency responses of structures has been widely studied in structural and mechanical engineering. There are various approaches developed to achieve this aim, among which structural topology optimization has been intensively investigated in the last three decades. The main idea of topology optimization is to find the optimum material distribution of a structure inside a design domain for enhanced structural performance.

Theories of continuum and solid mechanics have been used for decades as the basis of structural design in engineering practice and research. Aiming for better structural design and less material consumption, the field of

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design optimization of structures has been rapidly expanded with the increasing computer power, since the formulation of modern optimal layout theories by Prager and Rozvany [1].

The pioneering work by Bendsoe and Kikuchi [2] introduced the homogenization theory of periodic media [3,4] in structural topology optimization, in which the structure under design was assumed to be composed of porous materials. Later, the porous material was replaced by an artificial material model [5], the Solid Isotropic Material with Penalization (SIMP) model [6,7]. Other popular structural topology optimization methods developed in this area include the level set method [8,9], the Evolutionary Structural Optimization (ESO) method [10,11] and its advanced version the Bi-directional ESO (BESO) [12,13] method. Nowadays, topology optimization has been applied to not only structural design, but also to multiphysics problems [14–16].

Many works in structural topology optimization including those aforementioned consider the design of a structure under one single length scale, namely the macro scale, leaving the material micro structures out of the design scope; this also applies to methods using the homogenization theory [17,18]. On the other hand, topology optimization of materials aims at the design of material micro structures for tailored physical properties. It characterizes an inverse homogenization problem of modeling cellular materials and composites, where the objective is to design new micro structures that possess desired material properties in order to optimize the performances of the macro structure [19–23]. Recent research shows the current scientific efforts on this topic [24–26].

Most of the works on topology optimization have been restricted to either the macro or the micro scale, while optimization as a concurrent design on both scales is still limited. Rodrigues et al. [27] described a hierarchical procedure of simultaneous optimization of both the material and structure. Later, Coelho et al. [28] extended the idea to three-dimensional problems. Zhang and Sun [29] proposed a design element (DE) concept that is able to combine conventional design of materials and structures in a unified way, by changing the scale and aspect ratio of the DE. More recently, Xia and Breitkopf [30–32] presented models for concurrent topology optimization design of materials and structures using a nonlinear multiscale analysis.

Optimization for dynamic problems has been one of the most important topics of topology optimization. Most of the works in this area tackle design on the macro length scale while only few of them seek solutions on the micro scale; a large portion of these works considers shifting the natural frequencies of the structure. For macro scale approaches, several researchers such as Pedersen [33], Du and Olhoff [34] and Huang et al. [35], proposed various material interpolation schemes to adjust the SIMP-type model for dynamic problems. A few works for dynamic response can also be found that set scope within the macro scale, e.g. Rong et al. [36] applied the random dynamic theory to build an expression of dynamic response constraints imposed in topology optimization of macro structures, Jang et al. [37] simplified the macro structural topology optimization by replacing dynamic loads with equivalent static loads that generate the same displacement field in each time step. On the micro scale, Niu et al. [38] proposed a method to design cellular materials with maximum structural fundamental frequencies using a Porous Anisotropic Material with Penalization (PAMP) model [39]. On the other hand, a concurrent design approach for dynamic problems couples the otherwise independent single-scale design problems for the sole macro dynamic objective and/or constraints. Towards this goal, Zuo et al. [40] implemented an explicit scheme that iterates between the two scales, and topology optimization on each scale uses information from the other scale for sensitivity calculation; based on this effective explicit iteration scheme, a BESO approach is developed to maximizing structural natural frequencies with the consideration for composite materials and structures. Considering the minimization of the frequency response of fluid–structure systems Vicente et al. [41] proposed a single-scale optimization methodology using a modified BESO.

In this work, topology optimization for concurrent design on hierarchical materials and structures is extended to the frequency response function (FRF) problem. A topology optimization problem for this purpose is formulated under the finite element (FE) scheme. The sensitivity analysis is carried out on both the macro and micro scales. The FE analysis in the macro structure considers the boundary conditions and the external harmonic loads, while the periodic boundary conditions [17,18] are applied on the micro scale. A coupled design procedure using the BESO method is proposed to simultaneously conduct the optimization on both scales: the homogenized material elasticity matrix for the macro structure is calculated based on the layout of the micro structure, while the sensitivity analysis of the micro structure takes into account the displacement field from the macro structure [40].

This paper is outlined as follows: Section 2 illustrates the general multiscale model and presents the mathematical statement of the proposed optimization problem; Section 3 elaborates the sensitivity analysis on the two scales in detail; Section 4 describes the numerical implementation of the proposed BESO procedure for the multiscale