Available online at www.sciencedirect.com
ScienceDirect
Comput. Methods Appl. Mech. Engrg. 283 (2015) 503–516
Computer methods in applied mechanics and engineering
www.elsevier.com/locate/cma

Topology optimization for microstructures of viscoelastic composite materials

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Received 1 July 2014; received in revised form 2 October 2014; accepted 8 October 2014
Available online 16 October 2014

Highlights

- An extended BESO method for designing microstructures of viscoelastic composites.
- Unambiguous microstructures of viscoelastic composites are obtained.
- Composites with desirable viscoelastic properties are presented.
- Comparison with theoretical bounds of storage and loss moduli.

Abstract

The viscoelastic response of materials is often utilized for wide applications such as vibration reduction devices. This paper extends the bi-directional evolutionary structural optimization (BESO) method to the design of composite microstructure with optimal viscoelastic characteristics. Both storage and loss moduli of composite materials are calculated through the homogenization theory using complex variables. Then, the BESO method is established based on the sensitivity analysis. Through iteratively redistributing the base material phases within the unit cell, optimized microstructures of composites with the desirable viscoelastic properties will be achieved. Numerical examples demonstrate the effectiveness of the proposed optimization method for the design of viscoelastic composite materials. Various microstructures of optimized composites are presented and discussed. Meanwhile, the storage and loss moduli of the optimized viscoelastic composites are compared with available theoretical bounds.

Keywords: Topology optimization; Viscoelastic composite; Microstructure; Bi-directional evolutionary structural optimization (BESO)

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http://dx.doi.org/10.1016/j.cma.2014.10.007
0045-7825/

1. Introduction

Vibration is often undesirable for structures due to the demands for structural stability, durability and noise reduction. Viscoelastic materials such as rubbers are often applied for reducing the vibration level through damping mechanisms [1,2]. Those viscoelastic materials have favorable damping characteristics but often lack stiffness for constructing engineering products. Composites may produce the high damping and high stiffness by mixing two or more constituent materials with different physical properties [3]. The resulting viscoelastic composites will be of great interest to various industries such as automobile, aerospace, etc. The viscoelastic response of these artificial composites mainly depends on their microstructures apart from the proportion and physical properties of their constituents [1,3]. Designing viscoelastic composites with high damping and stiffness could be achieved by formulating a topology optimization problem for micro-structural topology and material properties at the macro scale.

Topology optimization methods, e.g. homogenization method [4], Solid Isotropic Material with Penalization (SIMP) [5–8], level set method [9–11], Evolutionary Structural Optimization (ESO) [12,13] and its later version Bi-directional ESO (BESO) [14,15], were originally developed to find a stiffest structural layout under given constraints. Topology optimization for the material design was initially proposed by Sigmund [16,17]. It was assumed that the material was microscopically composed of periodical unit cells (PUCs) and its effective macroscopic properties could be calculated through the homogenization theory. The inverse homogenization problem for seeking the best microstructure of the unit cell with the prescribed constitutive properties was then solved by topology optimization technique. Since then, extensive research has been carried out to investigate the material design with prescribed or extreme effective mechanical properties [18,19], thermal conductivity [20], permeability [21] and electromagnetic properties [22,23], the combination of properties [24–26], and so on.

Different from the pure elastic materials, viscoelastic materials have complex moduli, namely storage modulus and loss modulus. Early studies on viscoelastic composites focused on the bounds of effective complex moduli and found that multi-scale microstructures such as the Hashin–Shtrikman coated spheres assemblage or rank-N laminates could achieve high stiffness and high damping [27–30]. With the development of the modern manufacture technologies such as 3D printers, it is worthwhile to optimally design one-length scale microstructures with clear boundaries for viscoelastic composites. Topology optimization was firstly applied to the design of microstructures of viscoelastic composites for optimal damping characteristics by Yi et al. [31] and obtained the microstructures of viscoelastic composites. Prasad and Diaz [32] conducted the topology optimization of viscoelastic materials utilizing negative stiffness components. Recently, Chen and Liu [33] investigated topology optimization for the design of viscoelastic cellular materials with prescribed properties. Most recently, Andreasen et al. [34] investigated microstructures of viscoelastic composites which achieve the theoretical upper bound by topology optimization and Andreassen and Jensen [35] further studied viscoelastic composites for maximizing the loss/attenuation of propagating waves.

It has been revealed that optimized material microstructures highly depended on the used optimization parameters and algorithm because a number of different microstructures could possess the same physical property [16–19]. Because of the simplicity and computational efficiency of the BESO method [15,36,37], this paper will investigate the topology optimization of viscoelastic composites by using the BESO method with discrete design variables. Composite materials are assumed to be composed of two base materials (at least one is viscoelastic material) and their microstructures are uniformly represented by corresponding periodic unit cells. The optimization objective is to find the optimal distribution of two base materials within the unit cell so that the resulting composite has the maximum damping and/or stiffness. The homogenization theory will be used to calculate the effective properties of viscoelastic composites and then the BESO method will be applied for finding their optimal microstructures. Several numerical examples will be presented and compared with the theoretical bounds to demonstrate the effectiveness of the proposed BESO method.

2. Homogenization for viscoelastic composites

2.1. Properties of viscoelastic materials in the frequency domain

When a uniform viscoelastic material is subjected to a sinusoidally varying stress with the operation frequency, ω, the resulting strain also varies sinusoidally with the same frequency when a steady state is eventually reached. The