Artificial immune system for effective properties optimization of magnetoelectric composites

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Abstract

The optimization problem of the effective properties for magnetoelectric composites is considered. The effective properties are determined by the semi-analytical Mori-Tanaka approach. The generalized Eshelby tensor components are calculated numerically by using the Gauss quadrature method for the integral representation of the inclusion problem. The linear magnetoelectric constitutive equation is used. The effect of orientation of the electromagnetic materials components is taken into account by so called the orientation distribution function. The optimization problem is formulated and the artificial immune system is applied to solve it. In the final version of the paper the numerical examples and the discussion will be given.

Keywords: optimization, effective properties, magnetoelectric composites, Mori-Tanaka scheme, artificial immune system

1. Introduction

The magnetoelectric composites, which are also called the multiferroic composites have many interesting properties and they are widely used in the modern microsystem technology [9]. The physical properties of magnetoelectric composites are derived from the coupled field phenomenon, which is called the magnetoelectric effect. To determine the optimum microstructure of the multiferroic composite, a micromechanical method of modelling may be applied [1]. The Mori-Tanaka method is one of the micromechanical approaches to estimating the concentration tensor and then the effective properties [2]. The closed form solutions for the effective properties is quite complicated due to complexity of coupled field equations, then the numerical method can be applied. In the present work the artificial intelligence method, namely the artificial immune system [10] is used to optimize the effective properties of the magnetoelectric composite.

2. Magnetoelectric composite model

The linear constitutive equations of the magnetoelectric composite can be expressed as [5]:

$$\begin{aligned} D_i &= \kappa_{il} E_l + a_{il} H_l, \\ B_i &= a_{il} E_l + \mu_{il} H_l, \end{aligned} \tag{1}$$

where D_i and E_l denote the electric displacement and electric field vectors; B_i and H_i are the magnetic induction and magnetic field vectors; κ_{il} and μ_{il} are the dielectric and magnetic permeability tensors. The electric and magnetic fields are coupled through the magnetoelectric a_{il} moduli tensor. To simplify the notation of equations, generalized quantities can be introduced [1].

In the present formulation, the magnetoelectric composite is modeled as homogeneous, anisotropic and linear magnetoelectric.

The particles of the dielectric or magnetic phases, which are embedded in the matrix have identical shape, but varying orientations of the magnetic or electric polarization axis. The orientations of different particles may be described by the Euler angles [4, 7, 8]. Due to the anisotropy of the dielectric and magnetic materials, particles of different orientations will have different constitutive material tensor components in a global coordinate system, and thus orientational averaging has to be performed, which is necessary for the effective properties calculation.

3. Mori-Tanaka scheme

The generalized Mori-Tanaka model allows to obtain the effective properties of the multi-field composite [1, 2]. For the two-phase multi-field composite the effective moduli tensor is given by [7, 8]:

$$\mathbf{L}^* = (1 - f_2)\mathbf{L}_1\mathbf{A}_1 + f_2\left\langle \mathbf{L}_2(\theta,\psi,\phi)\mathbf{A}_2(\theta,\psi,\phi)\right\rangle, \tag{2}$$

where f_2 is the volume fraction of the active material component; $\mathbf{L}_1$ and $\mathbf{L}_2$ denote the magnetoelectric moduli tensor of the matrix and the active material, respectively; $\mathbf{A}_1$ and $\mathbf{A}_2$ are the electromagnetic field concentration tensor for the matrix and the active material, respectively; (θ,ψ,ϕ) denotes the Euler angles; $<\cdot>$ is the orientational averaging operator [7, 8]:

$$\left\langle H(\theta,\psi,\phi)\right\rangle = \int_0^{2\pi}\int_0^{2\pi}\int_0^{\pi} H(\theta,\psi,\phi)W(\theta,\psi,\phi)\sin\theta d\theta d\psi d\phi, \tag{3}$$

where $W(\theta,\psi,\phi)$ is the orientation distribution function, and H denotes the averaged physical quantity. The most popular form of the orientation distribution function is the Gauss distribution function [7, 8]. The Mori-Tanaka electromagnetic field concentration tensor for the active material inhomogeneity has the following form [9]:

$$\mathbf{A}_2(\theta,\psi,\phi) = \mathbf{A}_2^{dil}(\theta,\psi,\phi) : \left[(1 - f_2)\mathbf{I} + f_2\left\langle \mathbf{A}_2^{dil}(\theta,\psi,\phi)\right\rangle\right]^{-1} \tag{4}$$

where $\mathbf{I}$ is the generalized unit tensor and the dilute electromagnetic field concentration tensor $\mathbf{A}_2^{dil}$ is given by [8]:

$$\mathbf{A}_2^{dil}(\theta,\psi,\phi) = \left\{\mathbf{I} + \mathbf{S}(\theta,\psi,\phi) : \mathbf{L}_1^{-1} : \left[\mathbf{L}_2(\theta,\psi,\phi) - \mathbf{L}_1\right]\right\}^{-1}. \tag{5}$$

The magnetoelectric Eshelby tensor $\mathbf{S}$ can be defined by using the volume integral over the inhomogeneity domain Ω [5]:

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$$S_{MnAb} = -\iiint_{\Omega} G_{MJ,in} L^1_{iJAb} dV, \quad (6)$$

where G_{MJ} is the magnetoelectric Green's function. The above volume integral can be transformed into the volume over the unit sphere by the Radon transform, for example as in [5].

In (6) the magnetoelectric moduli tensor of the matrix is used. The integrals (3) and (6) are calculated numerically by using the Gauss quadrature method.

The Mori-Tanaka approach allows to estimate the effective properties of the composite as a function of the constituent material properties and the microstructure of the composite, which is described by the volume fractions, the shape of the inhomogeneity and the texture of the composite modeled by the function $W(\theta,\psi,\phi)$.

4. Optimization problem

The various optimization problems can be formulated [3]. For example, the optimization problem for the second-order magnetoelectric moduli tensor can be formulated as follows:

$$\max_{\mathbf{x}\in X} W(\mathbf{x}):\ W(\mathbf{x}) = \sqrt{\mathbf{a}^*(\mathbf{x}) : \mathbf{a}^*(\mathbf{x})}, \quad \mathbf{x}_{\max} \geq \mathbf{x} \geq \mathbf{x}_{\min}, \quad (7)$$

where the design parameters vector $\mathbf{x}$ may depend on the inhomogeneity shape parameters, the volume fractions and the parameters of the distribution function. The upper and lower bounds are imposed on the design parameters vector $\mathbf{x}$ as shown in (7). The objective function $W(\mathbf{x})$ expresses the norm of the magnetoelectric moduli tensor. Other forms of the objective function are possible, it depends on the material properties requirements. Due to complexity of the problem (7) the heuristic solution method, namely the artificial immune system [6, 10] is applied.

5. Artificial immune system

The artificial immune systems (AIS) are developed on the basis of a mechanism discovered in biological immune systems [6]. An immune system is a complex system which contains distributed groups of specialized cells and organs. The main purpose of the immune system is to recognize and destroy pathogens - funguses, viruses, bacteria and improper functioning cells. The lymphocytes cells play a very important role in the immune system. The lymphocytes are divided into several groups of cells. There are two main groups B and T cells. The artificial immune systems [10] take only a few elements from the biological immune systems. The most frequently used are the mutation of the B cells, proliferation, memory cells, and recognition by using the B and T cells. The unknown global optimum is the searched pathogen. The memory cells contain design variables and proliferate during the optimization process. The B cells created from memory cells undergo mutation. The B cells evaluate and better ones exchange memory cells. In artificial immune algorithm the crowding mechanism is used - the diverse between memory cells is forced. A new memory cell is randomly created and substitutes the old one, if two memory cells have similar design variables. The crowding mechanism allows finding not only the global optimum but also other local ones. The Gaussian mutation in the presented approach is used. The selection process exchanges some memory cells for better B cells. The selection is performed on the basis of the geometrical distance between each memory cell and B cells (measured by using design variables).

The Figure 1 presents the flowchart of an artificial immune system.

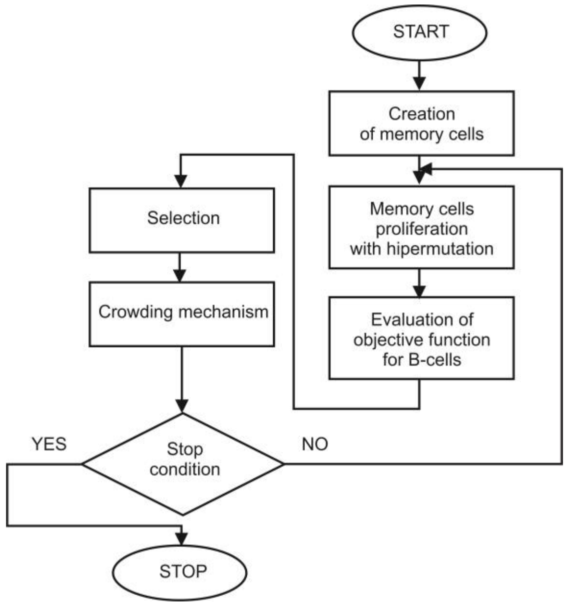

Figure 1: The artificial immune system

The numerical results and discussion will be presented in the full version of the paper.

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