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The magnetostriction in a superconductor-magnet system under non-uniform magnetic field

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ABSTRACT

This paper describes a numerical model to examine the magnetostriction of bulk high-temperature superconductor (HTS) under non-uniform magnetic field in conjunction with finite element analysis. Through this model, the magnetostriction of homogeneous and nonhomogeneous HTS can be implemented under non-uniform magnetic field. Further, the effects of critical current density, applied field frequency and amplitude are also considered. The computational study can provide a fundamental mechanistic understanding the effects of non-uniform magnetic field on magnetostriction of HTS.

1. Introduction

Superconductors and magnets systems have a wide range of applications in recently years, such as noncontact bearings, flywheels, and momentum wheels [1]. The phenomenon of magnetostriction in the system is a basic feature when the superconductors are placed in a magnetic field. The experiments had manifested the giant magnetostriction phenomenon when the superconductors were in a varied magnetic field [2,3]. The levitation phenomenon between superconductor and magnet is a result of flux pinning in the interaction between a magnet and a type II superconductor [4]. The interaction forces in a superconducting magnet system are determined not only by the geometry and electromagnetic properties of its components, but also by the cooling processes of the superconductor employed [5,6]. The mechanical properties of the superconducting magnet system may be influenced by some electromagnetic properties of superconductors [7]. Mechanical properties of superconductors have been extensively studied by some researchers. Gao and Zhou built a coupled model to account for the giant magnetostriction in type-II superconductors under alternating magnetic field [8]. Feng et al [9] studied the flux-pinning-induced stress and magnetostriction of a functionally graded type-II superconductor shaped as a rectangular slab. Ren et al [10] evaluated the stress distributions of superconductor by using a single flux-pinning-induced magnetostriction model. Yong and Zhou quantitatively illustrated the effects of coupling parameters on the magnetostriction and magnetization [11]. Celebi et al studied the contribution of the Meissner current fish-tail effect and coexistence of critical and normal state to the magnetostriction in a high Tc superconductor [12–14]. In the previous literatures, the magnetostriction of superconducting are studied in a uniform magnetic field. In this paper, we will focus on the mechanical properties of the superconductor under non-uniform magnetic field. The objective of this paper is to determine the superconductor giant magnetostriction in a magnet-superconductor system under non-uniform magnetic field by using finite element method.

This paper is organized as follows. Section 2 addresses the superconductor-magnet system which can analyses the giant magnetostriction phenomenon. Section 3 presents and discusses giant magnetostriction behavior. Finally, conclusions are presented.

2. Superconductor-magnet system and governing equations

Fig. 1 illustrates the configuration of the problem considered in this work. A two-dimensional plane strain mechanical model

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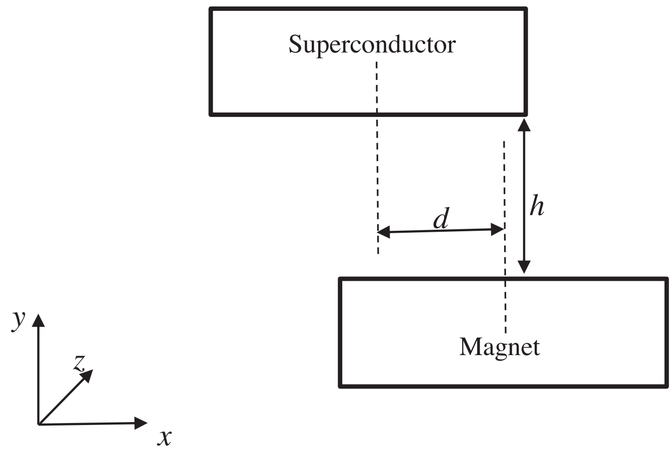

Fig. 1. Schematic illustration of a superconductor-magnet system.

is built to describe the interaction between a superconductor and a magnet. The magnetostriction of superconductor under non-uniform magnetic field can be modeled by an elastic body as shown in Fig. 1. The distance between the magnet and superconductor is *h*. *d* indicates the deviation distance that means the superconductor in a non-uniform magnetic field.

The electromagnetic governing equation of two-dimensional superconductor can be induced by two partial differential equations [15]

$$\begin{bmatrix} \dfrac{\partial\left(E_0\left(\frac{\frac{\partial H_y}{\partial x}-\frac{\partial H_x}{\partial y}}{J_c(B)}\right)^n\right)}{\partial y} \\ -\dfrac{\partial\left(E_0\left(\frac{\frac{\partial H_y}{\partial x}-\frac{\partial H_x}{\partial y}}{J_c(B)}\right)^n\right)}{\partial x} \end{bmatrix} = -\mu_0\mu_r \begin{bmatrix} \dfrac{\partial H_x}{\partial t} \\ \dfrac{\partial H_y}{\partial t} \end{bmatrix} \tag{1}$$

where H_x and H_y are the components of the magnetic field in the x- and y-directions. J_{sc_z} can be expressed as $J_{sc\_z} = \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y}$.

The mechanical constitutive relation of the superconductor material is taken to be as [16]

$$\sigma = \mathbf{C}\boldsymbol{\varepsilon} \tag{2}$$

where $\mathbf{C}$ is the stiffness matrix. $\boldsymbol{\sigma}$ denotes stress and $\boldsymbol{\varepsilon}$ is the elastic strain. $\mathbf{C}$ is the elasticity tensor:

$$\mathbf{C} = \frac{E_0}{1-\nu_0^2}\begin{bmatrix} 1 & \nu_0 & 0 \\ \nu_0 & 1 & 0 \\ 0 & 0 & \dfrac{1-\nu_0}{2} \end{bmatrix} \tag{3}$$

where $E_0 = \frac{E}{1-\nu^2}$ and $\nu_0 = \frac{\nu}{1-\nu}$.

The numerical model has been proposed by Gao and Zhou which can calculate the flux pinning induced magnetostriction in type-II superconductors under alternating magnetic field [8]. The magnetic field generated by the electromagnet in y-direction is

$$\begin{cases} \mathrm{H_x} = 0 \\ \mathrm{H_y} = \mathrm{H_0}\sin(2\pi f\mathrm{t}) \end{cases} \tag{1a}$$

where H_0 is the magnitude of the applied magnetic field, and f is the frequency of applied magnetic field.

The electromagnetic force between the superconductor and the electromagnet is the Lorentz force [11]. According to the electromagnetic theory, the electromagnetic force can be expressed as

$$\mathbf{F} = \mathbf{J} \times \mathbf{B} \tag{2a}$$

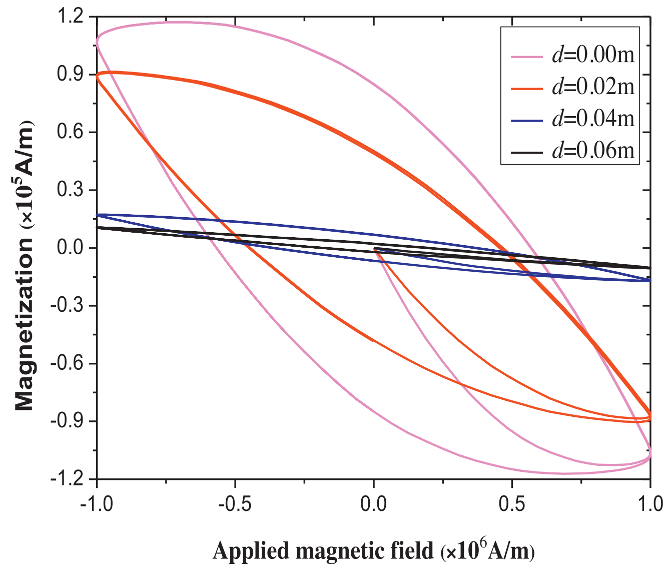

Fig. 2. The magnetization curves of superconductor in different non-uniform magnetic field.

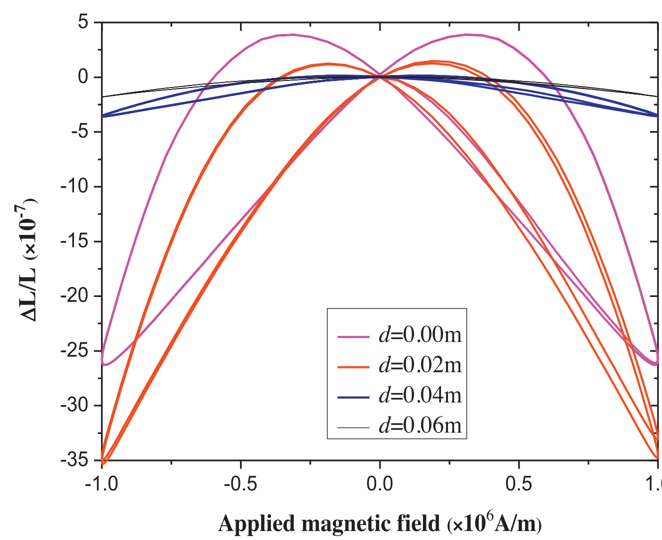

Fig. 3. The magnetostrictive curves of superconductor in different non-uniform magnetic.

In the model, the $\mathbf{J}$ only has z direction component J_{z_sc}, $\mathbf{B}$ only has x direction and y direction of the components B_x and B_y, and

$$B = \mu_0 H \tag{3a}$$

Lorenz force can be simplified as

$$\mathbf{F} = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ 0 & 0 & \mathrm{J_{z\_sc}} \\ \mu_0\mathrm{H_x} & \mu_0\mathrm{H_y} & 0 \end{vmatrix} = -\mu_0\mathrm{H_y}\cdot\mathrm{J_{z\_sc}}\mathbf{i} + \mu_0\mathrm{H_x}\cdot\mathrm{J_{z\_sc}}\mathbf{j} \tag{4}$$

where μ_0 is permeability.

Therefore, the forces in the x direction and the y direction can be expressed as

$$\begin{cases} \mathrm{F_x} = -\mu_0\mathrm{H_y}\cdot\mathrm{J_{z_{sc}}} \\ \mathrm{F_y} = \mu_0\mathrm{H_x}\cdot\mathrm{J_{z\_sc}} \end{cases} \tag{5}$$

3. Numerical results and discussion

When the high-Tc superconductors are placed in a magnetic field, the magnetostriction phenomenon is a basic feature. Both