Numerical Investigation on Applicability of Scanning Permanent Magnet Method to Crack Detection in High-Temperature Superconducting Film

Teruou Takayama¹ and Atsushi Kamitani²

¹Department of Informatics, Faculty of Engineering, Yamagata University, Japan
²Graduate School of Science and Engineering, Yamagata University, Japan

1 Introduction

As is well known, a critical current density \( j_C \) is one of the most important parameters for engineering application of high-temperature superconductors (HTSs). Although the standard four-probe method is generally used to measure \( j_C \), it may lead to degradation of HTS characteristics. For this reason, some contactless methods such as the inductive method [1], the hall sensor method, and the hall probe method have been proposed. These methods have been applied to the measurement of \( j_C \)-distributions for a large-area samples such as an HTS tape or wire.

As a novel contactless method, Ohshima et al. proposed the standard permanent magnet method for measuring \( j_C \) in an HTS thin film. While moving a permanent magnet above an HTS film, the electromagnetic force \( F_e \) acting on the film is measured. Consequently, they found that the maximum repulsive force \( F_M \) is roughly proportional to \( j_C \). This means that \( j_C \) can be estimated from the measured value of \( F_M \). Although the standard method is used for the determination of \( j_C \)-distributions or the detection of any cracks in an HTS film [2], it becomes time-consuming due to the measurement of \( F_M \) at each measurement point.

Recently, Ohshima et al. have proposed a modified permanent magnet method [3]. In the method, the magnet is first placed just above an HTS sample at the constant distance between an HTS surface and the magnet bottom, and it is subsequently moved in the direction parallel to the surface. As a result, they found that a spatial distribution of \( j_C \) can be obtained from a measured \( F_e \)-distribution. In addition, they have concluded that, from the standpoint of the saving of the measurement time, this method is superior to the standard one. In the following, this method is called the scanning permanent magnet method.

In the previous study, a numerical code was developed for analyzing the time evolution of a shielding current density in an HTS film [4]. By using the code, the standard permanent magnet method was reproduced for an HTS film without any cracks. The results of computations showed that, even if the symmetry axis of the magnet approaches the film edge, the maximum repulsive force \( F_M \) is almost proportional to \( j_C \). From this result, we conclude that the standard method is applicable to the measurement of \( j_C \) even near the edge. However, any cracks were not at all taken into consideration in the code.

The purpose of the present study is to develop a numerical code for analyzing the time evolution of a shielding current density in an HTS film with a crack, and to reproduce the scanning method by using the code. Moreover, we investigate whether or not the scanning method is applicable to the crack detection in an HTS film.

2 Governing equation and numerical method

In Fig. 1, we show a schematic view of a scanning permanent magnet method. A cylindrical permanent magnet of radius \( r_m \) and height \( h_m \) is placed above a rectangle-shaped HTS film of width \( a \), length \( c \), and thickness \( b \). Also, a constant distance between a magnet bottom and a film surface is denoted by \( L \).

Throughout the present study, we use the Cartesian coordinate system \( (O : \mathbf{e}_x, \mathbf{e}_y, \mathbf{e}_z) \), where the \( z \)-axis is parallel to the thickness direction and the origin \( O \) is the centroid of the film. In terms of the coordinate system, the symmetry axis of the permanent magnet can be expressed as \( (x, y) = (x_m, y_m) \). For the purpose of characterizing the magnet strength, we use the magnitude \( B_F \) of a magnetic flux density at \((x, y, z) = (0, 0, b/2)\).

As usual, we assume the thin-layer approximation [5]: the thickness of an HTS film is sufficiently thin that a shielding current density can hardly flow in the thickness direction. The shielding current density \( j \) is closely related to the electric field \( \mathbf{E} \) through the \( J-E \) constitutive equation: \( \mathbf{E} = E(|j|)|j/j||. As the function \( E(|j|) \), we use the power law: \( E(|j|) = E_C |j/j|^{\alpha} \), where \( E_C \) is the critical electric field.

Under the above assumptions, the shielding current density \( j \) can be written as \( j = (2/b)(\nabla S \times \mathbf{e}_z) \) and its time evolution is governed by the following integro-differential equation [5]:

\[
\mu_0 \partial_t (W S) + \partial_t (\mathbf{B} \cdot \mathbf{e}_z) + (\nabla \times \mathbf{E}) \cdot \mathbf{e}_z = 0, \quad (1)
\]

where \( \langle \rangle \) is an average operator over the thickness, and \( \mathbf{B} \) is an applied magnetic flux density. In addition, \( W S \) is
In Fig. 3, we show the distribution. The crack position and size can be estimated from the force for the film containing a crack:

\[ F_{xy} \]

almost constant for this figure that, for the case with distribution of the electromagnetic force on the film:

\[ j_c(x, y) \]

out the present study, the crack is assumed to be parallel to the plate, and the crack size is given by \( R = 0 \) mm, \( E_c = 0.1 \text{ mV/m} \), \( N = 20 \), \( B_T = 0.3 \text{ T} \), and \( L = 0.5 \text{ mm} \). Moreover, we assume that \( j_c \) is uniform all over the film: \( j_c = 1.5 \text{ MA/cm}^2 \). Incidentally, the magnet is moved from the left end of the film to the right one except for Fig. 4, and the magnet position is controlled as \( x_m(t) = -a(2t/\tau_0^2 - 1)/2 \). Here, \( \tau_0^2 \) is fixed as \( \tau_0^2 = 140 \text{ s} \).

3 Numerical results

We investigate whether or not the scanning method is applicable to the crack detection in an HTS film. Throughout the present study, the crack is assumed to be parallel to the y-axis and its shape is assumed to be a line segment. The center position of the crack is denoted by \( (x, y) = (xc, 0) \) in xy-plane, and the crack size is given by \( L_c \).

Let us first investigate the influence of the crack size on the distribution. In Fig. 2, we show the spatial distribution of the electromagnetic force \( F_{xy} \). We see from this figure that, for the case with \( L_c = 0 \text{ mm} \), \( F_{xy} \) becomes almost constant for \(-7.5 \text{ mm} \leq x_m \leq 7.5 \text{ mm} \). On the other hand, a widely different behavior of \( F_{xy} \) is observed for the film containing a crack: \( F_{xy} \) becomes an attractive force \( F_a \) for \( x_c > x_m \), whereas it becomes a repulsive force \( F_r \) for \( x_c < x_m \). In addition, the magnitudes of \( F_a \) and \( F_r \) increase with the crack size \( L_c \). This means that the crack position and size can be estimated from the \( F_{xy} \) distribution.

Next, let us investigate the detectable range of a crack. In Fig. 3, we show the distribution for various crack positions \( x_c \)'s. We see from this figure that, for \( x_m \leq -7.5 \text{ mm} \), \( F_a \) cannot be observed because of the edge effect. In conclusion, it is found that, when the crack is located near the film edge, the crack position cannot be estimated from \( F_a \) and \( F_r \).

Finally, let us investigate how the distribution is affected by changing the scanning direction of the magnet. For the case where the magnet is moved from the right end to the left one, \( F_{xy} \) is calculated as a function of \( x_m \) and is depicted in Fig. 4. In this figure, two curves of \( F_{xy} \) intersect at the crack position \( x_c \). From this result, we can conclude that, if two \( F_{xy} \)-distributions are obtained by using two scanning directions of the magnet, the crack position can be accurately determined from the intersection of two curves for \( F_{xy}(x_m) \).

References