Inverse Analysis for Magnetic Field Source Searching in Thin Film Conductor

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Abstract — **Previously, we have proposed the sampled pattern matching (SPM) method solving for the inverse problem. In the present paper, we propose a generalized SPM method. The generalized SPM method makes it possible to estimate both the direction and magnitude of currents. We apply this new method to the current estimation in a thin film conductor. Numerical simulation suggests the validity of the method. As a result, this paper presents an effective methodology to estimate a current distribution in a thin film conductor.**

I. INTRODUCTION

Magnetic field source searching is one of the extremely important problems in electronic device design as well as electromagnetic compatibility (EMC) problems. The magnetic field source searching requires the solution of the inverse problems [1-4]. The inverse problem is generally reduced to solving an ill-posed system equation. Therefore, various methodologies have been proposed [1], e.g. the least square method and statistical approaches. On account of solving the ill-posed equation, however, it is difficult to obtain a unique solution. In most of the inverse strategies, it is difficult to evaluate both the magnitude and distribution of current from the locally measured magnetic fields. Previously, we have proposed the sampled pattern matching (SPM) method for solving inverse problems in biology as well as in non-destructive testing [2-4].

On the other hand, we have previously proposed the novel film transformer without any magnetic materials [6]. The operation principle of this film transformer is based on the magnetic coupling under skin effect appeared at edges of films [7]. Actually, the efficiency of the film transformer depends on its shape and structure. Hence, it is essential to know a relationship between the current distribution and film shape in order to carry out the optimum design. This means that the shape design of the film transformer is reduced into solving an inverse problem.

In the present paper, we propose the "generalized SPM method" for the magnetic field source searching problems. To examine the validity of our method, we carried out a numerical simulation. Also, we applied our method to estimating a current distribution in a thin film conductor. As a result, numerical and experimental results verified the validity of our new method. Finally, we have succeeded in evaluating the current distribution in a film transformer from the locally measured magnetic fields.

II. GENERALIZED SAMPLED PATTERN MATCHING METHOD

A. Key ideas

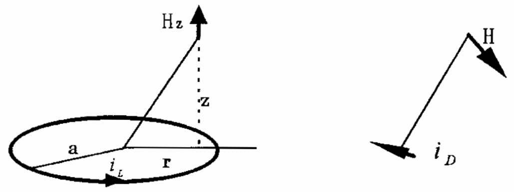
Our new method is based on the following key ideas:

First is the employment of a loop current model, whereas most of inverse analyses have employed the current dipole model. Second is that the estimated currents are represented by loop currents with integral multiple magnitude. This means that our method is capable of estimating both the direction and magnitude of currents. The integral multiple magnitude of a loop current is called the "dynamic range".

B. Loop Current Model

In the magnetic field source searching problems, the current dipole model [2-4] has usually been employed. However, the current dipole model does not always satisfy the continuity equation of currents $\nabla \cdot \mathbf{J} = 0$. This is one of causes leading to the estimation error in the magnetic field source searching. In order to satisfy $\nabla \cdot \mathbf{J} = 0$, a current should be modeled by a combination of the loop currents. Actually, the loop current model always satisfies $\nabla \cdot \mathbf{J} = 0$.

In this paper, it is assumed that the loop currents having a clockwise and counterclockwise directions take the positive and negative values, respectively. The entire current distribution is given by a combination of the loop currents. The Introduction of the loop currents as variables is equivalent to a solution based on the computation of the distribution of a surface density of equivalent dipole moments.



(a)The loop current (b)The current dipole

Fig.1 The loop and dipole currents.

C. Algorithm

The magnetic field source searching is reduced into solving for a following system equation

$$\mathbf{H} = \sum_{i=1}^{m} J_i \mathbf{d}_i = D\mathbf{X}, \tag{1a}$$

or

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$$\begin{bmatrix} H_1 \\ H_2 \\ \vdots \\ H_n \end{bmatrix} = \begin{bmatrix} d_{11} & d_{12} & \cdots & \cdots & d_{1m} \\ d_{21} & d_{22} & \cdots & \cdots & d_{2m} \\ \vdots & \vdots & & \ddots & \vdots \\ d_{n1} & d_{n2} & \cdots & \cdots & d_{nm} \end{bmatrix} \begin{bmatrix} J_1 \\ J_2 \\ \vdots \\ \vdots \\ J_m \end{bmatrix}, \quad m >> n, \qquad (1b)$$

where D, $\mathbf{X}$ and $\mathbf{H}$ are a system matrix determined by the modified Biot-Savart law for loop currents distribution vector to be estimated, and a measured magnetic field vector, respectively. The n and m are the number of measured and estimated points, respectively.

The loop current distribution vector $\mathbf{X}$ is estimated as follows.

1) We assume an arbitrary dynamic range from $-P$ to $+P$, which corresponds to the integral multiple magnitude of a loop current J at each point.
2) The dynamic range $-P$ as magnitude of a loop current is set up at all of the estimated points of currents.
3) A similar process to that of the conventional SPM method is carried out, i.e., the pattern matching figures based on the Cauchy-Schwarz relationship are calculated at the all estimated points. If a point h out of all estimated point takes the maximum of pattern matching figures :

$$\gamma_i = \frac{\mathbf{H}^{\mathrm{T}} \bullet \mathbf{d}_i}{\|\mathbf{H}\| \|\mathbf{d}_i\|}, \quad i = 1,2,\cdots,m, \qquad (2)$$

   then the dynamic range $-P$ of the point h is added to +1. The point h is called the "pilot point" [2-4]. At the same time, the pattern matching figures γ_h of the first process is obtained.
4) Based on the result on process 3), the pattern matching figures are calculated by

$$\gamma_i = \frac{\mathbf{H}^{\mathrm{T}} \bullet (\mathbf{d}_h + \mathbf{d}_i)}{\|\mathbf{H}\| \|\mathbf{d}_h + \mathbf{d}_i\|}, \quad i = 1,2,\cdots,m, i \neq h, \qquad (3)$$

   in order to search for the second pilot point. Then, the dynamic range at the point having the maximum pattern matching figure is added to +1. These processes for all estimated points are continued until the dynamic range +P.
5) Finally, we select an estimated solution having the maximum pattern matching rate in entire processes.

III. MAGNETIC FIELD SOURCE SEARCHING IN FILM CONDUCTOR

A. Numerical Simulations

Fig.2 shows a magnetic field source (current) searching problem. Figs 2(a), 2(b) and 2(c) show a schematic diagram, an exact current distribution in the film conductor, and a computed magnetic field distribution on the measured surface, respectively. The magnetic fields at 400 (20x20) equispaced locations above the film conductor were computed. The current distribution in the film conductor is estimated from these computed magnetic fields [in Fig.2(c)].

In this paper, shading density represents the magnitude of current and of magnetic field. Lighter and darker shadows denote the higher and lower intensities, respectively.

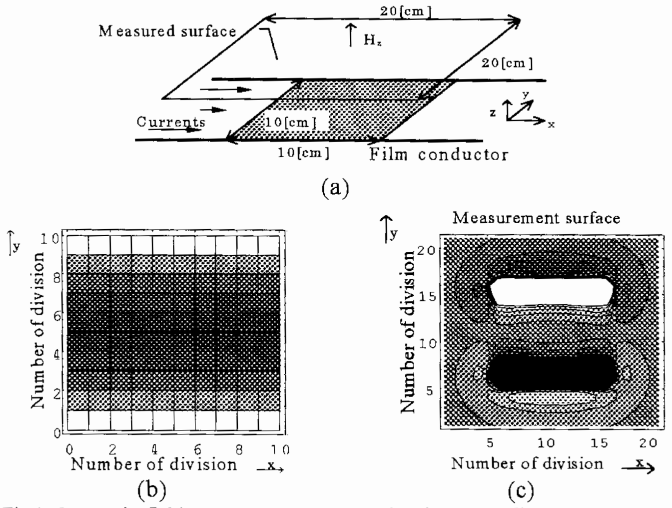

Fig.2. Magnetic field source (current) searching in a thin film conductor. (a) Schematic diagram, (b) the exact current distribution, (c) Measured magnetic field distribution. White is positive and black is negative.

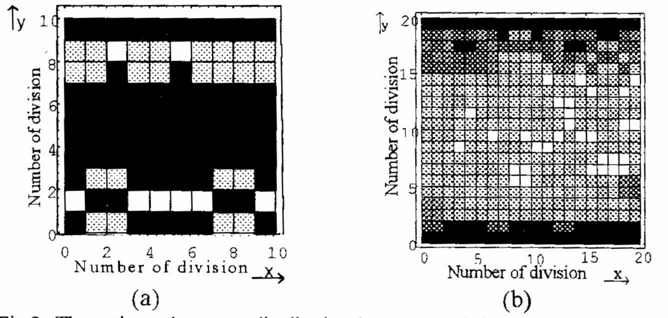

Fig.3. The estimated current distribution by means of the conventional SPM method extended to the loop currents model. (a) The current distribution estimated at 400 (20x20) and (b) at 1600 (40x40) equispaced loop currents.

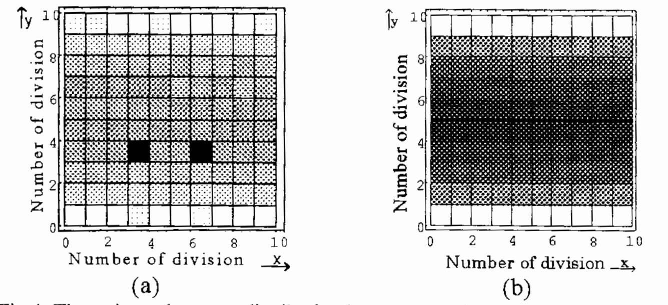

Fig.4. The estimated current distribution by means of the new method. (a) The current distribution estimated having the dynamic range from P=-10 to P=+10 and (b) from P=-100 to P=+100.

Fig.3 shows the estimated results by means of the conventional SPM method. Figs. 3(a) and 3(b) show the estimated current distribution at 400 (20x20) and (d) at 1600 (40x40) equispaced loop currents, respectively.

The results in Fig.3 suggest that the conventional SPM method is capable of estimating the global current distribution. However, the conventional SPM method represents the magnitude of current by a number of unit current dipoles so that it is difficult to estimate the exact current distribution [compare Fig.3 with Fig.2(b)].

Fig.4 shows the estimated results by means of the generalized SPM method. Figs. 4(a) and 4(b) show the estimated current distributions having the dynamic range from P=-10 to P=+10 and from P=-100 to P=+100, respectively. The currents were estimated at 400 (20x20) equispaced loop currents.

Comparison between Figs. 4(a) and 4(b) shows that the increase of the dynamic range P improves the estimation accuracy both the direction and magnitude of the currents. Also, comparison between Figs. 3(b) and 4(b) shows that increasing the dynamic range P makes it possible to obtain a more accurate estimated result than increasing the number of estimated points.

Comparison between the conventional and generalized SPM methods shows that the generalized SPM method yields the more accurate solution.

B. Experimental verification

Fig.5 shows the result for the film conductor having L=12[cm]. Figs. 5(a), 5(b), 5(c) and 5(d) show measurement system, a schematic diagram, measured magnetic fields at 100[kHz] and an estimated current distribution, respectively. The magnetic fields at 525 (25x21) equispaced locations above the film conductor were measured. The magnetic fields H_z in a direction of vertical to a film surface is measured by search coil as shown in Fig.5(a). The currents were estimated at 200 (20x10) equispaced loop currents. The dynamic range was P=-100 to P=+100. Because of the skin effect caused by the 100[kHz] currents, Fig.5(c) reveals that the major currents are flowing along the edges of thin film conductor.

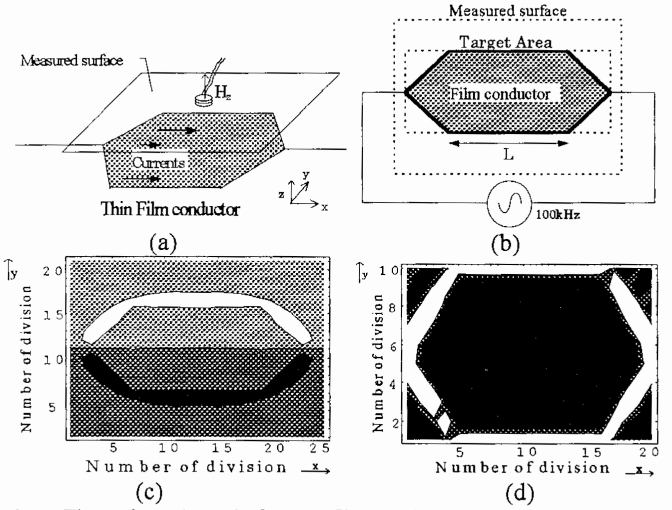

Fig.5. The estimated result for the film conductor having L=12[cm]. (a) measurement system, (b) schematic diagram, (c) measured magnetic fields, and (d) an estimated current distribution.

C. Current distribution in a film transformer

We apply the generalized SPM method to the estimation of current distribution in a film transformer.

Fig.6 shows an estimated current distribution in a simplified model of our film transformer [6]. Figs. 6(a), 6(b), 6(c) and 6(d) show the film transformer, schematic diagram, measured magnetic fields above both the primary and secondary conductors, and an estimated current distribution, respectively. The magnetic fields at 1690 (65x26) equispaced locations above the film conductor were measured. The currents were estimated at 1690 (65x26) equispaced loop currents. The dynamic range was P=-10 to P=+10.

From the result in Fig. 6(d), the current distribution due to the proximate effect can be observed.

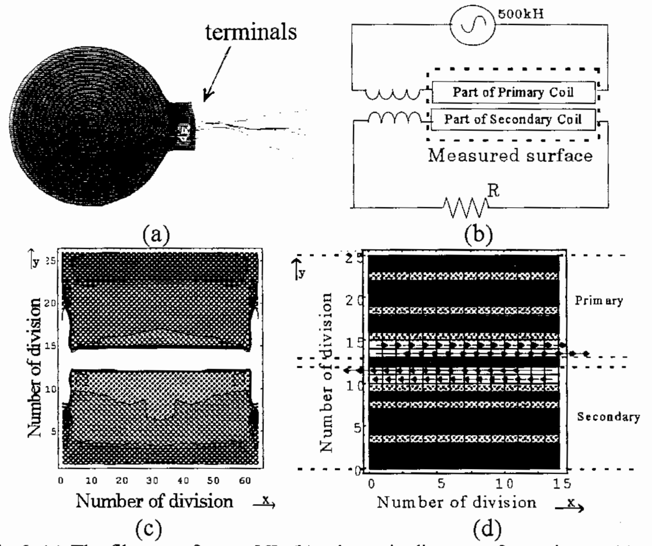

Fig.6. (a) The film transformer [6], (b) schematic diagram of experiment, (c) a measured magnetic field and (d) an estimated current distribution (small arrows refer to the direction of current flow).

IV. CONCLUSION

In the present paper, we have proposed the generalized SPM method. Numerical simulation has verified that the generalized SPM method yields the far superior solutions to these of conventional one.

We have applied the generalized SPM method to the estimation of current distribution in the simplified film transformer. As a result, it has been found that the operation of film transformer depends on the magnetic coupling not only under the skin effect but also under the proximate effect.

Our computational codes have not been fully optimized so that it is possible to improve its efficiency.

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