Evaluation of the effects of the screen based on an analytical solution of a simplified MIT system

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Abstract. Magnetic induction tomography (MIT) is a technology that reconstructs cross sectional conductivity distribution of an object from mutual impedance measurements of coils distributed around the object. In high frequency and low conductivity applications, an outer screen is generally used to confine the magnetic fields and to prevent electromagnetic interference from outside. However, the screen will alter the sensing and excitation field, hence the sensitivity distribution of the coil array. Therefore, the design parameters of the screen (thickness, distance to coil, materials) are important to the performance of the sensor system. This paper presents a simple method based on an analytical solution for the evaluation of the effects of the screen. The advantage of the approach includes efficient modelling of thin screens and physical insights into the effects of the screen.

1. Introduction

Magnetic Inductance Tomography (MIT) has been investigated during the last decade for industrial process applications (e.g. visualising industrial processes such as those in metal production [1]) and for biomedical applications (e.g. determining body composition [2], imaging human thorax and head [3] and imaging brain oedema [4] etc). A set of coils are employed and distributed around the object being imaged and measurements of mutual inductive coupling between the coils are taken and used for image reconstruction. The inductive coupling between the coils changes as the objects are subject to eddy current effects and generate secondary fields. In some applications, an outer screen may be used to confine the magnetic fields and to prevent electromagnetic interference from outside. In addition, it provides a ground to reduce the capacitive coupling between the coils. The introduction of the screen also alters the sensing and excitation field, hence the sensitivity distribution of the coil array. In order to evaluate the effects of the screen and its design parameters (thickness, distance to coil, materials), finite element models (FEM) have been used [5]. In this paper, we present an analytical model for a simplified MIT setup for the evaluation of the effects of the screen. The advantages of the approach include efficient modeling of thin screens and physical insights into the effects of the screen.

2. The simplified MIT and model description
A realistic FEM model could be built to evaluate any EM effects in MIT including the effects of the screen given sufficient computational power. However, such a model may be computationally intensive. Since FEM involves dissecting the domain into small elements and for structures with large geometrical ratio in one direction compared to the other, the general FEM is not efficient. Furthermore, for eddy current problems such as those encountered in MIT, elements sizes have to been smaller or at least comparable to the skin depth to gain acceptable results. This poses difficulties especially for high frequency MIT where frequency reaches 10 MHz and the skin depth for aluminum or copper is less than 100 μm.

Hence, an analytical model with certain simplified features but are capable of modeling the thin structures accurately would be useful to gain physical insight into the effects of such structures. A simplified model is illustrated in Figure 1. The following assumptions are made.

1. The coils are circular and filamentary.
2. Screens are made of homogenous metal.
3. Screens are treated as flat surfaces. This is valid for screens comprising of multi-flat pieces or for circular screens with much larger diameters than the size of the coils.

Based on above assumptions, the model in Figure 1 was used to represent the simplified MIT.

We start from the magnetic vector potentials in regions I, II and III shown in Figure 1. Ignoring the so called ‘wave propagation’ effects, the magnetic vector potentials in each region are as follows [6].

$$A^{(1)}(r, z) = \frac{\mu_0 I_0}{2} \int_0^\infty J_1(\alpha_0) J_1(\alpha r) e^{-\alpha z} | \frac{\text{d} \alpha}{\alpha_0}$$

$$+ \frac{\mu_0 I_0}{2} \int_0^\infty J_1(\alpha_0) J_1(\alpha r) e^{-\alpha_0 z} | \frac{(\alpha_0 + \alpha)(\alpha_0 - \alpha_0) + (\alpha_0 - \alpha)(\alpha_0 + \alpha_0) e^{2\alpha z}}{(\alpha_0 - \alpha_0)(\alpha_0 + \alpha_0) + (\alpha_0 + \alpha)(\alpha_0 + \alpha_0) e^{2\alpha z}} | \frac{\text{d} \alpha}{\alpha_0}$$

$$A^{(2)}(r, z) = \mu_0 I_0 \int_0^\infty J_1(\alpha_0) J_1(\alpha r) e^{-\alpha_0 z} | \frac{(\alpha_0 + \alpha)(\alpha_0 - \alpha_0) + (\alpha_0 - \alpha)(\alpha_0 + \alpha_0) e^{2\alpha z}}{(\alpha_0 - \alpha_0)(\alpha_0 + \alpha_0) + (\alpha_0 + \alpha)(\alpha_0 + \alpha_0) e^{2\alpha z}} | \frac{\text{d} \alpha}{\alpha_0}$$

$$A^{(3)}(r, z) = \mu_0 I_0 \int_0^\infty J_1(\alpha_0) J_1(\alpha r) e^{-\alpha_0 z} | \frac{2\alpha_0 e^{i(\omega z + k z)}}{(\alpha_0 - \alpha_0)(\alpha_0 + \alpha_0) + (\alpha_0 + \alpha)(\alpha_0 + \alpha_0) e^{2\alpha z}} | \frac{\text{d} \alpha}{\alpha_0}$$

(1)

(2)

(3)

Where $\mu_0$ denotes the permeability of free space; while $l$ denotes the height of the bottom of the excitation coil; and $c$ denotes the thickness of the media. $\alpha_0 = \alpha_1 = \sqrt{\alpha^2 + j \sigma_1 \omega}$; $\alpha_2 = \alpha_1 J_1(x)$ is a
first order Bessel function of the first kind. \( I \) is the current flowing through the excitation coil. \( r_0 \) is the radius of the coils.

The \( k \)th sensitivity map (\( k \)th column of the Jacobian matrix) is expressed as the dot product of electrical fields produced by the excitation coil and that by the receiving coil as if it is excited by a unit current:

\[
S_k = -\omega^2 A_i \cdot A_j
\]  

where \( A_i \) and \( A_j \) denote the vector potentials when sensing coils \( i \) and \( j \) are excited with unit current respectively. They can be obtained using equation (1).

3. The effects of the screen for different setups

Figure 2 lists three types of sensitivity maps (self coil, 90 degree coil and 180 degree coil) for different setups.

Figure 3 indicates:
1. That the screen has the effect of reducing the sensitivity;
2. That the screen needs to be at least three times the diameter away from the coil to avoid significant reduction of the sensitivity.
3. That as expected, as the distance between the coil and the screen reduces, and as the thickness of the coil increases, and as the conductivity of the screen increases, the effect of screen becomes more pronounced.
4. That even the thickness of the screen is much less than the skin depth, the screen still has a significant effect on the sensitivity maps.

4. Conclusions and Discussion

This paper presents a simplified model for the evaluation of the screen effects in MIT. The advantages of the model include its capabilities to model very thin screens and have less computational costs. Although in this case, the coil was treated as filamentary, analytical model of coils of finite sizes is available; therefore, the model can be extended to account for a realistic circular coil. The limitations of the model include its simplified constraints on the geometry of the screen and the coil, e.g. the screen has to be flat and the coil has to be circular to make the solution valid. Nevertheless, with this model, it has been possible to gain useful physical insights into the screen effect in MIT without resorting to a full FEM model. In addition, the model might provide information for specifying more accurate impedance boundary conditions required in FEM models.
Figure 3 plots the sensitivities along the line connecting the coils in cases of 180 degree coil. (a) different conductivities, (b) different thickness (c) different distance (d) normalized of (c) with minimum as 1.

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