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Response of the excitation condition to electromagnetic tomography

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ABSTRACT

Electromagnetic tomography (EMT) has potential practical value in the fields of industrial and biomedical detection. The sensitivity, stability and accuracy of the sensor system are significant in the detection of EMT. In this paper, the EMT excitation condition is analyzed through the COMSOL Multiphysics finite element analysis software. The effects on a sensor array of 8 equally spaced inductive coils are discussed in terms of two effects: the direct effect on the received signals due to the change of the excitation condition and the effect of variations on the sensitivity, which is calculated through the received signals. The relationship between the exciting frequency and the received signal is discussed both in the simulation and the experiment; a multi-coil excitation strategy is proposed, and the comparisons are presented. The results clearly show that the higher exciting frequency led to the higher received signal. The selection of the excitation strategy should be considered based on the object field distribution, and it is necessary to increase the coil number for the multi-coil excitation strategy to obtain a better performance. This paper estimates the sensing field status according to the simulation results and provides a theoretical foundation for image reconstruction optimization.

1. Introduction

Flow measurements for metallic and semiconducting melts are a troublesome problem in several industry processes, such as iron casting, silicon crystal growth etc. Some conventional measurement methods have limitations in these measurement environments. For example, ultrasonic techniques are difficult when applied to real processes in high temperature environments or to chemically aggressive melt conditions. The usual optical methods of flow measurement are not adequate for opaque fluids [1–3]. Fortunately, these types of measurement processes have a common characteristic: metallic and semiconducting melts are characterized by a high electrical conductivity [4]. Thus, electromagnetic methods can be used to solve these problems. The conventional standard electromagnetic flow meters with contact electrodes have been widely used in many industries [5]. However, the contact measurement design of a conventional electromagnetic flow meter still has some limitations when applied to the special environments mentioned above. These problems can be solved with electromagnetic tomography (EMT) or magnetic induction tomography (MIT), which is based on the measurement of the induction perturbations of an externally applied magnetic field.

EMT is an increasingly significant branch of electrical tomography [6] that is based on the electromagnetic induction principle. [7] An external magnetic field is exerted on the detected space by an exciting coil, and the induced perturbations of the magnetic field at the periphery of the detected space are measured to acquire the spatial distribution of the conductivity or the permeability [8]. According to the measurements of the observed field, the corresponding image reconstruction algorithm can reconstruct a 2-D or 3-D image of the object's field distribution. EMT has potential applications in many fields. These applications include the tracking of ferrite-labeled powder in separation processes; the detection of foreign material in food, textiles or pharmaceuticals; the detection of defects in metal components; and the monitoring of bulk ionized water in pipelines [9].

The earliest report of EMT is the preliminary feasibility study of the system from Al-Zeibak [10]. The designer hoped to apply this technology to biomedical research. The system acquired multi-projection through the mechanical movement of the detected object and reconstructed the distribution of the object space through the linear back projection algorithm. Korjenevsky et al. had developed a similar EMT experiment system and hoped to apply this system to biological tissue tomography [11,12]. Peyton and Yin et al. proposed a planar EMT system in 2005, which was used to detect defects in metal plates [13]. The spatial arrangement of the coils was different than that used in the EMT sensor array proposed before. The axes of the sensitive coils were distributed in a circle and were perpendicular to the test plate, rather than parallel to it. Peyton and Yin performed simulation research on horizontal plane and conductivity detection using EMT [14]. The results of the research demonstrated that EMT could be applied to geophysics and marine engineering. In recent years, this team has used EMT to inspect a two-phase liquid metal/gas flow, which is based on a continuous casting process. The research results showed that the injection of the argon gas is

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Nomenclature

$\vec{H}$	magnetic field intensity (A/m)
$\vec{J}$	current density (A/m2)
$\vec{D}$	electric displacement (C/m2)
$\vec{E}$	electric field intensity (V/m)
$\vec{B}$	magnetic flux density (T)
$\vec{A}$	magnetic vector potential (Wb/m)
f	excitation frequency (Hz)
n	turn number of coil
l	coil length
e	unit number
V	detected signal
S	sensitivity

Greek letters

ρ	charge density
∇	Hamilton operator
μ	magnetic permeability (H/m)
ε	permittivity
σ	electrical conductivity (S/m)
ω	radian frequency (rad/s)

Subscripts

p	number of projection directions
d	number of detected coils
emp	the conductivity of the unit is the same as that of the background
obj	the conductivity of the unit is different than that of the background

distinguishable from the single phase flow by observing the appearance of the oscillation patterns [2,15]. Soleimani et al., from the University of Bath, redesigned the conventional EMT sensor array from a single-layer array into a multi-layer array. In this configuration, a 3D image can be constructed by stacking several 2D images, improving on the 2D imaging system, for which the results mainly focus on the cross-sectional distribution and no axial (z-axis) information can be provided. The multi-layer array can lead to more potential industrial applications in which the axial information on the electrical and magnetic properties is needed. [16].

Subsequent generations of the EMT system have upgraded the sensor design, the acquisition system, the reconstruction algorithm and other components. However, there have seldom been definite discussions on the excitation condition, which is basic and significant for system performance. Currently, most of the determination methods for the excitation conditions are based on experience. However, different excitation current sources and excitation methods may affect the measurements of a specific spatial circumstance directly. Detailed discussions of this problem have much value for measurement observation and improvement of the EMT system performance. From the basic principles of the electromagnetic field, we utilize the COMSOL Multiphysics finite element method (FEM) simulation software to analyze the characteristics of the EMT sensing field. The main focus of this paper is on the response of the excitation frequency and the excitation strategy. Consequently, the aims of this experimental study are to present the obvious corresponding relation between the excitation frequency and the received signal and provide the factors that must be considered in the selection of the excitation strategy.

The paper is mainly composed of four parts. First, we will introduce the theoretical principle and mathematical processing basis of the simulation. Then, we will describe the simulation setup and the excitation conditions used in this study. After that, we will present the simulation results and the experimental results for various responses of the excitation conditions and circumstances. The paper ends with some conclusions and ideas for future work.

2. Forward problem

The forward problem of EMT is a general eddy current problem. Based on the electromagnetic induction principle, the generalized electromagnetic induction principle, the total current law, and the law of continuity of a magnetic flux, the EMT system presents the differential form of the Maxwell equations as follows [17,18]:

$$\begin{cases} \nabla\times\vec{H}=\vec{J}+\frac{\partial\vec{D}}{\partial t} \\ \nabla\times\vec{E}=-\frac{\partial\vec{B}}{\partial t} \\ \nabla\cdot\vec{B}=0 \\ \nabla\cdot\vec{D}=\rho \end{cases} \tag{1}$$

where ∇ is the Hamilton operator, $\vec{H}$ is the magnetic field intensity, $\vec{J}$ is the current density, $\vec{D}$ is the electric displacement, $\vec{E}$ is the electric field intensity, $\vec{B}$ is the magnetic flux density, and ρ is the charge density.

When a medium exists that changes the characteristics of the magnetic density and the magnetic flux density, the equations above are insufficient. It is necessary to supplement three equations to describe the characteristics of the medium. For an isotropic medium, the equations are as follows:

$$\vec{B}=\mu\vec{H} \tag{2}$$

$$\vec{D}=\varepsilon\vec{E} \tag{3}$$

$$\vec{J}=\sigma\vec{E} \tag{4}$$

where μ is the magnetic permeability, ε is the permittivity and σ is the electrical conductivity.

Substitution of the supplementary equations into the first of Eq. (1) $\nabla\times\vec{H}=\vec{J}+\partial\vec{D}/\partial t$ gives

$$\nabla\times\vec{B}=\mu\nabla\times\vec{H}=\mu\left(\sigma\vec{E}+j\omega\varepsilon\vec{E}\right) \tag{5}$$

$\vec{A}$ is defined as the magnetic vector potential, and its curl is the magnetic flux density, which is described as $\nabla\times\vec{A}=\vec{B}$. Take the curl of the magnetic flux density, $\nabla\times\nabla\times\vec{A}=\nabla\times\vec{B}$, and transform the left side of the expression:

$$\nabla\times\left(\nabla\times\vec{A}\right)=\nabla\left(\nabla\cdot\vec{A}\right)-\nabla^2\vec{A} \tag{6}$$

According to the Coulomb standard condition, which is defined as$\nabla\cdot\vec{A}=0$, Eq. (5) turns into $-\nabla^2\vec{A}=\mu(\sigma\vec{E}+j\omega\varepsilon\vec{E})$. With further transformation, the EMT electromagnetic field magnetic vector