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# Enhancement of EMAT and eddy current using a ferrite back-plate

X. Jian*, S. Dixon

*University of Warwick, Department of Physics, Coventry CV4 7AL, UK*

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**Abstract**

Electromagnetic acoustic transducers (EMATs) often have an electrically conducting surface behind the coil which we refer to as a back-plate, which could be there to act as an electromagnetic screen or could be a permanent magnet which is part of standard EMAT design. Eddy current probes can share many design features with EMATs, and both are designed to generate an eddy current in the electromagnetic skin-depth of a sample. In this paper we present an analytical solution for a quick and accurate calculation of the eddy current generated by a spiral coil and for the case of EMATs we also calculate the resultant Lorentz force which leads to ultrasonic generation. The Lorentz force can arise from an interaction of the eddy current with either a dynamic magnetic field from the coil or with a static magnetic field from a permanent of electromagnet. Theoretical predictions have shown that in the presence of a ferrite back-plate, the eddy current and the Lorentz force are enhanced greatly, and this has been verified experimentally. These developments will lead to improved EMAT and eddy current probe design.


*Keywords:* EMAT; Eddy current; Ferrite; Enhancement

## 1. Introduction

When considering the operation of an electromagnetic acoustic transducer (EMAT) for ultrasonic generation, one needs to consider the system as a whole to include the current pulse generator, the coil and the metal sample [1–6]. The generation efficiency of the transducer and the frequency characteristics of the generated ultrasonic waves are not determined by the coil alone but are dependent on the whole system [6]. In addition to the components of the system, the lift-off between the metal sample and the generating coil has an influence on the mutual inductance between the coil and the metal sample, and the equivalent coil inductance [6], so that lift-off also determines the characteristics of the EMATs operation.

Several publications have investigated the generation of eddy currents and ultrasonic waves based on a sinusoidal excitation current flowing in the coil [1–5,7–9]. An analytical solution of the eddy current produced by an EMAT coil carrying such a current, above a metal has been developed [8] and the ultrasonic generation mechanism has been discussed [1–5,7,9]. EMAT-generated ultrasonic waves have also been investigated experimentally using an EMAT as a particle velocity sensor and a laser interferometer [10]. Finite element methods (FEM) have also been used to simulate pulsed eddy currents and the subsequent ultrasonic waves generated by EMATs [7,11,12].

Eddy current induction [5] and ultrasonic generation [6] can be achieved using a coil alone where current is pulsed or modulated in the coil. However, it is of interest to investigate the eddy current induction and ultrasonic generation in the presence of an electrically conductive back-plate as, certainly for the EMAT, such a back-plate is a common design feature. Where an EMAT is used in a send-receive mode, a thin metal screen if often positioned between the coil and permanent magnet to prevent ultrasonic generation in the magnet. In the case where the coil is directly next to the permanent magnet, the permanent magnet itself may provide an electrically conducting plane or back-plate.

Eddy current induction in a metal sample is due a change in the magnetic flux [1–12] in the sample. The ultrasonic generation efficiency of an EMAT is much lower than that of a PZT transducer and there is an ongoing drive to try and increase the efficiency of EMATs.

Analytical calculations have revealed that eddy current and ultrasonic generation efficiency can be increased in the presence of a ferrite back-plate. We need to distinguish the fact that this is not a core as such and coils are not actually wrapped around

* Corresponding author. Tel.: +44 2476574116; fax: +44 2476692016.
*E-mail address:* x.jian@warwick.ac.uk (X. Jian).

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the ferrite. Experimental measurements confirm the theoretical findings, providing an improvement in the design of EMATs, being applicable to both a coil with or without a permanent magnet. This paper is organized such that we firstly describe the underlying theory and develop analytical solutions for the magnetic vector potential, the eddy current induced in the sample, the Lorentz force generated in the sample skin-depth and the coil inductance. Results are then presented and discussed, comparing theoretical predictions with experimental measurements.

## 2. Theory

### 2.1. Vector potential analytical solution

The magnetic vector potential is introduced by:

$$B = \nabla \times A \tag{1}$$

The differential equation for the vector potential, $A$, in an isotropic, linear and inhomogeneous medium due to an applied sinusoidal current density $i = i_0 e^{j\omega t}$ is given by [9]:

$$\nabla^2 A = -\mu i + \mu\sigma \frac{\partial A}{\partial t} + \mu\varepsilon \frac{\partial^2 A}{\partial t^2} + \mu \nabla \left(\frac{1}{\mu}\right) \times (\nabla \times A) \tag{2}$$

where $\mu$ is the magnetic permeability, $\varepsilon$ the electrical permittivity and $\sigma$ is the electrical conductivity of the medium. Therefore the vector potential is of term has a temporal dependent form of $e^{j\omega t}$. Most coils used for eddy current and ultrasonic generation have axial symmetry, as shown in Fig. 1 for a circular flat 'pancake' coil.

For a better description, we call the material in zone 1 a back-plate. The vector potential is symmetric about the axis of the coil. As there is only a $\theta$-direction component of excitation current density $i$, the vector potential, $A$, also only has a $\theta$-direction component. For simplicity, we still use $A$ for $A_\theta$ in the following arguments. Expanding equation (2) and canceling out the term

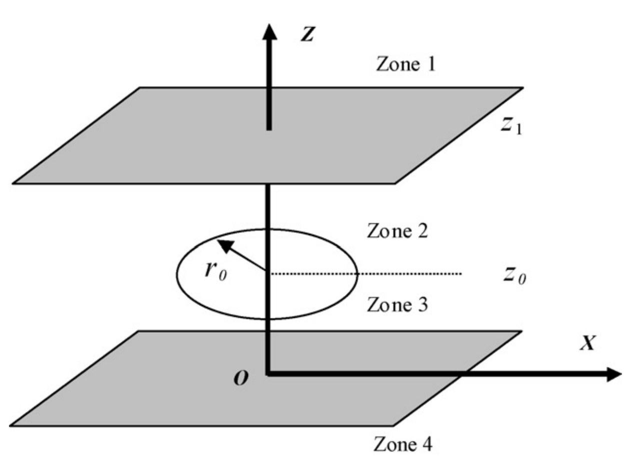


Fig. 1. A coordinate system with a circular coil. The $z$-axis overlaps with the axis of the coil and the $XOY$ plane overlaps with the surface of the bottom metal. The circular coil is parallel to the surfaces of both top and bottom metals, called back-plate and metal sample respectively with corresponding air gaps of $z_1 - z_0$ and $z_0$ between the coil and the two metals respectively. The circular coil is of radius $r_0$ with its axis overlapping with $z$-axis.

$e^{j\omega t}$, one obtains:

$$\begin{aligned}\frac{\partial^2 A}{\partial r^2} + \frac{1}{r}\frac{\partial A}{\partial r} + \frac{\partial^2 A}{\partial z^2} - \frac{A}{r^2} &= -\mu i_0 + j\omega\mu\sigma A - \omega^2 \mu\varepsilon A \\ &\quad - \mu \left\{ \frac{\partial}{\partial r}\left(\frac{1}{\mu}\right) \frac{1}{r} \frac{\partial (rA)}{\partial r} + \frac{\partial}{\partial z}\left(\frac{1}{\mu}\right) \frac{\partial A}{\partial z} \right\}\end{aligned} \tag{3}$$

Assuming the vector potential in zones 1–4 as $A_1$, $A_2$, $A_3$ and $A_4$ respectively, which are obtained after laborious manipulation and are given below [9],

$$\begin{aligned}A_1(r, z, \omega; r_0) &= i_0 r_0 \int_0^\infty \left( \frac{1 - R_{34} e^{-2\alpha_2 z_0}}{1 - R_{21} R_{34} e^{-2\alpha_2 z_1}} \right) \\ &\quad \times \left( \frac{e^{-\alpha_1 (z - z_1) - \alpha_2 (z_1 - z_0)}}{\alpha'_2 + \alpha'_1} \right) J_1(\alpha r_0) J_1(\alpha r)\, d\alpha\end{aligned} \tag{4}$$

$$\begin{aligned}A_2(r, z, \omega; r_0) &= i_0 r_0 \int_0^\infty \left( \frac{1 - R_{34} e^{-2\alpha_2 z_0}}{1 - R_{21} R_{34} e^{-2\alpha_2 z_1}} \right) \\ &\quad \times \left( \frac{-R_{21} e^{\alpha_2 (z - 2z_1 + z_0)} + e^{-\alpha_2 (z - z_0)}}{T_{12}(\alpha'_2 + \alpha'_1)} \right) J_1(\alpha r_0) J_1(\alpha r)\, d\alpha\end{aligned} \tag{5}$$

$$\begin{aligned}A_3(r, z, \omega; r_0) &= i_0 r_0 \int_0^\infty \left( \frac{1 - R_{21} e^{-2\alpha_2 (z_1 - z_0)}}{1 - R_{21} R_{34} e^{-2\alpha_2 z_1}} \right) \\ &\quad \times \left( \frac{e^{\alpha_2 (z - z_0)} - R_{34} e^{-\alpha_2 (z + z_0)}}{T_{43}(\alpha'_3 + \alpha'_4)} \right) J_1(\alpha r_0) J_1(\alpha r)\, d\alpha\end{aligned} \tag{6}$$

$$\begin{aligned}A_4(r, z, \omega; r_0) &= i_0 r_0 \int_0^\infty \left( \frac{1 - R_{21} e^{-2\alpha_2 (z_1 - z_0)}}{1 - R_{21} R_{34} e^{-2\alpha_2 z_1}} \right) \\ &\quad \times \left( \frac{e^{-\alpha_2 z_0 + \alpha_4 z}}{\alpha'_3 + \alpha'_4} \right) J_1(\alpha r_0) J_1(\alpha r)\, d\alpha\end{aligned} \tag{7}$$

where $J_1(\alpha r_0)$ and $J_1(\alpha r)$ are Bessel functions of the first kind. $R_{ij}$ and $T_{ij}$ are reflection and transmission coefficients, and are given by:

$$R_{ij} = \frac{\alpha'_j - \alpha'_i}{\alpha'_i + \alpha'_j} \tag{8}$$

$$T_{ij} = \frac{2\alpha'_j}{\alpha'_i + \alpha'_j} \tag{9}$$

$$\alpha'_i = \frac{\alpha_i}{\mu_i} \tag{10}$$

where

$$\alpha_i \equiv \sqrt{\alpha^2 + j\mu_i \sigma_i \omega - \mu_i \varepsilon_i \omega^2} \tag{11}$$