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Analytical and Fundamental Study of EMATs System

A. Doniavi, M. Eskandarzade, J. Malekani

1University of Urmia, Iran
2Urmia University of Technology, Iran
3University of Tabriz, Iran

Tel.: 0914 354 1326
E-mail: M.Eskandarzade@gmail.com, a.doniavi@mail.urmia.ac.ir, j.malekani@gmail.com

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Abstract: Electromagnetic Acoustic Transducers (EMATs) is one of the most important methods in NDE field that generate ultrasonic waves due to Lorentz and magnetostrictive forces. However, only the Lorentz mechanism is present in non-magnetic conducting materials. In most of the previous researches the effect of dynamic magnetic field has been neglected. Where is, it is significantly influence the wave propagation phenomena in an EMAT system. In this study have been investigated the Lorentz type EMAT system and complete equations of ultrasonic wave excitation force is derived. The developed equation shows that the dynamic component of total Lorentz force is in a different direction with static magnetic field one. And in some cases this type of force is significantly influence the total Lorentz force. Copyright © 2008 IFSA.

Keywords: EMATs, Acoustic, Force density, Lorentz mechanism, Magnetostrictive force, Static magnetic field

1. Introduction

In spite of this fact that the fabrication of first electromagnetic acoustic Transducers has been performed in many years ago, however, the accurate mechanism of ultrasonic generation in an EMAT system is still unknown. Many researches has been established to explain the relationship between electromagnetic and electrodynamics foundations in such systems [1-2]. A valuable effort has performed by Thompson (1978) to model the ultrasonic generation in ferromagnetic material [3]. The magnetization and magnetostrictive effects of EMATs in ferromagnetic materials are observed in the study of Shkarlet (1974) [4].
Numerical simulation of EMAT systems can be found in references [4-6]. Maxfield and Fortunko developed the theory of electromagnetic and acoustic fields for generating Rayleigh surface wave by a meander coil configuration in ferromagnetic metal [7].

A considerable theoretical model of EMATs has been established based on the equations of electromagnetic field on the sinusoidal steady state [3-11].

In an EMAT system static magnetic field is induced by magnets upper on a sample. There are coils that located approximately close to the surface of the sample but not in contact with it and are excited by RC current. The coils induce dynamic magnetic field in a skin depth of a sample. If the sample is be a magnetic material the eddy currents will be produced because of present of dynamic magnetic field. The interaction of static magnetic field and induced eddy currents will be cause to launch a force on a material according to the Lorentz Mechanism. Though, in Lorentz type EMAT system, this force is known as a dominant one, but however, there are other sources of force in an EMAT system including magnetization and magnetostrictive forces that affect the wave propagation phenomena.

Dynamic magnetic field is important not only because of its participation in eddy currents production mechanism, but also because of this fact that it is significantly influence the wave propagation phenomena in an EMAT system. In most of previous researches, the effect of dynamic magnetic field in produced Lorentz force is neglected, but the recently published researches [10] show that that it is mostly influence the total force. In this research the Lorentz type EMAT system have been investigated and complete equations of ultrasonic wave excitation force has derived.

2. Theoretical Background

Guided waves are elastic waves propagating along a thin walled structural boundaries, based on the structure geometry and particle movement with respect to the wave propagation direction guided waves are usually categorized into Rayleigh wave which propagates along the surface of a semi-infinite media and lamb wave, which propagates in a thin walled structure with traction free boundaries.

Electro magnetic acoustic transducers (EMATS) is ultrasonic transducer that can generate guided waves like Rayleigh, lamb and shear horizontal (SH) waves in metal materials in the hollow cylinder. Two types of guided waves are possible to propagate. One of them is a plane-strain vibration wave which is similar to lamb wave and another is a longitudinal shear vibration which is similar to the SH wave that is considered in this research because of it’s widely application.

The analytical derivation of frequency equation of the guided circumferential SH waves begin with Navies equation of motion (1), where $\mathbf{u}$ is the displacement vector $\lambda$ and $\mu$ are lame’s elastic constants, respectively.

$$\mu \nabla^2 u + (\lambda + \mu) \nabla \cdot u = \rho \left( \frac{\partial^2 u}{\partial t^2} \right)$$  \hspace{1cm} (1)

Considering Hook’s low and Thomson (2) representation the maximum material particle displacement (wave amplitude) is proportional with a force on particles (F) and wave velocity in a material, means:

$$A \alpha \left( v, fda \right)$$  \hspace{1cm} (2)

The wave velocity is depends on a material type and a total force on a material particles is effected by sensor’s parameters.
3. Modeling of EMAT System

In practical applications, Magnetic field quantities are greater than Electrical ones, so the operation of Magnetic field that obeys Ampere’s law is completely separated from the operation of electrical field which obeys Farade’s law.

In EMAT system the sample under the coils caring eddy currents and is located under the static Magnetic field that varied with displacement. In this condition, in addition to Lorenz force, there are other sources of force are act on Magnetic dipoles that can be written:

\[
F = \text{idl} \times (B \cdot i_x + B_y i_y + B_z i_z)
\]

By considering current direction the total force on dipoles is result:

\[
f = f(x) + f(x + \Delta x) + f(y) + f(y + \Delta y) = i\Delta x\Delta y [\frac{B_x(x + \Delta x)}{\Delta x} i_x - \frac{B_x(x + \Delta x) - B_x(x)}{\Delta x} i_z + \frac{B_y(y + \Delta y) - B_y(y)}{\Delta y} i_y - \frac{B_y(y + \Delta y)}{\Delta y} i_y - \frac{B_z(y + \Delta y) - B_z(y)}{\Delta y} i_z] \]

Then,

\[
\lim_{\Delta x \to 0} f = M[\frac{\partial B}{\partial x} i_x - (\frac{\partial B}{\partial x} i_x + \frac{\partial B}{\partial y} i_y) i_z + \frac{\partial B}{\partial y} i_z]
\]

By considering Guess law in Magnetic, it can be written:
By doing some simple calculations the total force on magnetic dipoles of material in an EMAT system is be:

\[ F = \mu_0 (M \nabla) H + \mu_0 J_f \times H \]

(7)

This force acts on a volume element of material. Each element is tolerating an other force due to performed deformation in material under stress. This force is appearing as a divergence of a stress term and is known as a Maxwell stress tensor.

\[ T_k = -c : \nabla u \]

(9)

Maxwell stress tensor is expressed as:

\[ T_c = \frac{1}{2} \mu_0 H^2 I - \mu_0 HH \]

(10)

So the total force will be:

\[ f_k = \mu_0 J_f \times H + \nabla.X + \mu_0 H \nabla.M \]

(11)

4. Considering Dynamic Magnetic Field

In most of the last researches the effect of the Lorentz force has been neglected. Because the researchers were believed that magnetic field due to coils are lower than static magnetic field. However, the newer studies show that dynamic magnetic field has significant effect on total launched force [5]. The direction of the forces has been shown in Fig. 2, where index ‘d’ and ‘s’ are used for dynamic and static magnetic field, respectively. As it has been shown, dynamic magnetic field is in a direction that tries to run away the sample from the coil. Plan XZ is in a same direction with a part and Z axis is perpendicular to the paper surface. It suppose that, the direction of static magnetic field is in opposite of ‘y’ axis. Also, the direction of current in meander coil is in direct of Z axis. Eddy current that induced in a sample is in an opposite direction of source current. So, for Lorentz force it can be written like:

\[ f_i = f_s + f_d \]

(12)

\[ f_s = \mu J_f \times M_s + \mu J_f \times H_s \]

(13)

\[ f_d = \mu J_f \times M_d + \mu J_f \times H_d \]

(14)
or

\[ f_s = -J_f \vec{K} \times (B_{xt} \vec{i} + B_{yt} \vec{j}) = +J_f B_{yt} \vec{i} - J_f B_{xt} \vec{j} \] (15)

\[ f_d = -j_f \vec{k} \times (B_{dt} \vec{i} + B_{dt} \vec{j}) = -J_f B_{dt} \vec{j} \] (16)

So the total Lorentz force in an EMAT system will be:

\[ f_s = J_f B_{yt} \vec{i} - j_f (B_{xt} + B_{dt}) \vec{j} \] (17)

Fig. 2. Directions of static and magnetic fields.

5. Conclusion

In most previously published researches, the effect of dynamic magnetic field on Lorentz force has been neglected. However, due to the importance of this force, it is taking into account at solution in this study. This model is applicable to solve the received voltage based on material, coil type and lift-off parameters. The offered model can be used to solve Finite Element Model of EMAT System. As a result the EMAT model can be completed perfectly.

References


Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in Sensors & Transducers Journal will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually.

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Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

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