A Theoretical Investigation of the Penetration Depth in Motion Induced Eddy Current Testing

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Abstract

Conventional eddy current testing is a well-established technique in the non-destructive evaluation of materials which is limited by the fact that due to the penetration depth only defects close to the surface of the component can be detected. In this paper the concept of motion induced eddy current testing is presented which makes use of the relative motion between a permanent magnet and the test object. The corresponding Lorentz force influences the motion of electrons and disturbances in the current flow due to defects can be measured. The results are penetration depths two orders of magnitude larger than those recorded for conventional eddy current testing. In this way even deep lying defects can be detected yielding a considerable improvement compared to conventional eddy current testing.

Keywords: eddy current testing. Lorentz force. Penetration depth.

(1) Introduction

Eddy currents are generated in conducting materials because of the electromagnetic induction effect. According to Faraday's law

$$U_{ind} = -\frac{d}{dt}\,\Phi_{mag} = -A\,\frac{d\,B}{dt} \tag{1}$$

a voltage is induced as a result of a time dependent magnetic field. The corresponding currents flow in closed loops perpendicular to the magnetic field and are known as eddy currents. Eddy currents are induced in the conducting material due to (1) B being explicitly time dependent, or (2) the relative motion between a permanent magnet and the conductor.

Option (1) describes the method used in conventional eddy current testing ECT. ECT is an electromagnetic testing technique that is successfully applied, for example in composite materials or in carbon fibre reinforced plastics [1,2]. Alternatively, it can also be applied for thickness and conductivity measurements [3].

If there are defects present in the specimen, the flow of electrons is obstructed which can be measured by a change of impedance in the test coil. It follows from the diffusion equation that the wave penetrates the material only up to a skin depth δ that according to

$$\delta\,(f) = \frac{1}{\sqrt{\pi\, f\, \mu_r\, \mu_0\, \sigma}} \tag{2}$$

depends on the conductivity, the permeability of the material, and the frequency f of the wave. As a result, skin depths of the order

$$\delta\,(f = 1\,kHz) \sim\ 5\ \cdot 10^{-3}\,m$$

are observed in the case of good conductors. The full $\delta\,(f)$ dependence for several materials is depicted in Figure 1 below.

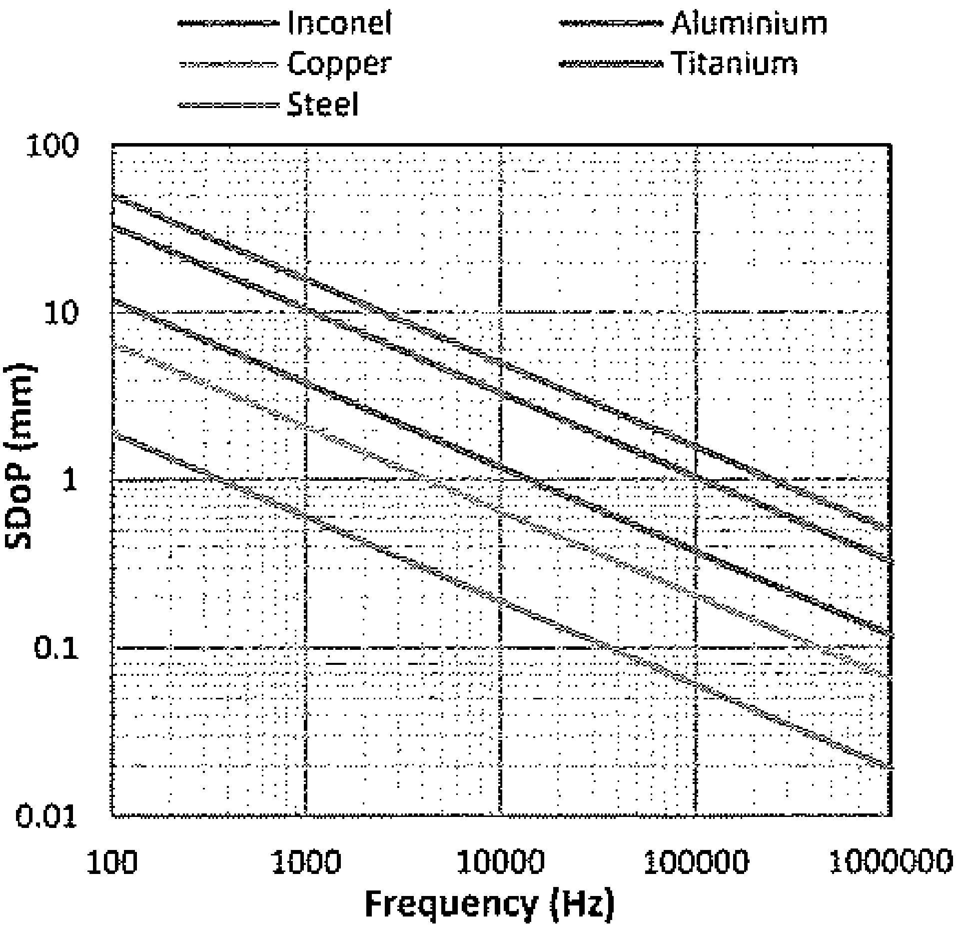

Figure 1: Skin depth δ as a function of frequency f for several materials. Adopted from ref [4]

Because of this skin effect ECT can only be applied for surface inspections such as heat exchanger surfaces and applications in the petrochemical or aerospace industry [5,6]. To overcome some of the disadvantages of conventional ECT the eddy current array technique was developed which uses a series of single elements in a row to benefit a faster and improved flaw detection [7].

Option (2) of above refers to Lorentz force eddy current testing. This idea was first introduced in reference [8] and then further investigated in reference [9] using the motion of a free-falling permanent magnet in an electrically conducting pipe. Studying this method further is the aim of this paper. In particular, we demonstrate how the conventional eddy current testing technique can be improved so that discontinuities even deep inside the material are detected. It is investigated how the skin depth depends on the relative motion between magnet and specimen. Furthermore, it is shown that δ comes out orders of magnitude larger than in conventional ECT so that Lorentz force eddy current testing offers indeed a real improvement of the testing technique. A detailed comparison between Lorentz force and conventional ECT is presented in references [10,11] with regards to defect detection limits. New applications and challenges regarding the use of eddy currents in the non-destructive evaluation of materials are the subject of reference [12].

This paper is organized as follows. In the next section it is shown how the Lorentz force can be used to produce eddy currents in the conducting material. An alternative expression for the penetration depth will be derived and numerically evaluated. From the respective results conclusions are drawn regarding the applicability and suitability of the method.

(2) Lorentz Force Eddy Current Testing

In Lorentz force eddy current testing eddy currents are obtained by the relative motion of a stationary magnetic field produced by a permanent magnet. If the permanent magnet moves with velocity v relative to the specimen, a Lorentz force

$$F = q\,(v \times B) \tag{3}$$

is exerted on the conductor. The Lorentz force acts on a moving particle of charge q in a magnetic field B. As F is perpendicular to v by construction the magnetic force does no work, and the charged particle follows a circular path in the magnetic field; its radius is related to the particle speed v as

$$m \frac{v^2}{r} = q\, v\, B$$

$$r = \frac{m\, v}{q\, B} \tag{4}$$

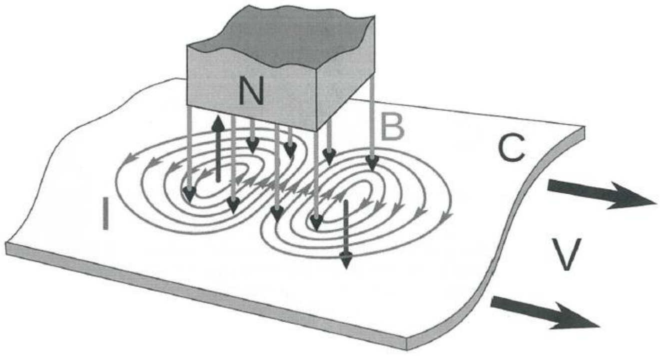

Figure 2: Eddy Currents produced by a moving permanent magnet. Adopted from the web source https://physcs.stackexchange.com

For the technique to be successful the design of the magnet is important. R Schmidt et al [13] present a special arrangement of multiple permanent magnets that augment and focus the magnetic field. In reference [14] a rotating permanent magnet is used to cause a torque

$$M = \int \big(r \times (j \times B)\big)\; dV \tag{5}$$

on the current density j. If j defines via

$$j = \frac{N}{V}\; q\; \overline{v} \tag{6}$$

the average velocity of the charged particle, then Eq. (5) simplifies to

$$M = \sum_{i=1}^{N} (r_i \times F_i) \tag{7}$$

The total torque is the sum of the torques acting on each individual particle. Disturbances in the current density due to defects are detected and measured.

K Weise et al [15] propose a procedure for determinung the optimum magnetic structure for Lorentz force eddy current testing. In general, one can say that the important parameters for the magnetic design are the conductivity of the specimen, the relative velocity of the magnet, the strength of the magnetic field, and the distance h between magnet and conductor.

In the next section a permanent magnet in the vicinity of a linearly moving conductor is discussed and an expression for the penetration depth useful for motional eddy current testing is presented and evaluated.

(3) Results

The skin depth for motional ECT is derived from the differential equation for the space and time dependent current density $j_z\,(x,t)$ of a conducting material, namely

$$\left(\frac{\partial^2}{\partial\,x^2} - \mu_r\;\mu_0\;\sigma\;\frac{\partial}{\partial t}\right)\; j_z\,(x.t)\;=0 \tag{8}$$

Here the coordinate z describes the direction of the current while x symbolizes the depth within the material. Eq. (8) is solved by the ansatz $j_z\,(x,t) = A\,e^{-\,\kappa\,x}\;e^{-i\frac{v}{L}\,t}$

Inserting $j_z\,(x,t)$ into Eq. (8) yields the algebraic equation

$$\left(\kappa^2 + i\,\frac{v}{L}\;\mu_r\;\mu_0\,\sigma\right)\; j_z\,(x,t)\;=0 \tag{9}$$

with the complex solution

$$\kappa = \sqrt{\frac{v\;\mu_r\;\mu_0\,\sigma}{2\,L}}\;\,(1-i) \tag{10}$$

for the parameter κ. The penetration depth δ is defined as the x-value where $e^{-\,\kappa\,x} = e^{-1}$. It thus follows

$$\delta = \;(Re\;\;\kappa)^{-1}\;\;= \sqrt{\frac{2\,L}{v\;\mu_r\;\mu_0\;\sigma}} \tag{11}$$

The skin depth δ of Eq (11) for motional eddy current testing agrees with that of conventional eddy current testing if we replace the frequency ω with

$$\omega = {}^{v}/_{L} \tag{12}$$

Furthermore, a numerical evaluation of Eq. (11) for the case of good conductors, yields

$$\delta\,(v = 1\ {}^{m}/_{s}) = 5\ \cdot\ 10^{-2}\,m \tag{13}$$

Comparison with the corresponding result of Eq. (2) for conventional eddy current testing shows an increase in the penetration depth by roughly one order of magnitude. Lorentz force eddy current testing thus leads to a real improvement compared to conventional ECT as now even deep lying defects have the potential of being detected. The full functional behaviour of $\delta\ (v)$ is depicted in Figure 3 below.

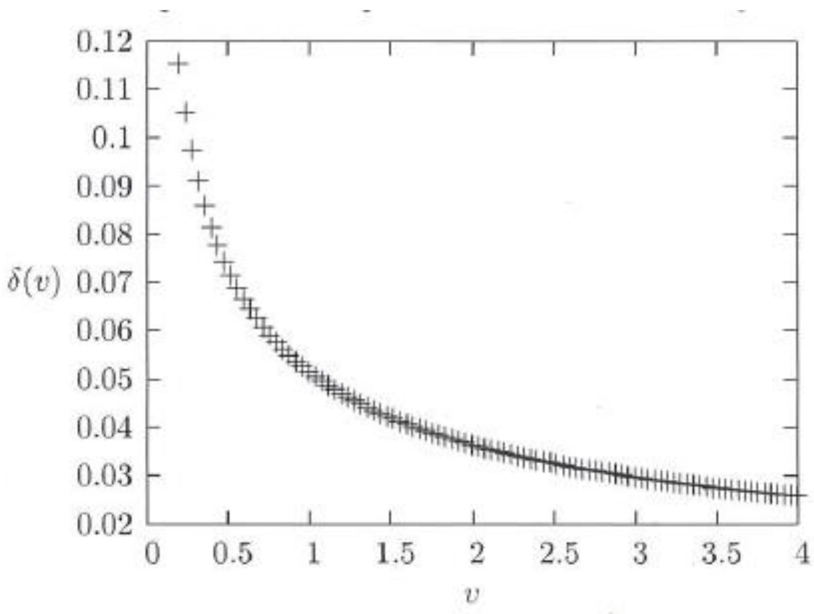

Fig 3: Penetration depth δ as a function of velocity v in the case of Lorentz force eddy current testing.

Note that δ decreases as a function of v with $\delta \sim v^{-\,{}^{1}/_{2}}$. Also note the qualitative agreement with the results of reference [16] which are based on a model experiment and thus serve as an experimental confirmation of the theoretical data presented in this study. Lorentz force eddy current testing is thus a useful and workable method for the detection and localization of defects in specimen. Limits for the measurement technique are determined by the signal quality. The signal to noise ratio can be improved by using either Fourier filtering or suitable error correction techniques as established by signal processing.

For future work yet more numerical simulations and experimental applications are necessary as a benchmark for research on motion induced ECT.

(4) Conclusions

A new NDT method of Lorentz force eddy current testing is introduced which is based on the relative motion of a stationary magnetic field produced by a permanent magnet. It is shown that compared to conventional ECT skin depths are increased by at least one order of magnitude so that much deeper lying defects may be detected using this method. Lorentz force eddy current testing thus has the potential to overcome the cancelation of the current density near the centre of the conductor and is a real improvement compared to conventional NDT methods.

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