Lorentz Force Eddy Current Testing

A Novel Electromagnetic NDE Technique

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***Abstract*—A novel electromagnetic nondestructive evaluation technique, so-called Lorentz force eddy current testing (LET), is presented enabling the detection of defects lying deep inside a moving nonmagnetic conducting material.**

***Keywords*—Lorentz force; eddy current testing; permanent magnet; inverse problem; deep lying defects; finite element analysis**

I. INTRODUCTION

Computations of eddy current problems involving parts in motion have undergone an extensive research over the past decades. A keen interest in this area has been demonstrated recently by numerous publications in many fields of research concerning coupled multiphysics problems. They mainly include different types of electromechanical devices in applications such as electrical machine design [1], inductive heating [2], magnetohydrodynamics [3], and nondestructive testing [4].

II. PROBLEM DESCRIPTION

A. Basic Principle

The Lorentz force eddy current testing technique (LET) represents a modification of the common eddy current testing (ECT) [5]. In LET, the induction of eddy currents in the conductor under test is obtained by the relative motion with respect to the static/primary magnetic field. If there is a defect in the material, the perturbation of induced currents or its secondary magnetic field is detected by a change in the Lorentz force acting on the permanent magnet (Fig. 1).

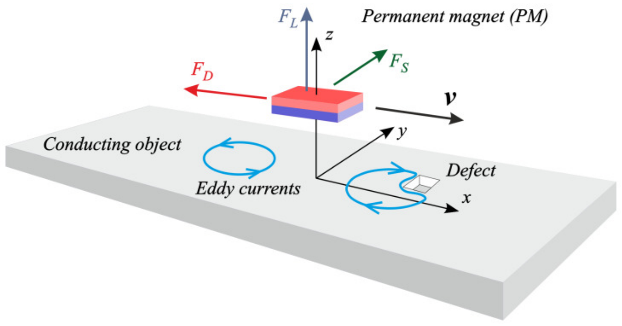

Fig. 1. Lorentz force eddy current testing principle: a conductor is moving with velocity v with respect to a permanent magnet, causing Lorentz force components (drag force F_D, lateral force F_S, lift force F_L) exerting on the magnet as well.

This principle of motion induced eddy currents can be used to overcome the drawback of the common ECT, the limitation by the frequency dependent skin effect [5]. Consequently, it is expected that LET can be used to detect defects lying deeper inside conducting materials when the inspection is performed at similar testing speeds.

B. Experimental Setup

The LET measuring system built in our laboratory, which is used for all experiments is shown in Fig. 2. For arbitrary positioning of artificial defects, the solid conductor is approximated by a package of metallic sheets (Aluminum, each 2mm thick). In order to provide relative motion between the specimen and the magnet, a linear belt-driven servo-drive is used. The neodymium permanent magnet is mounted directly on a three component force sensor that is built in strain gauge technology providing medium accuracy and high dynamics built in strain gauge technology providing medium accuracy and high dynamics [6].

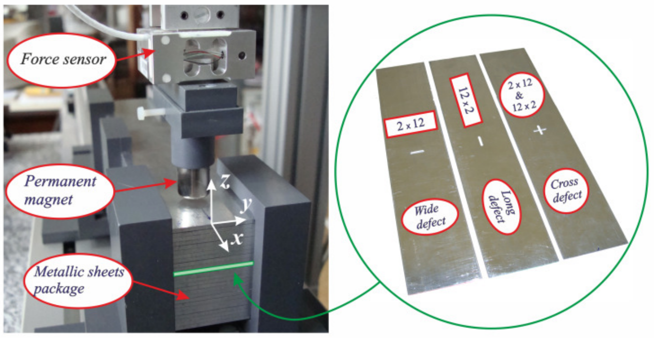

Fig. 2. Experimental LET setup for testing of a conducting bar, which has been substituted by a metallic sheet package, and three sample sheets each including an artificial single defect.

III. NUMERICAL METHOD

The basic configuration of the LET model under investigation is shown in Fig. 3. The cylindrical permanent magnet described by the magnetization vector $\boldsymbol{M}$ is moving with constant velocity $\boldsymbol{v}$ and lift-off distance z_0 from a conductor containing an artificial defect at depth d. Due to the symmetry of the model with respect to the $X0Z$-plane, the side component (F_S) of the LF acting on the PM vanishes.

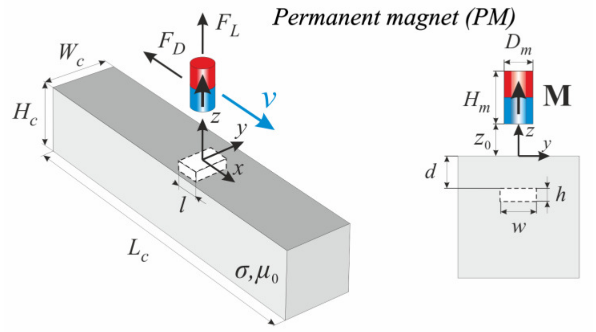

Fig. 3. Basic LET model configuration used in numerical simulations.

The analysis for various testing velocities and defect shapes has been performed to test their influence on the resulting Lorentz force acting on the permanent magnet. The experimental and numerical methods used for solving the given LET problem are described briefly.

The LET physics are governed by the general magnetic field induction equation. Depending on the definition of the frame of reference, two equivalent types of governing equations together with the optimal electromagnetic formulation for 3D LET investigations can be distinguished.

In the fixed frame of reference, the global coordinate system is associated with the conducting object, and the permanent magnet is moving with velocity *v* along *x*-axis. The governing equations can be derived using the magnetic vector and electric scalar potentials defined as $\mathbf{B}=\nabla\times\mathbf{A}$ and $\mathbf{E}=-\partial\mathbf{A}/\partial t-\nabla V$. In this study the moving frame of reference has been used, where the global coordinate system is associated with the moving permanent magnet, i.e. the conducting object moves in the opposite direction along the *x*-axis with velocity *v*. In this case, a velocity term $\mathbf{v}\times\mathbf{B}=\mathbf{v}\times\nabla\times\mathbf{A}$ has to be introduced [7]

$$\nabla\times\left(\frac{1}{\mu_0}\nabla\times\mathbf{A}-\mathbf{M}\right)=-\sigma\left(\frac{\partial\mathbf{A}}{\partial t}+\nabla V-v\times\nabla\times\mathbf{A}\right). \quad (1)$$

If the conducting object moves with a constant velocity and has a constant cross-section normal to the direction of motion, e.g. the object is free of defects, (1) can be simplified to

$$\nabla\times\left(\frac{1}{\mu_0}\nabla\times\mathbf{A}-\mathbf{M}\right)=-\sigma\left(\nabla V-\mathbf{v}\times\nabla\times\mathbf{A}\right), \quad (2)$$

$$\nabla\cdot\left[\sigma\left(\nabla V-\mathbf{v}\times\nabla\times\mathbf{A}\right)\right]=0. \quad (3)$$

Following the Newton's 3rd axiom, the total force $\mathbf{F}_{PM}$ acting on a permanent magnet can be calculated indirectly using the Lorentz force acting on the conductor

$$\mathbf{F}_{PM}=-\mathbf{F}_{L}=\iiint_{\Omega_c}\mathbf{j}\times\mathbf{B}\,d\Omega, \quad (4)$$

where $\mathbf{j}$ is the induced eddy currents density vector, and Ω_c represents the volume of the conducting object. Considering the LET problem shown in Fig. 1, the governing equation finally can be further simplified [7].

IV. RESULTS

All geometrical and material parameters used for the analysis, which are obtained from corresponding measurements. The specimen (Aluminum bar, 50mm x 50mm x 250mm), used in the experiments is approximated with a laminated package of metal sheets (Fig. 2) enabling easy defect positioning at different depths. The tests are performed with a speed of v = 0:5 m/s whereas the lift-off distance of the magnet was fixed to 1mm. This approximation is handled numerically by introducing an anisotropic electrical conductivity, which has zero value in the z-axis direction [7].

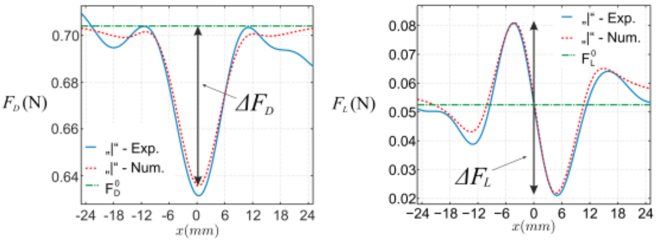

Fig. 4. Characteristic Lorentz force perturbations ΔF obtained for long defect (12mm x 2mm, see Fig.2) placed at depth d = 2mm. F_D and F_L define the drag force and lift force, respectively, whereas F_D^0 and F_L^0 are the reference Lorentz force components, measured for the bar without defect (705 mN and 56 mN, respectively).

In Fig. 4 are shown the results of defect detection for a single defect located 2mm below the surface of the sheet package. Numerical and experimental results are in very good agreement. Further results will be given in the full paper. With the available experimental setup such defects could be detected (so far) up to a depth of 6mm.

V. CONCLUSION

The 3D numerical analysis of LET benchmark problems have been performed providing reference results to understand the feasibility and testing capabilities of Lorentz force eddy current testing. The simulation results are validated by experiments, which underline the ability of LET to detect defects lying deep inside conducting objects.

ACKNOWLEDGMENT

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