07 - 10 September 2009

PROCEEDINGS

54. IWK

Internationales Wissenschaftliches Kolloquium
International Scientific Colloquium

Information Technology and Electrical Engineering - Devices and Systems, Materials and Technologies for the Future

Faculty of Electrical Engineering and Information Technology

TECHNISCHE UNIVERSITÄT
ILMENAU

Impressum

Herausgeber: Der Rektor der Technischen Universität Ilmenau
Univ.-Prof. Dr. rer. nat. habil. Dr. h. c. Prof. h. c.
Peter Scharff

Redaktion: Referat Marketing
Andrea Schneider

Fakultät für Elektrotechnik und Informationstechnik
Univ.-Prof. Dr.-Ing. Frank Berger

Redaktionsschluss: 17. August 2009

Technische Realisierung (USB-Flash-Ausgabe):
Institut für Medientechnik an der TU Ilmenau
Dipl.-Ing. Christian Weigel
Dipl.-Ing. Helge Drumm

Technische Realisierung (Online-Ausgabe):
Universitätsbibliothek Ilmenau
ilmedia
Postfach 10 05 65
98684 Ilmenau

Verlag: isle
Verlag ISLE, Betriebsstätte des ISLE e.V.
Werner-von-Siemens-Str. 16
98693 Ilmenau

ISBN (USB-Flash-Ausgabe): 978-3-938843-45-1
ISBN (Druckausgabe der Kurzfassungen): 978-3-938843-44-4

Startseite / Index:
http://www.db-thueringen.de/servlets/DocumentServlet?id=14089

LORENTZ FORCES EDDY CURRENT TESTING FOR MOVED CONDUCTIVE OBJECTS

Yahia Cheriguen; Hartmut Brauer; F. Hermann Uhlmann

Faculty of Electrical Engineering and Information Technology, Ilmenau University of Technology,
98693 Ilmenau, Germany

ABSTRACT

Eddy current testing (ECT) is one of the most used non-destructive methods to test the safety of conductive materials. In this paper, a new methodology based on the Lorentz forces is investigated to detect cracks in defected conductive parts. The goal of this work is to demonstrate that the forces generated by the interaction between eddy currents flowing in the object under test and the primary constant magnetic field due to a permanent magnet, can be used successfully to detect cracks. A 2D numerical modelling and simulations with and without cracks are performed.

Index Terms - Non-destructive testing, Eddy currents, electromagnetic forces calculation, 2D ectromagnetic field computation, Lorentz-Forces-NDE.

1. INTRODUCTION

Eddy current testing is one of the often used non-invasive methods to detect cracks or defects in conductive materials [1-3]. A frequency depended exciting current is commonly used to measure the change of the voltage on the pick-up coil caused by the crack in the specimen under test. To detect cracks sensitively, a large rage of frequencies (Swept Frequency Methods) [4] or pulsed eddy-current [5,6] methods are systematically used. However, it is difficult to detect internal cracks, due to the skin effect.

The principle of the Lorentz Forces Eddy current testing for moved conductive objects is sketched in figure 1.

A constant magnetic field is created by a permanent magnet or a set of permanent magnets. The conductive object (the plate) under test is moved with a certain velocity closely to the magnet. As result, eddy currents are flowing in the volume of the tested conductive object, generating finally Lorentz forces. These forces are influenced and disrupted by the presence of cracks in the plate. In this way, we can use the generated Lorentz forces to detect cracks in the tested system.

2. THE 2D NUMERICAL - FINITE ELEMENT MODELING

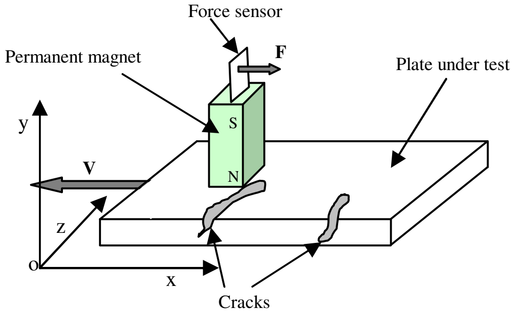


Figure 1. Lorentz forces ECT Method

Let us to consider the system shown in the figure 1. Lorentz forces eddy current testing method requires relative movement between the permanent magnet and the material under test. We suppose the system sufficiently long in the z direction. That means the physical variables doesn't change in this direction (z direction). In this case a 2D Cartesian modeling can be performed.

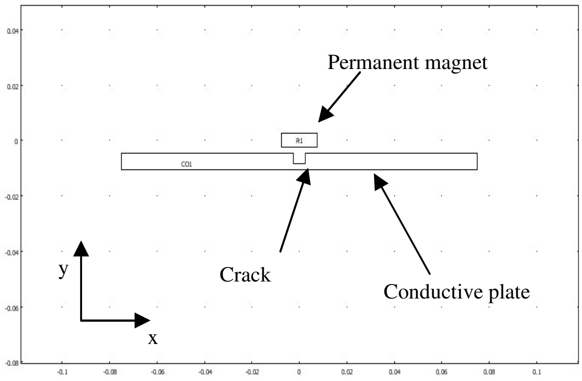


Figure 2. 2D model geometry

From the Maxwell equations, under the quasi-static assumption, we can easily obtain the field equation governing the system of the figure 1. This equation is:

$$\sigma\frac{\partial \mathbf{A}}{\partial t}+\nabla\times\left(\frac{1}{\mu}\nabla\times\mathbf{A}\right)-\sigma\mathbf{v}\times\left(\nabla\times\mathbf{A}\right)=0 \qquad (1)$$

where $\mathbf{A}$ is the magnetic vector potential and has only z-component; σ is the electrical conductivity of the tested material and $\mathbf{v}$ its velocity in the x-direction. For systems with permanent magnets the equation 1 can be rewritten as:

$$\nabla\times\left(\frac{1}{\mu}\nabla\times\mathbf{A}-\mathbf{B_r}\right)-\sigma\mathbf{v}\times(\nabla\times\mathbf{A})=0 \qquad (2)$$

$\mathbf{B_r}$ .is the remanent flux density of the permanent magnet. Note that $\mathbf{B_r}$ has only the y-component.

3. LORENTZ FORCES COMPUTATION

In the Lorentz forces ETC, the force computation is fundamental. The numerical model can predict the force density distribution in the plate or the total force acting on the plate or on the magnet. But the interesting quantity is the total force because only the total force can be measured in the laboratory. The force sensor returns the force acting on the permanent magnet which is equal and in the opposite direction to the force acting on the plate.

The literature provides three different methods for the force computation used in the numerical modeling: Maxwell stress tensor, Virtual displacement method and the Lorentz force formula.

In this works, in order to obtain the total force acting on the specimen under test, we use the numerical integration of the Maxwell stress tensor and (or) the integration of the Lorentz force formula. The last one is commonly used to evaluate the forces acting on the conductive materials [7,8]. The volume force density is given by the Lorentz force formula as:

$$\mathbf{F_d}=\mathbf{J}\times\mathbf{B} \qquad (3)$$

$\mathbf{J}$ is the eddy current density and $\mathbf{B}$ the magnetic flux density.

The total force per length acting on the plate can be evaluated as:

$$\mathbf{F}=\int_s(\mathbf{J}\times\mathbf{B})d\mathbf{s} \qquad (4)$$

ds is the elementary surface on the plate surface. The integral is calculated through the plate surface.

The methods based on the Maxwell stress tensor are commonly used to compute forces and torques in the finite element analysis. The electromagnetic force is obtained as a surface integral of the Maxwell stress tensor.

$$\mathbf{F}=\int\limits_{surface}\left[\frac{1}{\mu_0}(\mathbf{B}\cdot\mathbf{n})\mathbf{B}-\frac{1}{2\mu_0}\mathbf{B}^2\mathbf{n}\right]dS \qquad (5)$$

$\mathbf{n}$ is unit normal vector of the integration surface S. In a two-dimensional model, the surface integral is reduced to a line integral along the air gap.

4. RESULTS OF THE NUMERICAL 2D-SIMULATION STUDY

The finite element method is used to solve the field equation and the numerical model was implemented under the FEM-software COMSOL-multiphysics. All the magnetic variables can be calculated, and the results are obtained using the following physical and geometrical parameters:

Permanent magnet

length	15 mm
width	5 mm
Remanent flux density	370 mT

Aluminium plate

length	150 mm
width	6 mm
Electrical conductivity of the plate	37.7 MS/m

Lift-off

d	2 mm

Crack dimensions

Crack width	4 mm
Crack depth	3 mm

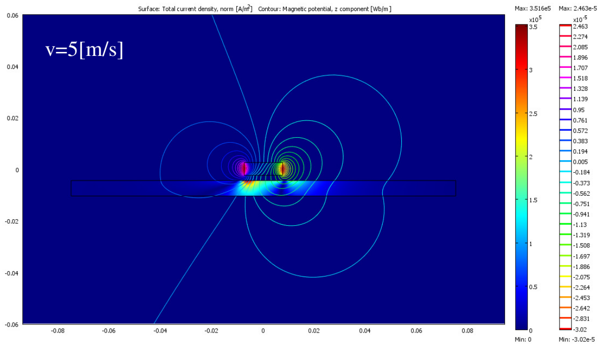
Table 1. Physical and geometrical parameters

It is well known that the electromotive term (velocity term) $\sigma\mathbf{v}\times(\nabla\times\mathbf{A})$ appearing in the in the electromagnetic equation obtained from the Maxwell's equations (equation 2) makes the solution instable [9-12] when numerical methods as finite element method or finite differences method are used to solve such equation. This kind of methods leads to algebraic equations system badly conditioned.

In our case, we deal with 2D modeling. The linear algebraic systems generated by the finite element method are not very large. To achieve the FEM computation, big memories are not required. As a result, the easier way to avoid this problem is to refine the mesh.

4.1. System without cracks

Systems without cracks are simulated at first for a basic characterization and then, a defect is introduced in the plate. We suppose that the crack has a rectangular shape. The following figures show some results.



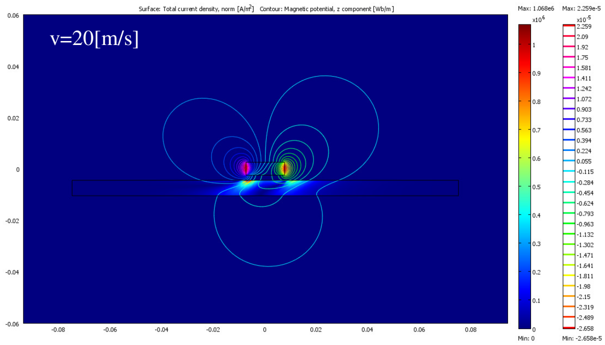


Figure 3. Isovalues of Magnetic potential (contour), Eddy current distribution on the plate (surface)

The figure 3 shows that the distribution of the eddy currents in the plate depends on the velocity because of the penetration of the magnetic field through the thickness of the plate. At low velocities, the magnetic field penetrates better as at high velocities. Also we can see that the magnetic potential lines are distorted at the high velocities in the direction of the movement.

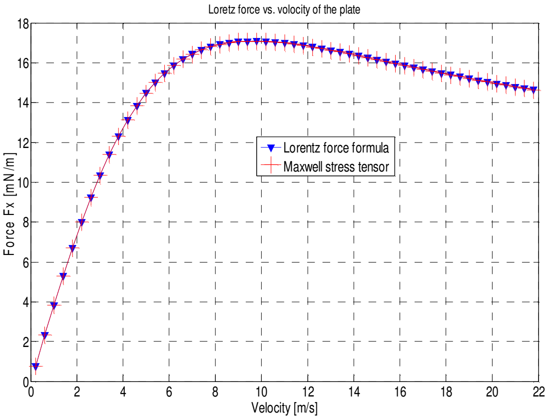


Figure 4. Force vs. velocity. lift-off = 2[mm]

In the figure 4 we can see that when the velocity increases the Lorentz force increases too. But there is a saturation effect for very high velocities. Also, we observe a small difference between forces calculated using Maxwell stress tensor and those computed with the Lorentz force formula. This is due to numerical errors (approximation with finite element method) and to the errors of integration of the both forces calculation methods.

4.2. System with cracks

Here, systems with cracks are studied. The crack has a rectangular shape and its geometrical parameters are shown on the table 1. A surface and internal cracks are simulated. The following figures show some results.

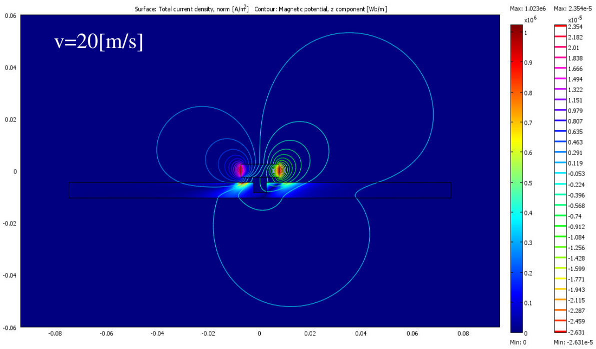


Figure 5. Isovalues of Magnetic potential (contour), Eddy current distribution on the plate (surface) surface crack (Surface crack).

In the figure 6 is shown that the force significant changes become visible when the crack is situated opposite to the permanent magnet during the movement (the scan) of the plate. In the proximity to the defect, the Lorentz forces are more important than the forces calculated without the defect. Note that here, the forces are computed by integrating the force densities given by the Lorentz force formula (Equation 4).

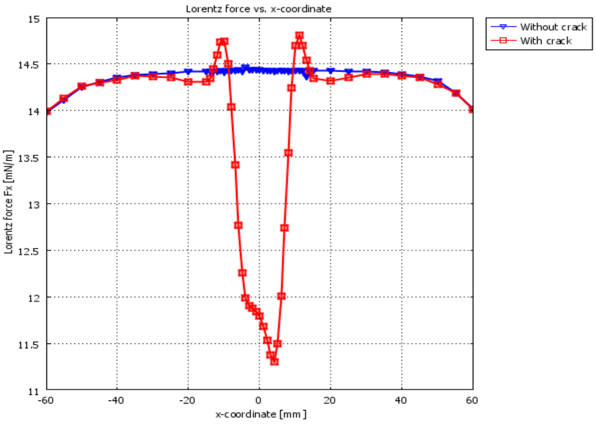


Figure 6. Force vs. x-coordinate of the magnet. velocity v=5[m/s], lift-off=2[mm] (Crack on the upper plate surface. Crack width= 4[mm], crack depth= 3[mm])

The figure 5 and the figure 10 shows the magnetic vector potential lines and the distribution of the eddy currents on the plate obtained for a surface crack at a velocity of 20 [m/s] and for an internal crack at a velocity equal to 5 [m/s] during the movement of the permanent magnet.

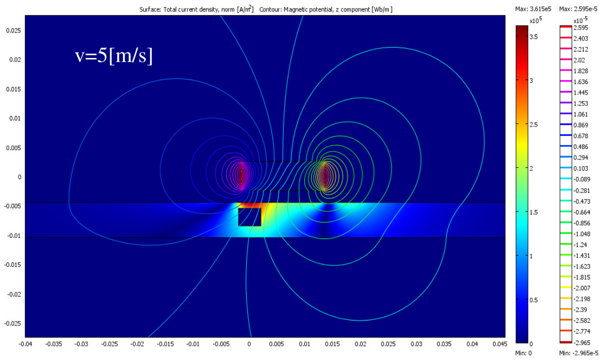


Figure 7. Isovalues of Magnetic potential (contour), Eddy current distribution on the plate (surface) Internal crack

The figure 8 shows the x-component of the total force computed for several positions of the permanent magnet during the movement at velocity v=5 m/s. The forces are computed for a system without crack, with crack on the upper surface of the plate and with an internal crack.

These results demonstrate that the system is more sensitive to the crack on the surface. However, it is possible to estimate an optimal velocity that offers a higher sensitivity of the magnet force ECT-system.

5. CONCLUSION

A 2D numerical FEM-model for the simulation of the Lorentz force ECT was implemented under the FEM-software COMSOL multiphysics. The field computation can predict all of the magnetic variables. Also, the forces can be calculated with the Maxwell stress tensor or with the Lorentz force formula. The numerical problem of the velocity term is avoid by mean a mesh refining, which is possible for the 2D modeling. Finally, the simulation study shows in this first investigation that it is possible to detect cracks in conductive materials by mean the computation of the Lorentz force.

6. REFERENCES

[1] H. Brauer and M. Ziolkowski, "Eddy current testing of metallic sheets with defects using force measurements" Serbian journal of electrical engineering, vol. 5, No 1 , may 2008.

[2] Y. Le Bihan, "3-D Finite-Element Analysis of Eddy-Current Evaluation of Curved Plates"IEEE Trans. Magn.,, Vol. 38, N°. 2, march 2002.

[3] R. C. McMaster, F. Föster, and H. L. Libby et al., "Nondestructive Testing Handbook" 2nd ed. Columbus, OH: American Society for Nondestructive Testing, 1986, vol. 4.

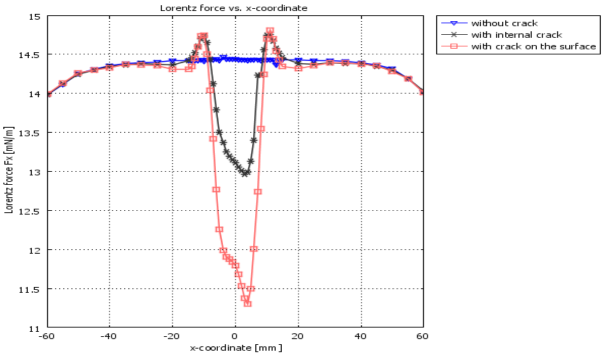


Figure 8. Lorentz force acting on the plate vs. x-coordinate of the permanent magnet at fixed velocity v = 5 [m/s] and lift-off = 2 [mm](Internal crack) Crack width= 4 [mm], crack depth= 3 [mm]

[4] P. Xiang, "Automatic multi-frequency rotating-probe eddy-current data analysis" PhD thesis, Iowa State University, 2005.

[5] H. Tsuboi, N. Seshima, I. Sebestyén et al. "Transient Eddy Current Analysis of Pulsed Eddy Current Testing by Finite Element Method"IEEE Trans. Magn., Vol. 40, N°. 2, march 2004.

[6] T. Clauzon, F. Thollon, and A. Nicolas, "Flaws characterization with pulsed eddy current N.D.T.," IEEE Trans. Magn., vol. 35, pp.1873–1876, May 1999.

[7] Z. Ren, "Comparison of different force calculation methods in 3D finite element modelling" IEEE Trans. Magn., vol. 30, No 5, pp.3471–3474, 1994.

[8] M. Bartsch, T. Weiland "2D and 3D calculation of forces" IEEE Trans. Magn., vol. 30, No 5, pp.3467–3470, 1994.

[9] F. Bouillaut " Contribution à la modélisation de structures électromagnétiques en mouvement comportant des parties ferromagnétiques massives. ", Thèse de doctorat 3ème cycle, Paris, 1984.

[10] B.Bendjima "Contribution à la modélisation par éléments finis des phénomènes électromagnétiques relatifs au magnétoformage" Thèse de doctorat, Nantes, 1997.

[11] H. Song,N. Ida, "Modeling of the velocity terms in 3D eddy current problems" IEEE Trans. Magn., vol. 28, No 2, March 1992.

[12] Y. K. Shin, W. Lord "Numerical Modeling of Moving Probe Effects for Electromagnetic Nondestructive Evaluation", IEEE Trans. Magn., Vol. 29, N°. 2, MARCH 1993.