Space discretized ferromagnetic model for non-destructive eddy current testing

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Accurate magnetic material laws are necessary to understand and interpret electrical signals generated by Eddy Current Testing (ECT) non-destructive control technique. Taking into account simultaneously, both microscopic and macroscopic eddy currents, a numerical resolution is obtained which leads to the global magnetic behavior that can be compared to measured quantities. 2 or 3 dimensional (depending on the dimension of the test sample) finite differences space discretization is used for the resolution of the diffusion equation and dynamic hysteresis model simultaneously and is locally solved for the microscopic eddy currents (domain wall movements) consideration. Local cracks defects are considered in this model as a variation in the local electrical conductivity and magnetic permeability. The numerical implementation of the problem and experimental validations are shown in the article.

***Index Terms*—Eddy current testing, magnetic hysteresis, electromagnetic modeling.**

I. Introduction

The development of new electromagnetic designs, such as the improvement of already existing ones require precise simulation tools. Similar tools can also be used for the understanding and interpretation of non-destructive eddy current testing and Barkhausen noise measurements' electrical signatures.

Eddy current testing (ECT) consists of setting up a magnetic flux by passing alternating current through a test coil. When this coil is brought closer to the conductive test sample, induced eddy currents are observed and the changes are interpreted in the coil impedance or the voltage drop.

Numerical simulations are of large interest in ECT domain. By coupling accurate model to experimental results one can precisely define the shape and the position of the defects and cracks in the ferromagnetic material.

Recent scientific investigations around ferromagnetic model mainly focus on coupling Space Discretization Techniques (SDT), Finite Elements Method (FEM), Finite Differences Method (DFM)) extended with accurate scalar or vectorial, dynamic or static, and considering hysteresis material law. For this magnetic material law, it seems that the best results come from the extension of the quasi-static hysteresis model (Preisach model [1]) to dynamic behavior as a result of the separation losses techniques as proposed by Bertotti [2].The simultaneous resolution between SDT procedures and hysteresis models can be realized by iterative techniques. One of them is the so-called fixed point scheme [3]. This technique leads to accurate results, but numerical problems of convergence appear in particular cases.

To correctly simulate ECT technique, the electromagnetic model must be able to provide the local and time evolution of both magnetic induction B and excitation field H. 2 dimensional resolution gives the evolution of both magnetic fields through the cross section of the test sample, 3 dimensional gives this local information through the whole tested sample. To overcome numerical issues due to fixed point or Newton Raphson's algorithm, solving the diffusion equation (linked to the macroscopic eddy currents) and the dynamic hysteresis model (microscopic eddy currents) simultaneously is proposed.

II. Model

A. Diffusion equation – Macroscopic eddy currents contribution

To correctly perform the ECT simulation a coupled resolution of dynamic material law and the magnetic field diffusion equation must be effected [4][5]. The magnetic diffusion equation (1) results from Maxwell's equations and the law, which describes the conductive property of the material:

$$\overrightarrow{rot}\left(\overrightarrow{rot}\overrightarrow{H}\right)=-\sigma.\frac{d\overrightarrow{B}}{dt} \quad (1)$$

As the magnetic field is considered perpendicular to the cross section, in 2-D the eq. (1) becomes:

$$\frac{\partial^2 H(x,t)}{\partial x^2}+\frac{\partial^2 H(y,t)}{\partial y^2}=-\sigma.\frac{d\overrightarrow{B}}{dt} \quad (2)$$

The diffusion equation gives precise description of the macroscopic eddy currents distribution through the cross section of the test sample.

B. Material law – Microscopic eddy currents contribution

Due to the domain's wall movements, microscopic eddy currents appear through the cross section of a magnetic sample as soon as it is exposed to a varying magnetic field. Beyond a threshold frequency (in the decreasing direction) hysteresis loop area becomes frequency independent, which can be called as the quasi-static state. Different approaches are available in the literature for the simulation of the quasi-static hysteresis behavior [1]. Among all, Preisach's model exhibits the interesting property of being easily reversible. It is indeed relatively easy to switch from H to B as input in the quasi-static hysteresis model. The material law solved in this study required an inverse hysteresis quasi-static contributions. Preisach's quasi-static model has been used to provide this information.

Preisach's model assumes that the material magnetization is determined by the contribution of a set of elementary hysteresis loops having a distribution function over the Preisach's triangle.

In order to model precisely the magnetic material behavior, it is necessary to accurately determine the distribution function from experimental data. There are mainly two ways to determine this distribution function. In this study, in order to minimize the required experimental data the Biorci's method has been chosen [6].

If only the quasi-static contribution material law is considered in the diffusion equation, the resolution is easy but leads to inaccurate results. In this case, the dynamic effects related to the high frequency dynamics of the wall motions are neglected. The dynamic contribution is considered in the material law by adding to the quasi-static lump model the product of a damping constant ρ to the time domain derivation of the induction field B.

$$\rho.\frac{dB(t)}{dt}=H_{dyn}(t)-f_{static}^{-1}(B(t)) \qquad (3)$$

This product is homogeneous to an equivalent excitation field H.

C. *Simultaneous resolution*

The idea of the simultaneous resolution comes from the material law equation (3) (microscopic eddy current dynamic contribution). We note the dB/dt term in eq. (1) constitutes also a part of the second term in the diffusion equation (2). It becomes natural to switch the dB/dt term of eq. (3) by the second member of eq. (1). A new formulation of the diffusion equation is obtained then:

$$\frac{\partial^2 H(x,t)}{\partial x^2}+\frac{\partial^2 H(y,t)}{\partial y^2}=-\sigma.\frac{H_{dyn}(t)-f_{static}^{-1}(B(t))}{\rho} \qquad (4)$$

Finite differences method is used for the space discretization resolution. Without the permeability calculation step, we avoid a lot of numerical issues.

D. *Defects taken into account*

All metals (including ferromagnetic materials) contain defects. Different aspects of defects exist. It includes holes, cracks, segregation, inclusions, surface marks, or undesirable metallurgical changes. From a physical point of view, defects in the matter are characterized by a local variation of the physical properties (permittivity ε_d, permeability μ_d, conductivity σ_d). In our simulation, defects will be considered through their physical properties, i.e. a local variation of μ and σ in the finite differences resolution of equation (2). In the case of crack defects, as cracks are filled with air a permeability equal to the vacuum permeability μ_0 and a very weak conductivity is considered.

III. Simulation Results, and Conclusion

Figure 1 shows numerical results obtained considering successively:

- The macroscopic eddy current contribution
- The microscopic eddy current contribution
- Both contributions.

The model has been set using soft iron silicon material referenced M400P50 (Euronorm) and excitation frequency has been set to 200Hz.

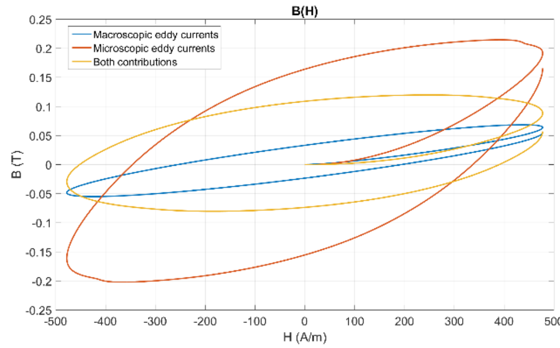

Fig. 1. Hysteresis loop considering different losses contribution.

Figure 2 shows the whole simulated experimental setup, including crack defect and magnetic field B distribution through the 2 dimensional cross section of the test sample.

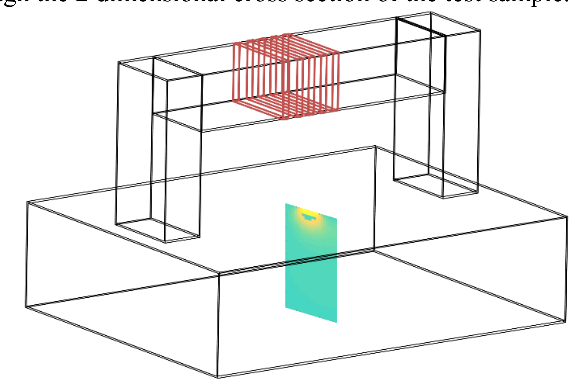
Fig. 2. Comparison simulation/measure for increasing frequency condition.

Finally, hysteresis loop derived from the measured electrical quantities (Voltage and current) in both cases is plotted: with and without defect presence.

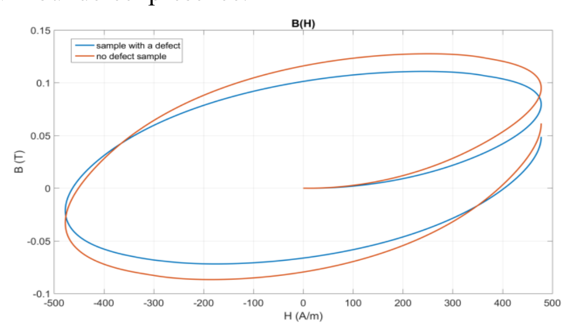

Fig. 3. Fractional dynamic lump hysteresis model.

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