Magnetic lump model for the hysteresis frequency dependence of a polymer matrix

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Based on complex space discretized hysteresis model of the ferromagnetic materials (including both macroscopic and microscopic eddy currents contributions), a simplified magnetic lump model of a polymer matrix material filled with magnetic particles is proposed in this paper. Due to its intrinsic nature, even for high percentage of magnetic particles, the tested sample exhibit high resistivity. This property implies a high limitation of the macroscopic eddy currents development. Considering this characteristic, the model proposed is limited to the microscopic eddy currents (related to the domain wall motions) contribution, and then checked and validated by comparing simulated/measured results on a large frequency bandwidth. A quite simple consideration of the frequency magnetic hysteresis dependence in such flexible magnetic materials is established and consolidated by testing it on a new material the validity of the microscopic eddy currents model.

***Index Terms*—Magnetic polymer matrix, magnetic hysteresis, electromagnetic modeling.**

I. Introduction

Composite materials or polymer matrix materials with magnetic nature are of high interest in the field of research because of its range of industrial uses, for the mechanical properties, and additionally for the fact that such materials are cheaper comparatively and are also low in eddy current energy losses.

In ferromagnetic materials, magnetic losses appear as soon as the test sample is exposed to a time varying external magnetic excitation field *H*. These magnetic losses have two origins:

- The microscopic eddy currents, i.e. magnetic domain walls interactions with the microstructure.
- The macroscopic eddy currents related to the magnetic field diffusion equation and varying according to the material's physical properties (conductivity and permeability).

Considering such ferromagnetic material properties, it is legitimate to assume that when a polymer matrix is developed filled with high density ferromagnetic particles, such properties of ferromagnetic materials will exist in such a polymer matrix as well. The special mechanical properties (flexibility) of ferromagnetic polymer matrix allow to envisage almost every shape of test samples. Toroidal shape according to international standards (CEI 60604-4) is well adapted for magnetic materials characterization. Surrounding primary coil supplied with high amplitude electric current can provide the magnetic excitation *H* while the induced magnetic field B is measured using a secondary coil.

A P(VDF-TrFE-CTFE) terpolymer has been used for the matrix polymer, this material exhibits interesting coupling and multi-physic properties. Even if it is saturated with magnetic particles, we notice that the conductivity remains relatively weak (< 5 10^{-10} S. cm^{-1}) [1]. It means that even under high frequency range the influence of the macroscopic eddy currents contribution will be low. On the contrary the other contribution: domain wall movements inside the magnetic particles should be preponderant. Our idea for this study is to check if the dynamic behavior can be obtained considering only the microscopic eddy currents contribution and then validating the simulation scheme used for this contribution.

II. Model

The characterization and the simulation of the scalar dynamic hysteresis in soft ferromagnetic materials have already been largely studied in the past, different approaches have been tested. Even if the fastest results can be obtained using a lumped model coupled to a first or second order dynamic contribution, when both microscopic and macroscopic contributions are required, best results are always obtained by coupling an accurate material law to the space discretization resolution of the Maxwell's equations [2]. In this simulation scheme, macroscopic contribution are considered through the Maxwell's diffusion equation and microscopic one through the material law.

A. Macroscopic eddy currents contribution

To correctly reach to measured quantities a coupled resolution of the dynamic material law and the magnetic field diffusion Maxwell equation must be taken into account. The magnetic diffusion equation (1) results from Maxwell's equations and a law, which describes the conductive property of the material:

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

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

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

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

B. Material law – Microscopic eddy currents contribution

Due to the domain 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. This behavior is called as the quasi-static state. Different approaches are available in the literature for the simulation of the quasi-static hysteresis behavior [3]. Among all, Preisach's model exhibits the interesting property to be easily reversible. It is indeed relatively easy to switch from *H* to *B* as input of the quasi-static hysteresis model. The material law solved in this study requires 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 [4].

If just 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 dynamic 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. Hysteresis model of the polymer matrix filled with magnetic particles

As explained previously, a simple measure of the circuit equivalent resistance allows to check no matter how high the percentage of the magnetic particles is, the proportion of macroscopic eddy currents in the dynamic contribution is weak. It means that the magnetic excitation will be homogeneously distributed through the cross section of the sample and that a lump model (space independent) will provide correct results.

III. Simulation results, and Conclusion

Simple measurement set up is used for the magnetic polymer characterization. An illustration of this experimental set up is given Fig. 1. The tested samples have toroidal shapes. The magnetic excitation field strength inside the analyzed toroidal shape core is generated by the current *i(t)* flowing in the primary coil constituted of 1400 turns. BOP 100-4M Kepco amplifier driven by Agilent 33220A provide this current.

The time variation of the magnetic excitation field through the tested sample results in a time varying magnetic flux inside the specimen, which can be measured by a secondary coil wound on the core. The secondary coil has 200 turns. Magnetic induction field B is deduced from the variations of this secondary coil voltage. Fig. 2 show a superimposition of simulated and measured averaged dynamic loops when the surface excitation field is a 100, 400, 1000 and 4000 Hz frequency sine wave. Fig. 3 shows comparison simulation/measure for the hysteresis area versus frequency curve <A>(f).

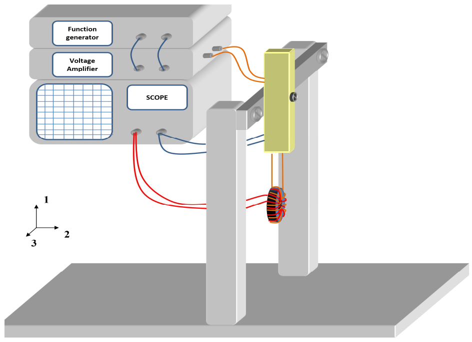

Fig. 1. Experimental set-up for the polymer magnetic toroidal sample characterization.

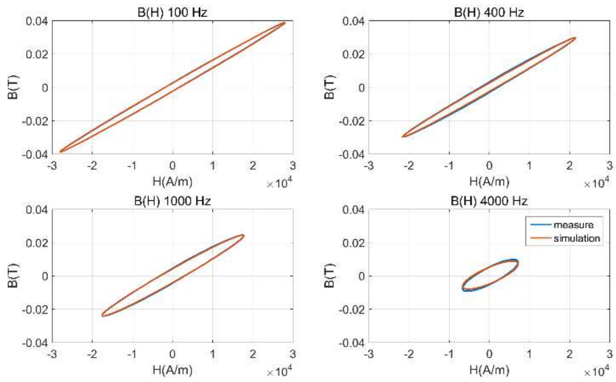

Fig. 2. Comparison measure/simulation on hysteresis loops (100, 400, 1k, 4kHz).

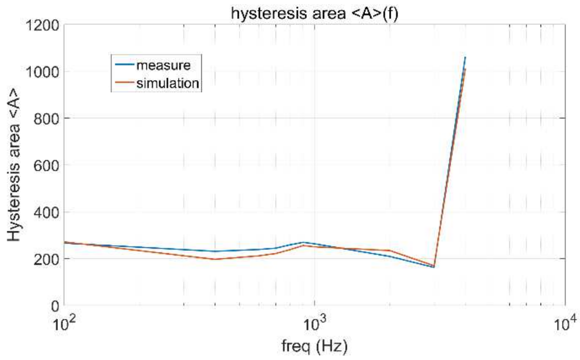

Fig. 3. Fractional dynamic lump hysteresis model.

Finally, the good fits obtained in both cases (fig. 2, 3) allow to validate the simulation scheme and to confirm that dynamic hysteresis magnetic materials of weak conductivity can be correctly modelled using first order consideration.

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