Reduce vector dynamic hysteresis model, for lump model applications or for integration in space discretized simulations.

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Even if vector dynamic hysteresis models have been proposed and studied since many years, the so-called ideal model (accurate, fast, and based on less parameters and memory allocation …) is still missing. Even if progresses in computer science have allowed large improvement in the numerical simulation domain, high non-linearity property of vector dynamic hysteresis is still a challenge. In this article, we described a non-congruent vector dynamic hysteresis model based on a dry-friction type equation quasi-static contribution extended to the dynamic behavior using fractional derivatives. The model is fast, accurate and particularly well adapted to space discretized simulations.

Index Terms — **Vector hysteresis model, dry-friction equation, fractional derivatives.**

I. Introduction

The development of electromagnetic devices, as well as the enhancement of existing ones, require accurate simulation software. The very last progresses in this domain have confirmed that the most accurate results can be obtained by coupling space discretized resolutions of the Maxwell equations (finite elements method (FEM), finite differences method (DFM), boundary element method (BEM) …) to precise material laws. In the particular cases of ferromagnetic materials simulations, this laws have to be hysteretic, frequency dependent and vector [1][2]. Such resolution in the time domain means a step time evolution of the permeability value for each node of the simulation mesh. Since the complexity of electromagnetic devices is increasing, fine meshes are expected and number of nodes are always unfortunately excessive. Hysteresis behavior in a space discretized resolution simulation means to manage the material memory for each node of the mesh and consequently to allocate a memory space linearly proportional to the number of nodes. Concerning the material law, several methods have been proposed. Historically, the classic quasi-static Preisach model has been tried first, but the complex memory management is a major limitation [2]. The well-known Jiles-Atherton model seems particularly adapted to an integration in a space discretized resolution. In its original version, the memory management such as the number of parameters are extremely reduced. From a numerical point of view, the J-A simulation consists on a differential equation resolution. Of course, J-A model in its first attempt was not frequency dependent nor vector but ever since, different methods have been proposed to extend it with such properties [3][4]. The issue with the J-A model comes from the determination of the parameters. Physic based methods or numerical ones (Neural networks, genetic algorithms, optimization techniques … [5]-[9]) have been successively proposed for the identification of these parameters. On one hand, very accurate results can be obtained in a large majority of materials but on the other hand for some of them, of non-usual magnetic behavior (extreme permeability …), not a single combination of parameters is able to reproduce the experimental observations. In this abstract, a vector frequency dependent hysteresis model adapted to lump hysteresis simulations such as integration in space discretization codes is described. The hysteresis model is made of two contributions:

_ A quasi-static vector contribution based on an analogy between quasi-static magnetic domain wall motions and mechanical dry frictions [10].

_ A dynamic contribution, frequency dependent, and introduced in the model final expression as an equivalent magnetic excitation field [11][13].

In the final version of this paper, we will successively describe these two different contributions. An example of integration in a space discretization scheme will be detailed as an illustration of the new method efficiency and performances.

II. Simulation

A. Quasi-static contribution, domain wall behavior

Due to the complex set of elastic, magnetic and electric boundary conditions at each grain, magnetic grains in ferromagnetic materials are always split into large number of domains [10]. A macroscopic magnetic state can be observed on polycrystalline ferromagnetic materials under large amplitude magnetic field. The magnetization mechanisms are extremely complex as they consist of several physical properties and events taking places in different space scales through a given material. Coercivity, spontaneous or/and remnant magnetizations, and in a general way hysteresis loop shapes are dependent on many factors, including geometrical properties, presence of cracks and defects, mechanical stress, preparation conditions and thermal treatments [10]. Ferromagnetic domain wall movements can be described as a succession of dynamic movements between pinning periods [10]. The displacement of domain walls under weak magnetic fields has a deep influence on the local permeability property of a ferromagnetic material. At the domain wall scale, the

magnetic effective/internal excitation field H_{eff} can take various aspects: the external excitation electrical field H, a demagnetizing field due to the inter-domain interactions and dependent on the material magnetization state:

$$\overrightarrow{H_{eff}} = \vec{H} + \alpha.\vec{B} \quad (1)$$

A *B(H)* major hysteresis cycle shape can be easily generated by the translation of an anhysteretic curve (langevin-type monotonous and saturating function f) depending on the sign of the time derivative of B.

$$\vec{B} = f\left(\overrightarrow{H_{eff}} - H_c.sign\frac{d\vec{B}}{dt}\right) \quad (2)$$

This equation behaves similarly to a mechanical dry friction, and is restricted to major-type shape hysteresis cycles. *Hc* set the displacement threshold. To simulate dissymmetrical behaviors like minor cycles, first magnetization curves … a distribution of mechanical dry frictions is necessary. It is worth mentioning that such distribution fits the physical interpretation, i.e. domain wall motions such as defects are heterogeneously distributed and consequently triggered by varying magnetic excitation strength levels.

$$\vec{B} = \sum f\left(\overrightarrow{H_{eff_i}} - H_{c_i}.sign\frac{d\vec{B_i}}{dt}\right) \quad (3)$$

B. Dynamic contribution

Hysteresis behavior in ferromagnetism can be defined as the time delay between the material magnetization variation and an external magnetic stimuli. This delay has several origins, domain wall motions are obviously one of them. Macroscopic eddy currents ruling the penetration of the magnetic excitation is another. Hysteresis is consequently, a succession of a cluster of relaxing behaviors appearing through the geometrical scales. Hysteresis is highly frequency dependent … sometime the excitation speed is just too high and overpass the material characteristics relaxation times, forbidden any variations in the global magnetization states. In phenomenological approaches, where users limit the simulation to measured electric quantities, dynamic consideration can be the simple but inaccurate classic first order contribution (i.e. product of a constant ρ to the time derivation of the induction). Better results can be obtained by a distribution of these first order dynamic terms, and even better by non-entire fractional derivative order [4][11][14]. In the simulation scheme, this dynamic contribution is introduced as an equivalent electric field:

$$\begin{aligned} \overrightarrow{H_{equ}} &= \rho.\frac{d\vec{B}}{dt} \\ \overrightarrow{H_{equ}} &= \sum \rho_i.\frac{d\vec{B_i}}{dt} \\ \overrightarrow{H_{equ}} &= \rho.\frac{d^n\vec{B}}{dt^n} \qquad n \in \mathbb{R} \end{aligned} \quad (4)$$

In space discretized simulation approach, where material law is simultaneously solved to the Maxwell equations, a first order dynamic contribution seems to be enough to get correct simulation results (see [2]).

C. Coupled resolution and congruency issue

In the final version of the vector hysteresis model (eq. 5), both quasi-static and dynamic contribution are considered. The congruency issue is solved thanks to the induction contribution in the effective excitation.

$$\rho.\frac{d^n\vec{B}}{dt^n} = \overrightarrow{H_{eff}}(t) - \sum f\left(\overrightarrow{H_{eff_i}} - H_{c_i}.sign\frac{d\vec{B_i}}{dt}\right) \quad n \in \mathbb{R} \quad (5)$$

Isotropic behavior can be modelled considering the constant α as vector $\vec{B}$ dependent.

$$\begin{cases} \alpha = f\left(\vec{B}\right) \\ \overrightarrow{H_{eff}} = \vec{H} + f\left(\vec{B}\right).\vec{B} \end{cases} \quad (6)$$

f depends on the sample nature and geometry.

III. Conclusion

A vector dynamic hysteresis model has been described in this abstract. In the extended version of this paper, we will discuss the model performances, we will show comparisons simulations/measures and explained why, this model is particularly well adapted to space discretization simulations.

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