# Homogenised magnetic diffusion: influence of the static hysteresis model

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**Abstract — The aim of this study consists in comparing the contribution of two static hysteresis models ("chemical" and Jiles-Atherton models) in dynamic representation of magnetic behaviour using the magnetic diffusion equation. It has been homogenised and tests have been performed on a toroidal core of non-oriented FeSi sheets. The material has been excited at a rather low frequency in order to avoid the skin effect. First results are given by considering excitation fields leading to major loops then minor loops.**

## I. INTRODUCTION

The increasing performance of electromagnetic devices leads to more severe electrical stresses. For example high frequency or non-sinusoidal signals cause more iron losses in magnetic materials. Thus, it becomes very important to develop accurate modelling tools taking into account the behaviour of magnetic materials in these conditions. The choice of good static and dynamic hysteresis laws for these magnetic materials is crucial.

Among many static models available, the "chemical" and the Jiles-Atherton models are considered. This choice is led by modelling accuracy and ease of implementation. Both models are implemented in the dynamic model based on homogenized magnetic diffusion equation in order to highlight the contribution of static models.

The aim of this paper is to compare the influence of these two static hysteresis models in terms of accuracy, convergence and computing time on the results of magnetic diffusion model.

## II. THE MODELS

### A. Dynamic Static Feedback model ("DSF")

One of the most common dynamic model is probably the magnetic diffusion.

From this model, several modifications and simplifications can be done under some specific conditions, in order to obtain a dynamic model taking into account eddy currents and wall motion [1].

When the sheet is thin compared to the skin effect, a macroscopic dynamical model (1) based on homogenised diffusion equation is used [2]. This model requires a $H_{stat}(B)$ static law and only one parameter named $\gamma$ lumping eddy currents and the wall motion effects.

$$\frac{dB_m(t)}{dt} = \frac{1}{\gamma}\left[H_{dyn}(t) - H_{stat}\left(B(t)\right)\right] \quad (1)$$

### B. Static magnetic models

As presented previously, the dynamic model of diffusion requires a static magnetic law involving the variable B. Thus, the model of static hysteresis Jiles-Atherton is available under the two formulations H(B) or B(H), so it is quite suitable for our modelling.

Just recall the main equation (2) of the model H(B) [3] used in our implementation in the dynamic model.

$$\frac{dM}{dB} = \frac{(1-c)\frac{dM_{irr}}{dB_e} + c\frac{dM_{an}}{dB_e}}{1+\mu_0(1-c)(1-\alpha)\frac{dM_{irr}}{dB_e} - \mu_0 c(1-\alpha)\frac{dM_{an}}{dB_e}} \quad (2)$$

The identification of the five parameters of Jiles-Atherton model will be detailed in the full paper.

Based on "thermodynamics" - "magnetic" analogies, this model [4] has the advantage of having a simple analytical formulation (3, 4, 5) like the Jiles-Atherton model. However, the problem of this model for our application relies on its formulation as a function of variable H. An inversion technique based on an iterative method has to be used to obtain the formulation with B variable. The inversion method used in our algorithm is based on the secant method which is not really the fastest one.

$$J' = J'_0 \cdot \tanh\left[\left(\frac{\beta \cdot h_T}{2}\right)\ln\left(\exp\left(\frac{H}{h_T}\right)+b\right) - \frac{\beta \cdot Hc}{2}\right] \quad (3)$$

$$J'' = J''_0 \cdot \cos(\theta) \quad (4)$$

$$\frac{h'}{24}\cdot\left(\theta-\frac{\pi}{2}\right)^4 - \frac{h'}{2}\left(\theta-\frac{\pi}{2}\right)^2 + h' + k_1\cdot\left(\theta-\frac{\pi}{2}\right) + k_3\cdot\left(\theta-\frac{\pi}{2}\right)^3 - p_1 = 0 \quad (5)$$

In the following paragraphs, the DSF model will be associated with JA and chemical models and will be named respectively "DSF+JA" and "DSF+chemical".

## III. FIRST RESULTS

### A. Experiment Protocol

The sample material characterized and modelled in this study consists of a stack of 9 thin non-oriented FeSi rings. For medium frequency range, we note a significant influence of the static hysteresis compared to dynamic effects. For example, the coercive field measured at 50Hz is 110A/m, while in static condition it is 60A/m.

The ring-shaped sample has an inner diameter of 105mm while its outer diameter is 119mm. We can suppose that the surface field is approximately the same in the whole sheet. Thus, the choice of a scalar model is justified. The choice of maximum frequency is easily estimated thanks to the equation (6) of the skin depth $\delta$.

$$\delta = \sqrt{\frac{2\cdot\rho}{\omega\cdot\mu_{\max}}} \quad (6)$$

For the sample tested, the thickness of each sheet is 0.35mm, the resistivity is equal to $45 \cdot 10^{-8} \Omega.m$ and the maximum relative permeability is 20000. So, the skin depth is estimated at 0.168mm (which is approximately half of the thickness of a sheet) for a frequency of 200Hz.

Therefore, if the frequency is below 200Hz, the magnetic flux density is relatively uniform in the thickness of the sheet and thus the use of dynamic model DSF seems justified.

The simulations shown in the following paragraphs have been obtained by exciting the model with the same magnetic excitation field $H_{dyn}$ than the one imposed during the measurement.

### *B. Minor loops*

For the simulation of B(H) minor loops, i.e. for excitation fields below the field necessary to reach the saturation, we can notice that the "chemical" model is more accurate than the Jiles-Atherton model (Fig. 1-4).

With the same excitation field ($H_{max}$=250A/m), the mean-square error between magnetic flux density measured and simulated with “DSF+chemical” is 3% against 12% for the “DSF+ JA” model (Fig. 1 and 2).

Similarly, for lower excitation field ($H_{max}$=100A/m), the mean-square error is twice smaller with the “DSF+ chemical” model. Therefore the losses will be better evaluated (Fig. 3 and 4).

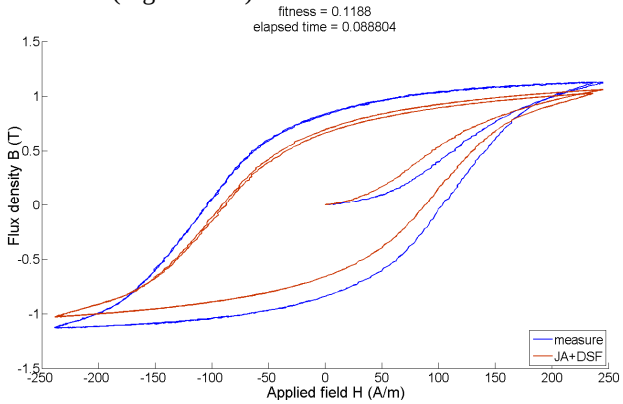


Fig 1. Measured and simulated B-H curves with DSF+JA model – $H_{max}$=250A/m – f=200Hz (fitness: $11.9 \cdot 10^{-2}$)

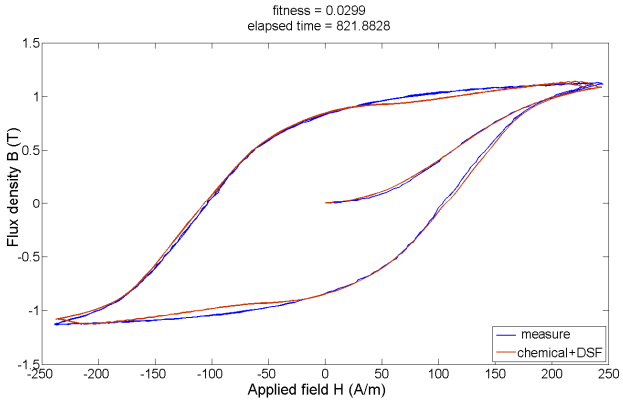


Fig 2. Measured and simulated B-H curves with DSF+chemical model – $H_{max}$=250A/m – f=200Hz (fitness: $2.99 \cdot 10^{-2}$)

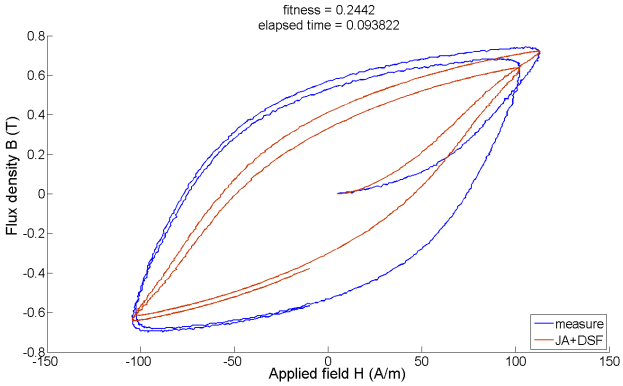


Fig 3. Measured and simulated B-H curves with DSF+JA model – $H_{max}$=100A/m – f=200Hz (fitness: $24.4 \cdot 10^{-2}$)

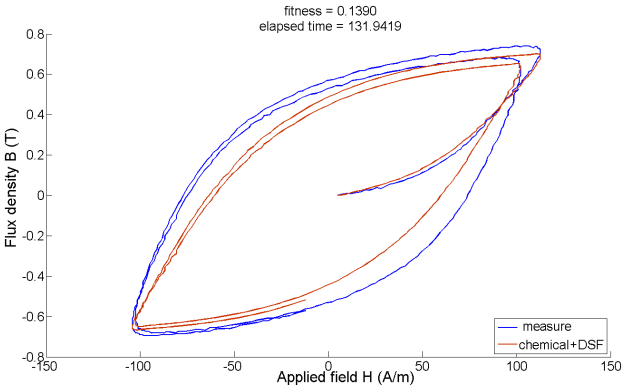


Fig 4. Measured and simulated B-H curves with DSF+chemical model – $H_{max}$=100A/m – f=200Hz (fitness: $13.9 \cdot 10^{-2}$)

However increasing accuracy requires a large computation time. For example, the “DSF + JA” model spends only a tenth of a second to simulate a loop, while “DSF + chemical” model may spend up to ten minutes. Indeed, this very big difference in simulation time is due to the numerical inversion of the “chemical” model made by an iterative method, while analytical equations H(B) is available for Jiles-Atherton model.

## IV. FUTURE PROSPECTS

In the full paper, we will quantify the contributions of the “DSF+JA” and “DSF+chemical” models to a wider area of study, particularly for non-sinusoidal waveforms leading to minor loops and recoil lines.

## V. REFERENCES

[1] Raulet M., Ducharne B., Masson J. and Bayada G., “The magnetic field diffusion equation including dynamic hysteresis : a linear formulation of the problem”, *IEEE Transactions on Magnetics*, 40 (2), pp. 872-875, 2004.

[2] Raulet M., Sixdenier F., Guinand B., Morel L., Goyet R., Limits and rules of use of a dynamic flux tube model, COMPEL vol. 27, pp 256-265, 2008.

[3] Sadowki N., Batistela N. J., Bastos J. P. A., Lajoie-Mazenc M., “An inverse Jiles-Atherton model to take account hysteresis in time-stepping finite-element calculations”, *IEEE Transactions on Magnetics*, 38 (2), 2002.

[4] Nourdine A., Kedous-Lebouc A., Meunier G., Chevalier T., “A new hysteresis model generation – application to the transverse axis of GO SiFe sheet”, *IEEE Transactions on Magnetics*, 37 (5), 2001.