Analysis of Magneto-Mechanical Jiles-Atherton-Sablik Model Regarding its Sensitivity to Non-linear Algorithm Parametrization

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Sources of mechanical loadings emerge in nearly every production stages of electromagnetic machines, and can also be found during their utilization. From residual plastic strain to in use stress generation, this non-homogeneity in the mechanical state of soft magnetic materials affects their properties. In that sense, the present paper reviews the capacity of modeling such coupled effect using an unidirectional phenomenological model based on the Jiles-Atherton hysteresis theory: the Jiles-Atherton-Sablik model. The identification of the required parameters is realized through different non-linear algorithms, and the dependence of the model accuracy regarding its own parametrization is analyzed. On this particular point, results show that a careful attention has to be payed while using non-linear optimization, as some unphysical behavior could appear, leading to convergence troubles in the case of a FEM utilization of the models.

***Index Terms*—Hysteresis, Magnetomechanical effects, Numerical models, Optimization methods.**

I. INTRODUCTION

IN THE PAST DECADES, the increasing demand for more effective and lightweight electromagnetic devices brought designers, engineers and researchers to enhanced their physical knowledge and description of these products. Thus, numerical tools made a big leap forward, leading to accurate description of material non-linearities such as magnetic saturation and hysteresis within computational simulations. Even with those detailed simulations, the discrepancy between observed and expected losses forced to further analyze the physical phenomena taking place within devices. It was deduced that part of the shift in losses could be due to a long-known – nevertheless, underestimated and regarded as insignificant comparing with other sources of losses – phenomenon called the magneto-mechanical coupling. Among the different models available to simulate such effect, the present article will focus on the phenomenological model originally proposed by Sablik [1] based on the Jiles-Atherton hysteresis description [2]: the so-called Jiles-Atherton-Sablik (JAS) model. In its crude implementation, the model needs five parameters to represent accurately the hysteresis of stressed or unstressed material, apart from the mechanical ones. It is here proposed to test various non-linear algorithms (NLA) [4], with the intention of analyzing the physical meaning of the obtained optimized model regarding the parameters chosen for the NLA. The capacity of the JAS of modeling the coupling for unidirectional and parallel excitations will be discussed, comparing the numerical results with experimental data.

II. THE JILES-ATHERTON-SABLIK MODEL

The main aspect of the modification to the Jiles-Atherton model proposed by Sablik [1] relies on the addition of stress-equivalent field H_σ to the effective field H_e (1). A convenient way to model this stress-dependent field is proposed in (2).

$$H_e = H + \alpha M + H_\sigma(\sigma, M) \tag{1}$$

$$H_\sigma(\sigma, M) = \frac{3}{2}\frac{\sigma}{\mu_0}\left(\frac{\partial \lambda_{(\sigma,M)}}{\partial M}\right)_T \tag{2}$$

Starting from this point and using the equations of the JA model [3], an inverse scalar model of the JAS can be developed, having the following basic equations (3):

$$M_{an} = M_s\left[\coth\left(\frac{H_e}{a}\right) - \frac{a}{H_e}\right];$$

$$\frac{\partial M_{irr}}{\partial B_e} = \frac{M_{an} - M_{irr}}{\mu_0 \delta k};$$

$$\frac{\partial M}{\partial B} = \frac{(1-c)\frac{\partial M_{irr}}{\partial B_e} + \frac{c}{\mu_0}\frac{\partial M_{an}}{\partial H_e}}{1 + \mathbb{K}\frac{\partial M_{irr}}{\partial B_e} + \mathbb{G}\frac{\partial M_{an}}{\partial H_e}}. \tag{3}$$

With:

$$\mathbb{K} = \mu_0(1-c)\left(1 - \alpha - \frac{\partial H_\sigma}{\partial M}\right);$$

$$\mathbb{G} = c\left(1 - \alpha - \frac{\partial H_\sigma}{\partial M}\right).$$

Using this model, it is possible to easily implement various versions of the JAS model by only varying the expression of magnetostriction λ in (2) and its second partial derivative which appears in the terms $\mathbb{K}$ and $\mathbb{G}$ (3). In the present work, different definitions of λ are tested in order to analyze their respective response and their capability to represent the stress-dependence of magnetic hysteresis.

III. NON-LINEAR OPTIMIZATION ALGORITHMS

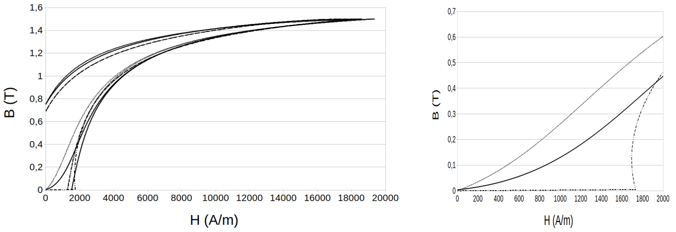
It has been observed [3] that non-physical behavior could emerge while using "common" non-linear algorithms for the parameter identification of the JAS model. Such event occurs mostly when the input data does not include the *first magnetization curve*. As this is the case for most of experimental data used in identification routine – commonly realized on a symmetric loop –, it appeared to be interesting reviewing the problem and delimiting it. In that sense, various *gradient-free* non-linear algorithms were used to find the optimized parameters $[M_s, k, c, a, \alpha]$ in order to compare their respective response in terms of computational resources and physical meaning.

TABLE I

JAS PARAMETERS: BOUNDARIES, VALUES FOR INPUT HYSTERETIC SIMULATION AND SOME RESULTS W/ AND W/O THE SIMULATED 1^{ST} MAGNETIZATION CURVE AS INPUT

Parameters $*$	M_s	k	c	a	α
Boundaries	[0;M_{max}+5e6]	[10;5e3]	[0,01;0,99]	[10;5e3]	[1e-6;5e-3]
Simulated	1,350e6	2000,000	0,20	3000,000	3e-3
NM-S w/ 1^{st}	1,349e6	2000,004	0,20	2999,999	3e-3
NM-S w/o 1^{st}	1,394e6	1311,541	0,01	4026,801	5e-3
DIRECT w/o 1^{st}	1,317e6	2597,407	0,44	2539,521	2,5e-3

$*$No input stress is added for those initial tests.



(a) (b)

Fig. 1. Hysteresis curves (a) and close-up on 1^{st} magnetization curves (b) obtained for the simulated hysteresis (continuous), the NM-S (coarsly-dashed) and the DIRECT (finely-dashed) algorithms, w/o 1^{st} mag. curve as input data.

A. *Brief description*

The open-source NLopt library [4] offers a large variety of gradient-free non-linear optimization algorithms. These algorithms can be local or global, bounded or not, and some of them accept the implementation of arbitrary (in)equalities.

First algorithm to be analyzed is the Nelder-Mead Simplex (NM-S), considered as the “reference” in this paper. Such choice is motivated by the fact that it is a widely implemented and used tool, which can be found in numerous numerical tools like MatLab (*fminsearch* function). Besides, the NM-S is of high interest since it is easy to use, fast (local) and requires very few parameters, limited to the evaluation function, the stop criterion and, eventually, boundaries of the search-space. Comparison between the performance of the NM-S and others, more complex methodologies, is here proposed. Within the chosen comparison algorithms, one can highlight the use of global, stochastic and genetic algorithms.

The implementation of the JAS model and of the identification routine has been realized on the open-source FE software FreeFEM++ [5].

IV. INITIAL RESULTS

In order to test the capabilities of optimization algorithms, initial tests are realized using a simulated hysteretic curve having fixed JAS parameters. The input parameters of the tested algorithms are then changed randomly within acceptable boundaries, and the simulated inductions values, with (w/) and without (w/o) including the first magnetization curve, provided. The evaluation function chosen is the RMSE of the magnetic field, and the stopping criterion is a restriction on the absolute difference of the evaluation function between two consecutive iterations. Some of the obtained results are presented in Fig. 1 and Table I.

The preliminary results show that a nearly perfect agreement between the output of all non-linear algorithms and the initial JAS parameters is obtained, when the simulated first magnetization curve is included in the algorithm input data. It can be verified in the Table I by comparing the values given by the NM-S algorithm in such case with the simulation parameters. On the contrary, most of the NLA give unacceptable solutions when the first magnetization curve is not considered, leading to non-physical behavior, as seen on Fig. 1 (b). In particular, it seems that the c and α parameters are not well managed by the tested algorithms. One potential cause of this phenomenon can be found looking at the search-spaces configuration of the problem posed here: indeed, as it can be observed in Table I, there is a great difference between the search-spaces of each parameters, some being really narrow like for c and α, whereas others are extremely wide (M_s). Thus, a careful attention has to be payed concerning the weight given to each dimension of the space, in order to better balance the algorithm convergence scheme and escape local or quasi-global minimums [4]. One variation of the DIRECT (DIviding RECTangle) algorithm allow such adaptation, and give promising results, even if far from being perfects, as seen on Table I and Fig. 1 (a,b).

V. FURTHER DEVELOPMENTS

This preliminary work takes place within a larger project, which include a strong experimental part. Then, this study will be extended and applied on experimental results obtained with an internally developed magneto-mechanical test bench. The capacity to represent the magnetization under stress of various versions of Jiles-Atherton-Sablik model will be analyzed, as well as the capability of the non-linear gradient-free algorithms discussed here. Some advises on the care to be taken while using these numerical tools will be given, and an all-integrated (taking into account experimental and numerical strategies) identification methodology proposed.

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