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CV-7 Modeling minor hysteresis loops with the GRUCAD description

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A peculiar feature of the Jiles-Atherton model [1] is the existence of negative $\mathrm{d}M/\mathrm{d}H$ slopes after a sudden field reversal, as pointed out e.g. in Refs. [2, 3]. This effect may hamper the model usability in FEM applications, leading to non-stability of numerical procedures.
Therefore it is usually suppressed by the introduction of an additional control variable δ_M, which cuts off the irreversible component of magnetization, δ_M=0.5[1+sign[(M_{an}-M_{irr})$\mathrm{d}H/\mathrm{d}t$ (or $\mathrm{d}B/\mathrm{d}t$)]]. The introduction of $\delta_M$may be justified theoretically [4], yet the resulting model equations cannot be traced back to the original derivation. As pointed out in Ref. [5] the source of problems with the original Jiles-Atherton approach is the assumption that total magnetization could be split into the reversible and the irreversible components.

In the present paper we focus on an alternative description, which relies on the decomposition of total field strength into reversible and irreversible terms [6-8]. Similar approaches have been considered previously by different authors [9-12]. It should be stressed that models based on field separation principles are consistent with the laws of thermodynamics and they do not have any artificially introduced ,,patches" for their correct operation.

The considered description is an example of the so-called inverse models, i.e. time dependent flux density $B(t)$ plays the role of independent variable.

$H_{an}(t)=B(t)/\mu_0-M_s[\coth(\lambda(t))-1/\lambda(t)]$ (1)

The equation defines the reversible (anhysteretic) field strength. The quantity λ is defined as

$\lambda(\mathrm{t})=1/a[(1-\alpha)H_{an}(t)+(\alpha/\mu_0)B\ (t)]$ (2),

where the parameter α acts as a weighting factor between the reversible and irreversible contributions.

The relationships, which define the irreversible field strength are as follows:

$H_h(\mathrm{t})=H_{Hs}[\coth(\lambda_H)-1/\lambda_H]=H_{Hs}L\ (\lambda_H)$, (3)

$\lambda_H=(H_h(t)+\delta H_{Hs})/\gamma$, (4)

where δ is the sign of $\mathrm{d}B/\mathrm{d}t$. The quantities α, a, M_s,H_{Hs} and γ are model parameters. Notation $L(x)$ denotes the Langevin function, $L(x)=\coth(x)-1/x$.

Equations (1) and (2) may be combined into a single expression, useful for direct integration if the time dependence of $B\ (t)$ is known (using chain rule for differentiation)

$\mathrm{d}H_{an}/\mathrm{d}B=(a-\alpha M_s L'(\lambda))/[\mu_0(\alpha+M_s(1-\alpha)L'(\lambda))]$. (5)

Notation $L'(x)$ denotes the derivative of Langevin function.

Total field strength $H(t)$ is determined from integration of the sum $\mathrm{d}H_{an}/\mathrm{d}t+\mathrm{d}H_h/\mathrm{d}t$. The set of ordinary differential equations may be solved using the standard variable-step Runge-Kutta (4-5) method, implemented in Matlab environment.

The values of model parameters α, a, M_s, H_{Hs} and γ were determined using experimental data for the major hysteresis loop of a non-oriented FeSi 3.2wt% steel lamination, referenced as M270-35A. Measurements have been done under standardized Epstein frame protocols.
The robust trust-region-reflective algorithm implemented as Matlab routine *lsqcurvefit* was used for the estimation purposes. The parameter set was: $\alpha=9.48\cdot 10^{-5}$, a=40A/m, $M_s=1.2\cdot 10^6$A/m, H_{Hs}=50A/m and γ=0.12A/m. The maximum flux density for the major loop was B_m=1.4T, whereas the excitation frequency was 3Hz. It was assumed that the distortion of hysteresis loop due to eddy currents could be neglected for this value of excitation frequency. The obtained set of model parameters was used next for modeling minor loops. Figure 1 depicts the modeling results for two amplitudes of flux densities, B_m=1.1 and 0.7T, respectively. It can be stated that the model is able to reproduce the shape of minor loops quite accurately.

A predictive model and easily implementable hysteresis model has been presented for ferromagnetic laminations subjected to various quasi-static magnetic loads. In this model, the description of magnetic hysteresis is based on the decoupling of the magnetic field strength in an reversible and irreversible part unlike as in the Jiles-Atherton model and it allows for a systematic parameter identification. The structure of the model enables an inclusion of eddy current effects and is ready for a further exploitation in the FE modelling of macroscopic devices.

The full paper will illustrate, in addition to comparisons with measured minor loops, the models sensitivity to variations of parameters.

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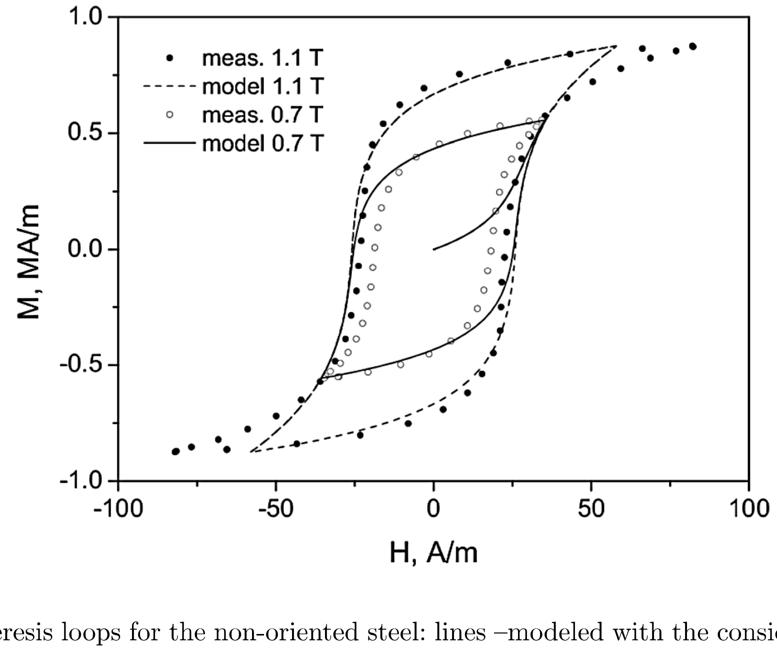

Figure 1. Minor hysteresis loops for the non-oriented steel: lines –modeled with the considered description, dots – experimental data points