

EVALUATION METHOD FOR THE PARAMETERS OF A MAGNETIC HYSTERESIS MODEL

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Introduction

The models of magnetic devices having a magnetic core without known parameters require the core evaluation by means of sophisticated measurement procedures and systems. For certain models, higher measurement accuracy is of key importance. For the other models, additional factors (speed, cost, measurement instruments and apparatus) may strongly limit achievement of the specific measurement requirements.

Numerous techniques have been developed for hysteresis description, among which the models of Preisach, Jiles-Atherton and Stoner-Wolfarth are the most widespread.

The existing hysteresis models can be roughly divided in two different classes: mathematical and physical models. Physical models, such as the model of Jiles-Atherton [1], consider the underlying physics of hysteresis to model the phenomenon. Mathematical models, such as the Preisach model [2], consider hysteresis as a superposition of elementary rectangular hysteresis loops. By measuring the Everett-function, a certain weight is assigned to every dipole. Sophisticated Preisach models also comprise dynamical effects and anisotropy. The Stoner-Wolfarth model regards the hysteresis loop as a superposition of an infinite number of dipoles. Here, the dipoles themselves can have a non-rectangular hysteresis loops, and that is why this model has a lot of numerical disadvantages when compared to the Preisach model.

The Jiles-Atherton model is the model of choice for the modeling of ferromagnetism in soft magnetic materials, such as electrical steel. Although it was developed over the course of several publications, the classic paper is generally considered to be [1]. David Jiles later published an entire text on magnetism [3], which contains the model, as well as extensions such as stress effects.

PSpice software currently includes non-linear magnetic cores based on the Jiles-Atherton model [4]. The Jiles-Atherton model requires both geometric parameters (such as effective air-gap length) and materials parameters (such as domain anisotropy). The required information is simply not available except for a limited number of cores in the supplied library. Vendor data sheet don't include values for domain anisotropy. Even a relatively innocuous sounding parameter like effective air gap length is fraught with dangerous complications.

This paper presents a method and the experimental measurement system for the determination of Jiles-Atherton parameters of the unknown magnetic core by minimizing the error between experimental and simulated magnetic field curves. Comparison of experimental and simulated results validates the procedure.

The Jiles-Atherton Parameters

The Jiles-Atherton method derives a hysteresis loop out of the Weiss-theory for ferromagnetism. The model relies upon a set of differential equations, for which five parameters have to be determined by a measurement of the hysteresis loop.

Jiles and Atherton (1983) used an energy balance to model magnetic hysteresis. The energy supplied to the material by a change in the applied field can be dissipated either as a change in magnetostatic energy, or as hysteresis loss. In the absence of hysteresis, all the energy supplied would go toward modifying the magnetostatic energy. In such a case, the magnetisation would be a reversible, single-valued function of the applied field. This anhysteretic magnetisation M_{an} can be modeled as:

$$M_{an} = M_S \cdot f(H_e) \quad (1)$$

where M_S is the saturation magnetisation, $H_e = H + \alpha M$ is the Weiss mean field.

A modified Langevin expression was used to model M_{an} :

$$M_{an}(H_e) = M_S \left[\coth\left(\frac{H_e}{a}\right) - \left(\frac{a}{H_e}\right) \right] \quad (2)$$

where a is a parameter with units of field.

The energy supplied E_{supp} can therefore be expressed in terms of M_{an} :

$$E_{supp} = \mu_0 \int M_{an}(H) dH \quad (3)$$

Hysteresis loss was attributed to domain wall pinning by sites distributed at random, all of which had the same pinning energy for 180° walls, $\langle \varepsilon_{\pi} \rangle$. For other domain wall angles θ , the pinning energy $\langle \varepsilon_{pin} \rangle$ is:

$$\langle \varepsilon_{pin} \rangle = \frac{1}{2} \langle \varepsilon_{\pi} \rangle (1 - \cos \theta) \quad (4)$$

For an average pinning site density per unit volume n , the total energy dissipated against pinning when a domain wall of area A sweeps out a distance x between domains at an angle θ to one another is:

$$E_{pin}(x) = \int_0^x \frac{n \langle \varepsilon_{pin} \rangle}{2m} [1 - \cos \theta] A dx \quad (5)$$

where m is the magnetic moment of a typical domain. This gives a net change in magnetisation dM :

$$dM = m(1 - \cos \theta) A dx \quad (6)$$

Hence E_{pin} can be expressed in terms of M :

$$E_{pin}(M) = \frac{n \langle \varepsilon_{pin} \rangle}{2m} \int_0^M dM \quad (7)$$

The constant $n \langle \varepsilon_{pin} \rangle / 2m$ was named the pinning parameter k .

Equating E_{supp} with the sum of E_{pin} and the magnetostatic energy due to the change in magnetisation dM gives:

$$\frac{dM}{dH} = \frac{M_{an}(H) - M(H)}{k} \quad (8)$$

A subsequent modification allowed for reversible magnetisation M_{rev} , assuming wall-bowing in the direction tending to reduce the difference between the actual magnetisation M and M_{an} :

$$M_{rev} = c(M_{an} - M) \quad (9)$$

where c is a constant. The final equation is then given by:

$$\frac{dM}{dH} = \frac{M_{an}(H) - M_{irr}(H)}{(k\delta / \mu_0) - \alpha [M_{an}(H) - M_{irr}(H)]} + c \left(\frac{dM_{an}}{dH} - \frac{dM}{dH} \right) \quad (10)$$

where M_{irr} is the irreversible component of magnetisation and δ is a parameter inserted to account for the direction of field increase:

$$\begin{aligned} \delta &= +1 & dH/dt > 0 \\ \delta &= -1 & dH/dt < 0 \end{aligned} \quad (11)$$

Hysteresis can therefore be expressed in terms of constants: α , a , M_S , c and k . Jiles and Atherton later modified k so that it had the same dimensions as H_C :

$$k = \frac{n \langle \varepsilon_{pin} \rangle}{2m\mu_0} \quad (12)$$

Extensions have been made to this model to allow the modeling of minor loops (Jiles and Atherton, 1984; Carpenter, 1991), and the effects of magneto crystalline anisotropy (Ramesh et al., 1996, 1997) and crystal texture (Shiet al., 1998). Methodologies for the extraction of modeling parameters from experimental data have also been developed (e.g. Jiles et al., 1992; Del Moral Hernandez et al., 2000).

The measurement problems appear during the stage of parameter evaluation of the hysteresis loop using the Jiles-Atherton model.

In measurements practice it is not easy and very time consuming to obtain all these magnetic parameters with the required accuracy [5], [6], [7]. There are two major reasons for considering a new measurement technique for solving these problems. On the one hand, the accurate modeling of the magnetic hysteresis in order to find information about particular conditions not likely to turn up in the actual device employing magnetic materials is of great interest. On the other hand, automatic parameter evaluation overcomes the problems arising from the technique based on successive trials and, moreover, represents a saving of time.

Pspice Method

The Jiles-Atherton model requires the evaluation of the core mechanical parameters and the magnetic parameters [8], [9], [10]. The core mechanical parameters are as follows:

- mean magnetic cross section (*AREA*);
- mean magnetic path length (*PATH*);
- the effective air-gap length (*GAP*);
- stacking factor (*PACK*).

These parameters must be determined according to the magnetic device data books, the design parameters, and the manufacturing characteristics (for example, determination of the air-gap length and the stacking factor depends upon the manufacturing characteristics).

The magnetic parameters must be determined experimentally according to the explanation of the magnetic hysteresis phenomenon assumed from the model.

In order to build the learning set, the Jiles-Atherton model implemented by the SPICE circuit simulator was utilized. Example circuit files:

```
IGEN 0 1 PWL(0 0, 2.7 2.7, 8.1 -2.7, 13.5 2.7)
L1 1 0 8 IC=0
K1 L1 .9999 KRM6PL_3C8
MODEL KRM6PL_3C8 CORE (MS=400E3
ALPHA=2E-5 +A=26 AREA=400
PATH=2.75)
TRAN .1 13.5 2.7 .1 UIC
PROBE
END
```

The measurement method for evaluating the parameters of the hysteresis loop of magnetic materials is organized as follows. Firstly, the method requires the acquisition of both current and voltage signals associated with, respectively, the magnetizing force and magnetic induction of the magnetic hysteresis loop of the material under test. Secondly, using a proper multidimensional optimization procedure, all the magnetic parameters are more accurately obtained.

The proposed method

The model assumes the following magnetic parameters:

- the magnetization saturation (*MS*);
- the mean-field parameter (*ALPHA*), representing inter-domain coupling;
- the shape parameter (*A*), with dimensions of the magnetic field and characterizing the shape of the anhysteretic magnetization curves;
- the domain wall flexing constant (*C*) determined by the ratio of the initial differential susceptibilities of normal and anhysteretic magnetization curves;
- the domain wall pinning constant (*K*), which modifies only the shape of the hysteresis.

In order to investigate the applicability of the optimization procedure for accurate parameter evaluation, numerical tests were carried out, organized as follows:

- setting up of the *MS*, *ALPHA*, *A*, *C* and *K* parameters of the Jiles-Atherton model implemented in the PSPICE circuit simulator;
- measurement of the hysteresis loop;
- determination of the hysteresis loop with the assigned parameter value;
- use of the optimization procedure to evaluate the parameters.

Measurement System and Experimental Results

The experimental curves shown in this paper were obtained with a measurement system based on an Epstein's frame 0.28 m long with 0.03 m width iron sheets – Figure 1.

The primary and secondary windings have 700 turns ($N_p = N_s = 700$). The magnetic mean path is $l_m = 0.94$ m. The secondary voltage $v_s(t)$ and the primary current $i_p(t)$ are measured simultaneously with a digital oscilloscope HP 5400A with RS 232 – Figure 2.

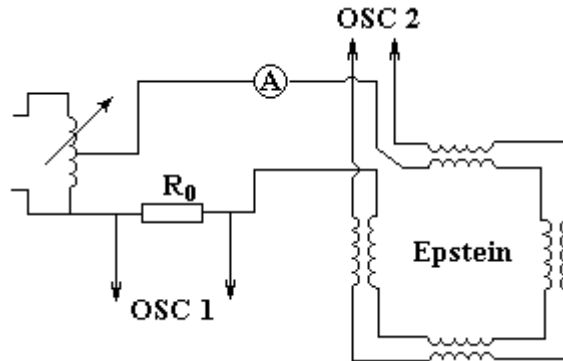


Fig. 1. The Epstein measurement method

The magnetic field is related to the $i_p(t)$ current by:

$$H(t) = \frac{N_p}{l_m} i_p(t) \quad (13)$$

The magnetic induction is obtained by time integration of the voltage $v_s(t)$ in the secondary coil:

$$B(t) = \frac{1}{N_s S} \int v_s(t) dt \quad (14)$$

where S is the cross section of the Epstein's frame.

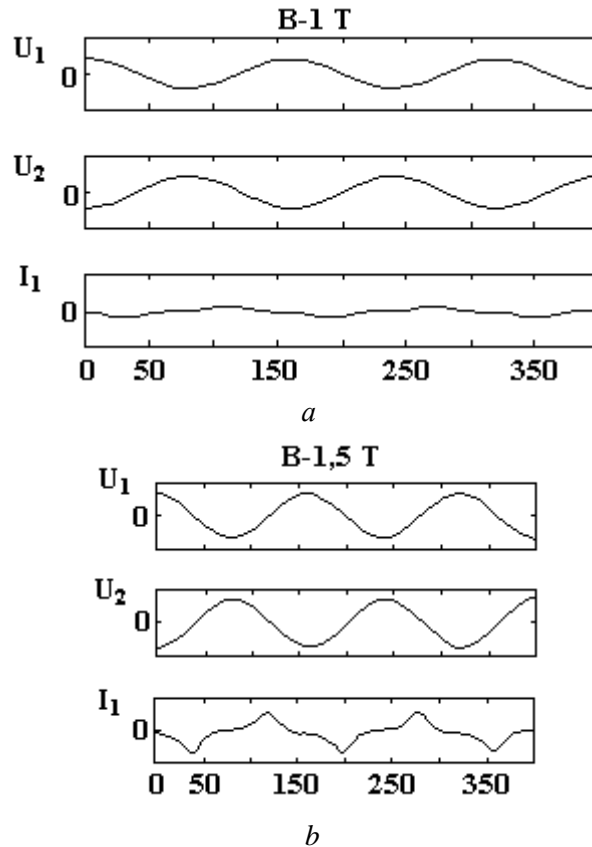


Figure 2. Experimental curves for voltages and primary current: a) $B = 1$ T; b) $B = 1,5$ T

The experimental hysteresis loop is presented in the figure 3. The curves refers to the experimental hysteresis loop for $B = 1\text{T}$ and $B = 1,5\text{ T}$.

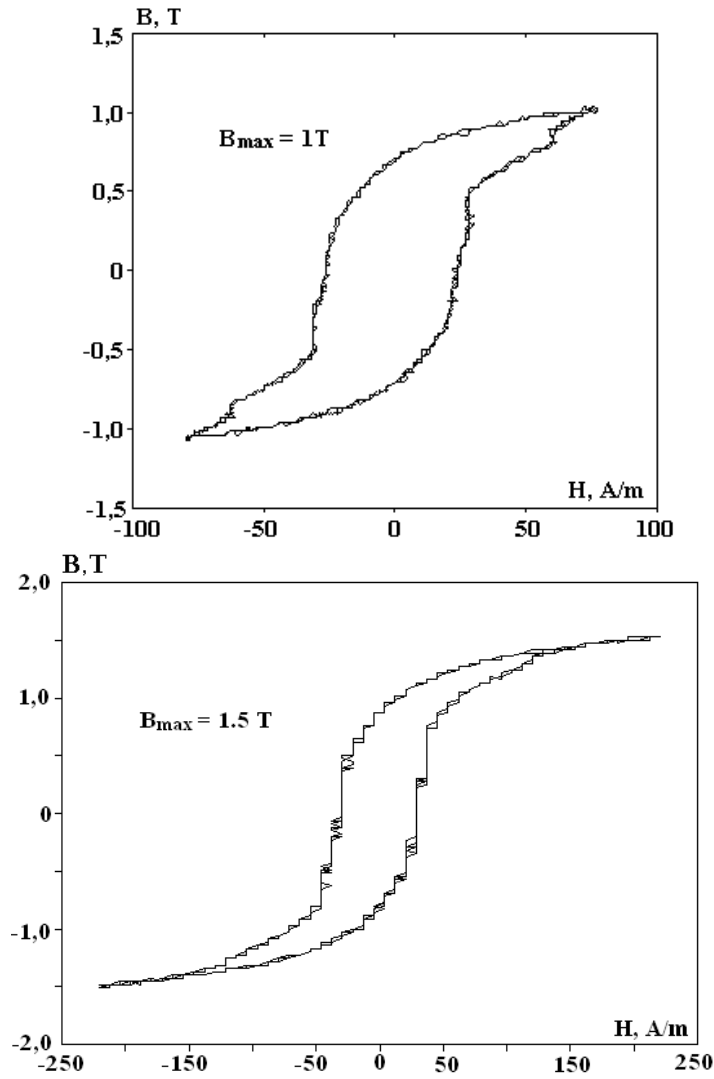


Figure 3. The experimental hysteresis loop

The method of determination of magnetic parameters of loop is presented in Figure 4.

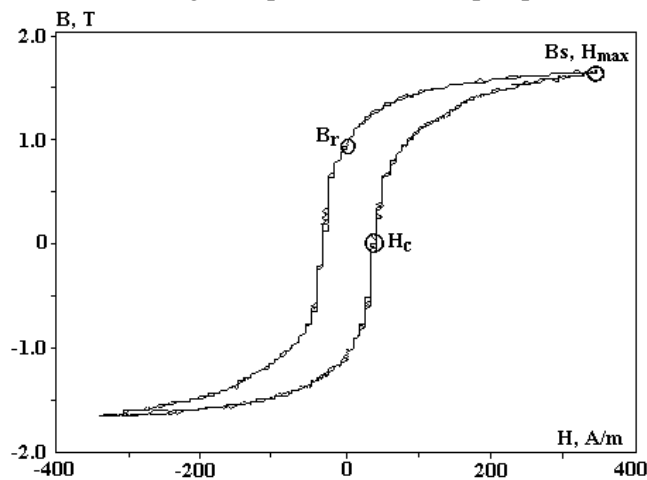


Figure 4. Parameters determination of measured magnetic loop

The results of simulation with the PSPICE simulator are presented in Figure 5 with the magnetic parameters set.

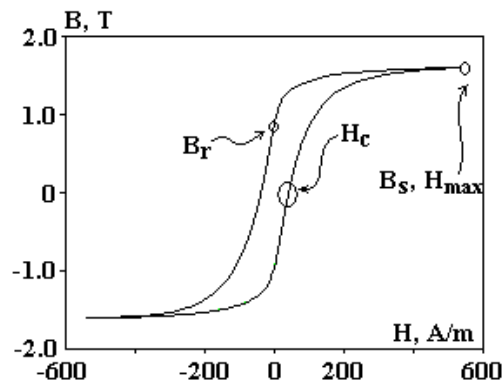


Figure 5. Parameter evaluation of the Jiles-Atherton model of the hysteresis loop

In order to determine the Jiles-Atherton parameters, each one of them is modified one at the time, taking into account that each coefficient has a different effect on the form and the dimensions of the hysteresis cycle. The obtained curve is compared with the real one using the PSICE program. In case the manufacturer has given the hysteresis curve, the Jiles-Atherton parameters must be chosen so that the curve from the PSPICE simulation is identical with it.

A faster way offers the representation on the same chart of more hysteresis curves resulted from the parameters variation. From the five parameters that influence the shape of the curve four are kept constant and the fifth is varied.

The optimization procedure is set on the basis of the MS variation:

```

PARAM X=1400e3
STEP PARAM X LIST 1200e3 1400e3 1600e3
IGEN 0 1 PWL(0 0,2.7 2.7,8.1 -2.7, 13.5 2.7)
L1 1 0 100 IC=0
K1 L1 .99 KSIL014
MODEL KSIL014 CORE (MS = {X} ALPHA=2e-5
A=25 K=18 C=2 AREA=70 PATH=25
+GAP=0 PACK=1)
.TRAN .1 13.5 2.7 .1 UIC
.PROB
.END

```

In Figure 6 is presented the result of optimization with the variation of MS.

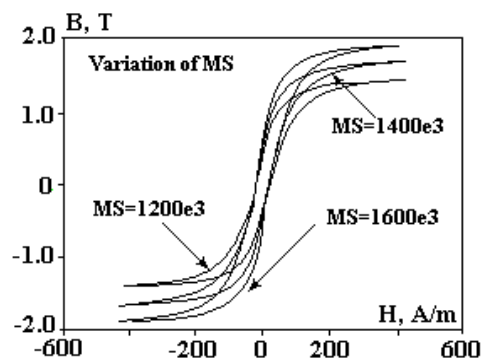


Figure 6. Simulated hysteresis loops

Results of applying the method for electro-technical steel with 0.25% Carbon are:

- MS = 1600e3
- Alpha = 1.6e-3
- A=1100
- k = 400
- C = 0.2

Conclusions

The paper presented a method for the evaluation of Jiles-Atherton model's parameters of the hysteresis loop of magnetic materials. The method starts with data acquisition of the current and voltage associated with magnetizing force and magnetic induction of the experimental magnetic loop.

The values of the parameters are obtained by using the optimization procedure. This procedure evaluates the model's parameters by comparing the experimental and the simulated magnetic loops.

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Summary

This paper presents a method based on use of a measurement system in order to improve the accuracy and to significantly reduce the time taken in evaluating parameters of the Jiles-Atherton's model of magnetic hysteresis. The steps of the proposed method: data acquisition from the experimental hysteresis loop of the magnetic material under test and evaluation of the model's parameters. In order to highlight the method's effectiveness, the results of experimental tests are also given.
