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PHENOMENOLOGICAL MODEL OF THE FREQUENCY-DEPENDENT HYSTERESIS OF FERRITE $NiFe_2O_4$

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In this paper, a phenomenological model of dynamic hysteresis based on the static Preisach model has been developed to generate hysteresis loops, which are assumed to be a frequency function of the exciting magnetic field. The frequency effect was introduced through a new model of the frequency-dependent behavior of the Student function parameters *a* and *b*. The simulated hysteresis loops obtained using our proposed model show a good agreement with a real hysteresis loop obtained via measurements performed on a ferrite material $NiFe_2O_4$.

1. INTRODUCTION

In the last decade, the fast development of wind and solar energy led to the large use of power electronics components [1]. This accelerating development has significantly increased frequency use in static power converters. Several types of research have been carried out to develop hysteresis models that accurately reflect the behavior of magnetic materials as a frequency function.

The most used hysteresis models are the dynamic Jiles model [2] and its extensions [3, 4]. In [5–8] authors suggest using dynamic Preisach models [5–8], which are also widely used.

Although the cited models led to good performances, they have drawbacks such as implementation difficulty and large computation time. Moreover, they do not consider the effect of frequency on the magnetic hysteresis loops. In this work, we present a simple approach to introducing the frequency effect through the Student distribution function. In addition, to consider the frequency effects in the Preisach model and precisely generate the frequency-dependent hysteresis loops, we suggest replacing the Student function constant parameters *a* and *b* [9,10], with two frequency-dependent dynamic functions. Our new model is validated by comparing the simulated hysteresis loops and an experimental one performed on a ferrite material $NiFe_2O_4$.

This paper is organized as follows: in section 2, we present the Static model of Preisach. Our proposed model is presented in section 3, and then section 4 is reserved for simulation results and discussions. Finally, we conclude our work in Section 5.

2. STATIC MODEL OF PREISACH

Preisach static model is composed of a set of elementary hysteretic operators. Each operator represents a function describing an elementary hysteresis loop with two possible states ($M = -1$ and $M = +1$) [11]. Where the values α and β correspond to the up (α) and down (β) values tilting the magnetic field, with $\beta \le \alpha$. This operator is also called hysteron (Fig. 1). The final function is obtained by summing the weighted hysterons. The Preisach model is then given as follows: $M(t)$ *represents* the magnetic magnetization resulting from the application of the field $H(t)$ at instant *t*, and $\rho(\alpha,\beta)$ represents Preisach distribution density function:

$$M(t) = \iint \rho(\alpha,\beta)\varphi_{\alpha\beta}[H(t)]\mathrm{d}\alpha\mathrm{d}\beta \,. \qquad (1)$$

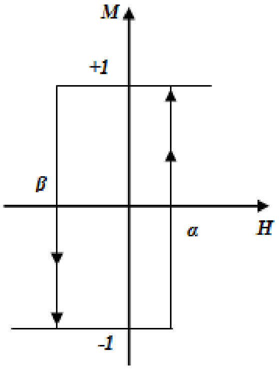

Fig. 1 – Elementary loop of a magnetic entity to write β under the axle.

2.1. PREISACH DISTRIBUTION DENSITY

The complete Preisach model definition requires *a priori* knowledge of the Preisach distribution function. Consequently, it is necessary to compute the final magnetization of the ferromagnetic sample described by (1).

Two research directions have been followed to determine it, the first from a single or a set of experimental loops [12–17], and the second is to approach it using an analytical expression [18–20]. In what follows, we propose to use the Student function proposed in [9]. The reason motivated for this choice lies in the fact that the variation of the parameter *b* of this function induces a significant variation of the coercive field, a slight variation of the saturation induction B_s, remanence induction B_r, and the surface of the hysteresis loop.

However, variation of the parameter *a* produces a variation of the saturation induction B_s, and remanence induction B_r. While the coercive field H_c is not affected by the parameter *a* variation. The frequency of the excitation field affects the coercive field and hysteresis loop surface. The parameter *b* of the student function has a slightly similar effect to that of the frequency compared to the influence of parameter *a*. This leads us to propose introducing the frequency effect in the scalar Preisach model by adapting the Student distribution function parameters *a* and *b*. Therefore, the function is given by the following expression [10]:

$$\rho(\alpha,\beta) = ka\sqrt{a}\left(a+\left(\frac{\alpha}{H_c}-b\right)^2\right)^{\frac{-3}{2}}\left(a+\left(\frac{\beta}{H_c}+b\right)^2\right)^{\frac{-3}{2}}, \qquad (2)$$

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where H_c represents a coercive field, k represents normalization coefficient, $a \in R_+^*$, $b \in [\, H_c/H_s,\ H_s/H_c]$, and H_s is the saturation field.

3. **INTEGRATION OF THE FREQUENCY EFFECT IN THE STATIC PREISACH MODEL**

The frequency effect of the exciting magnetic field is integrated into the static Preisach model using an adapted model of the parameter *a* and *b*.

3.1. DETERMINATION OF THE MODEL PARAMETERS AS A FUNCTION OF THE FREQUENCY

The variation of the hysteresis loop as a function of frequency follows a non-linear law; we will propose models whose parameters will be determined using experimental data. The laws of variation of the parameters *a* and *b* as a function of frequency that we propose are given by the following expressions:

$$a(f) = a_0(1 + a_1\sqrt{f^{a_2}}), \tag{3}$$

$$b(f) = b_0(1 + b_1\sqrt{f^{b_2}}), \tag{4}$$

where a_0, a_1, a_2, b_0, b_1, and b_2 are real constants.

3.2. PROCEDURE TO IDENTIFY PROPOSED MODEL PARAMETERS

To identify the parameters of the Student distribution function using a set of experimental data related to a hysteresis cycle, we suggest applying a metaheuristic optimization algorithm such as particle swarm optimization (PSO) [20]. PSO is widely used due to its simplicity and its efficiency in solving complicated nonlinear problems.

The complete steps used to identify the parameters of the student distribution function are well explained in [21].

In our case, the steps of the algorithm are the following:

A – Initialization: Generation of the initial population, initialization of the velocity and control parameters ω, p_1 and p_2.

B – Evaluation of the objective function of each solution (is the squared error between the measured and simulated loop).

C – Update of the gbest_i^t et pbest_i^t.

D – Update of velocities $\nu_i^t(\nu_{ai}, \nu_{bi}, \nu_{ki})$ and positions $x_i^t(a_i, b_i, k_i)$.

$$\begin{cases} \nu_i^{t+1} = \omega\nu_i^t + p_1\text{rd}_1 \times (\text{pbest} - x_1) + p_2\text{r}d_2 \times (\text{gbest} - x_i) \\ \text{rd}_1, \text{rd}_2 \in [0, 1] \\ x_i^{t+1} = x_i^t + x_i^t\ . \end{cases}$$

E – Repeat (B), (C) and (D) steps until the stop condition is verified.

Here x_i is the current position of particle *i*, pbest is the best position obtained by particle *i*, gbest is the swarm's global best position, ν_i is the velocity of particle *i*, ω is an inertia weight, p_1 and p_2 are social and cognitive parameters and *t* is the current iteration.

4. **EXPERIMENTAL RESULTS**

To validate our proposed dynamic Preisach model, we suggest comparing the simulated hysteresis loop with the one obtained using experimental data of a solid ferrite material NiFe$_2$O$_4$.

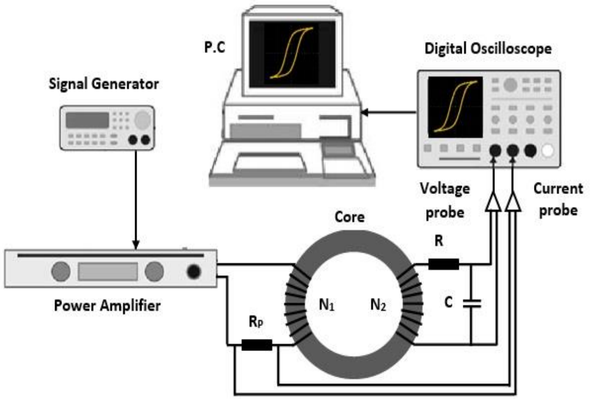


Fig. 2 – Experimental bench scheme [8]

The experimental bench (see Fig. 2) and the measurement method we used are well explained in [9]. The used core parameters and experimental conditions are summarized in Table 1.

Table 1

Core parameters and experimental conditions of the studied material

NiFe$_2$O$_4$ ferrite material	Diameter (Outer diameter d_o and Inner diameter d_i)	d_0 = 71mm d_i = 57mm
	Maximum magnetic induction B_s	B_s = 0.128T
	Remanence magnetic induction (B_r) at 200 Hz	B_r = 0.0773T
	Coercive field (H_c) at 200 Hz	H_c = 24.61A/m

4.1. RESULTS AND DISCUSSIONS

Figure 3 shows the evolution of the optimization process for the Student distribution function parameters *a* and *b* at 200 Hz frequency.

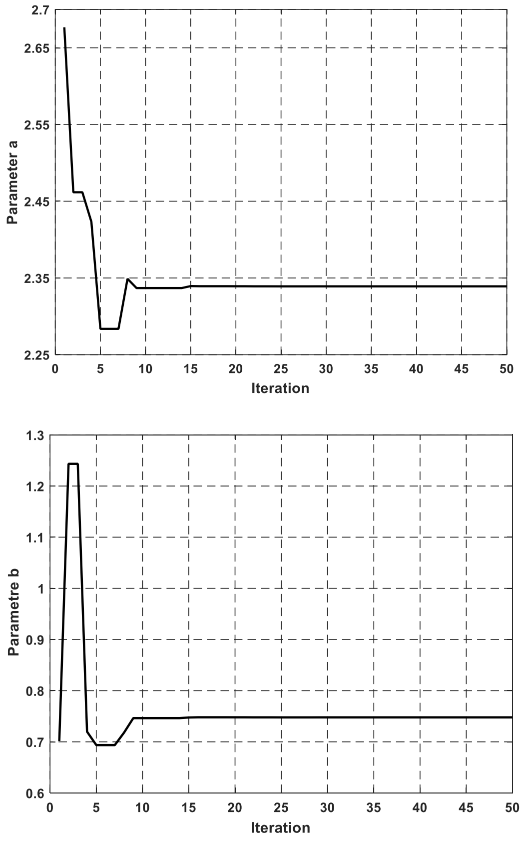


Fig. 3 – Optimization process evolution of parameters *a* and *b*.

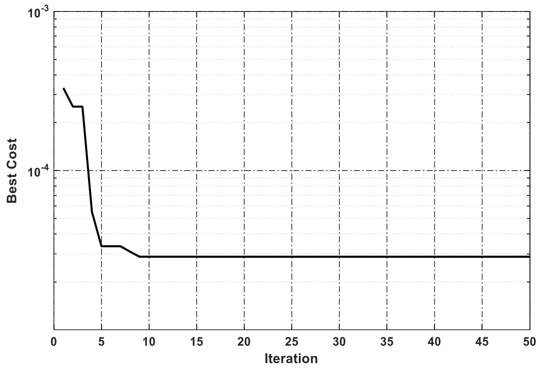
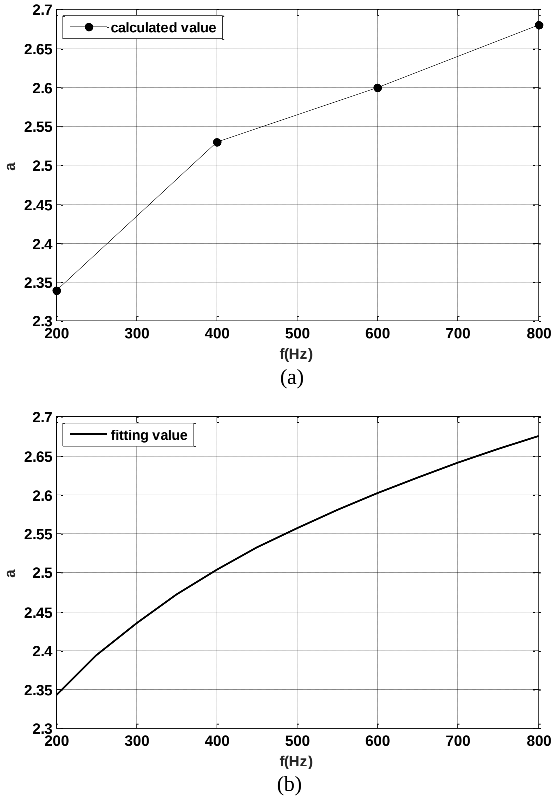


Fig. 4 – Convergence curve of the optimization process using PSO (*f*=200 Hz).

We show in Fig. 4, the evolution of the mean square error ε between simulated hysteresis loops and experimental data extracted from a descending branch of the experimental cycle (for $f = 200$ Hz).

The evolution curve of the parameter a as a function of frequency Fig. 5a was used to identify the constants a_0, a_1, and a_2 Fig. 5b, whereas the constants b_0 b_1, and b_2 (Fig. 6.b) can be identified using the evolution curve of the parameter b Fig. 6a.



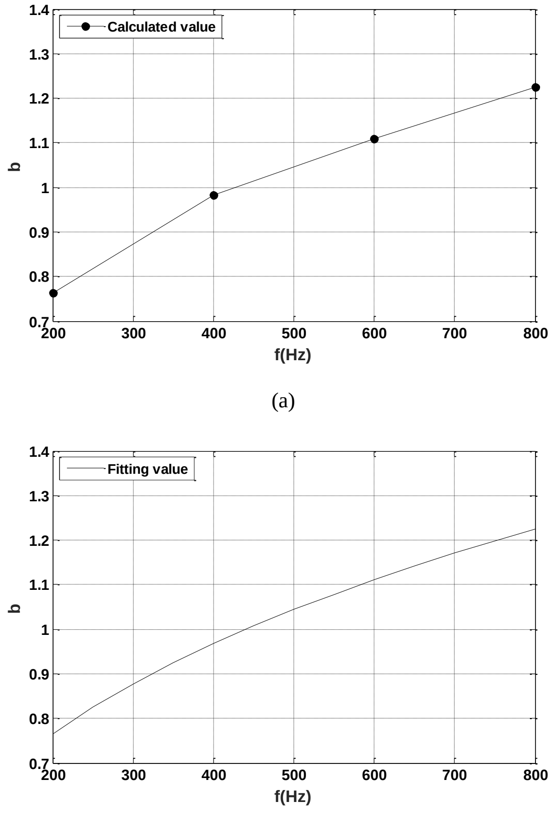
(a)

(b)

Fig. 5 – Parameter a evolution ($a_0 = 0.0239$, $a_1 = 58.1481$ and $a_2 = 0.1933$).

After the introduction of the two parameters $a(f)$ and $b(f)$ (eqs. 3 and 4) into the Student function (eq. 2), we associate the dynamic distribution function with the static Preisach model which will allow us to easily produce a hysteresis loop as a function of frequency as shown in Fig. 7.

The curves that are shown in Fig. 8 represent the comparison between the simulations results and those obtained experimentally using a ferrite material $NiFe_2O_4$ with working frequencies that are respectively: $f = 200$ Hz, $f = 400$ Hz, $f = 600$ Hz, and $f = 800$ Hz.



(a)

(b)

Fig. 6 – Parameter b evolution ($b_0 = 0.0018$, $b_1 = 7\ 0$ and $b_2 = 0.6796$).

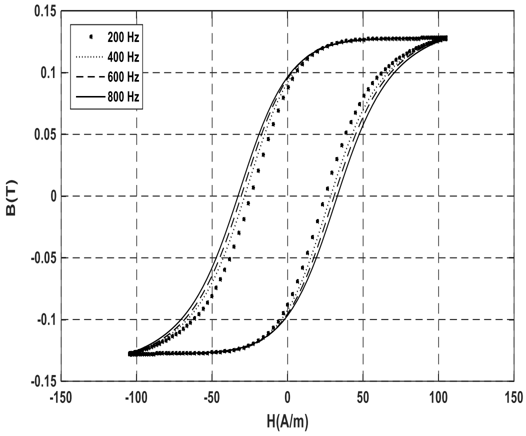
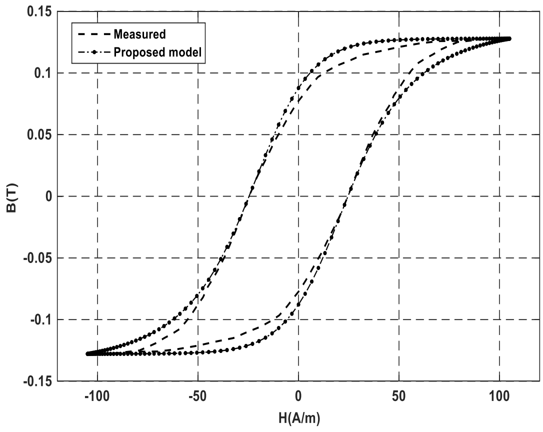
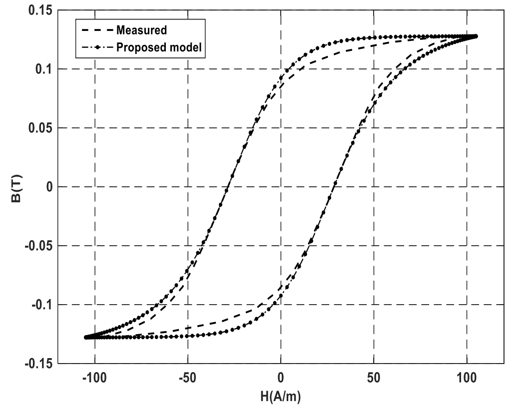


Fig. 7 – Hysteresis loops evolution generated by the proposed model as a function of frequency for $B_s = 0.128$ T.



(a)



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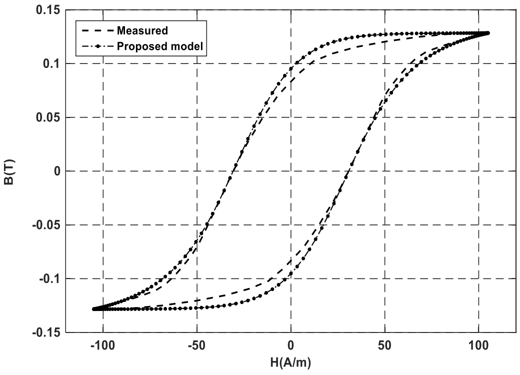
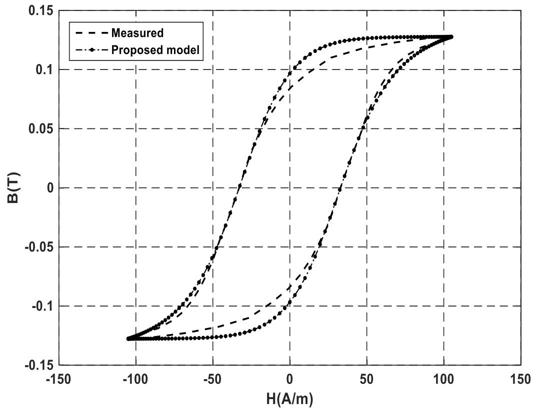


(c)



(d)

Fig. 8 – Measured and simulated hysteresis loops at different frequencies: a) $f = 200$ Hz; b) $f = 400$ Hz; c) $f = 600$ Hz and d) $f = 800$ Hz for $B_s = 0.128$ T.

Table 2 compares the measured and simulated values of saturation magnetic induction B_s, remanence B_r, and coercive field H_c at different frequencies. The errors between the measured and simulated values of H_c, B_r, and B_s are very small. These results show the efficiency of our proposed model.

Table 2

Comparison between simulation and experimental results at different frequencies

Frequency (Hz)	200	400	600	800
B_s (T) Measured	0.128	0.128	0.128	0.128
B_s (T) Simulated	0.1278	0.1278	0.1284	0.1276
Error (%)	0.16	0.16	0.31	0.31
B_r (T) Measured	0.0773	0.0851	0.0832	0.0839
B_r (T) Simulated	0.0878	0.0923	0.0953	0.0967
Error (%)	13.58	8.46	14.54	15.26
H_c (A/m) Measured	24.61	28.4885	30.7870	32.9076
H_c (A/m) Simulated	24.6116	28.4956	30.7872	32.9035
Error (%)	6.5×10^{-3}	2.59×10^{-2}	6.50×10^{-4}	1.25×10^{-2}

5. **CONCLUSIONS**

In this paper, a dynamic hysteresis model has been proposed. The frequency effect of the excitation field has been introduced in the static Preisach model by exploiting the two parameters a and b of the Student function. We replaced the two parameters, a and b, with two functions that depend on the excitation magnetic field frequency. The particle swarm optimization (PSO) is used to identify the values of the Student distribution function parameters. Simulation obtained by our proposed model has been compared with real measurements performed on a ferrite material $NiFe_2O_4$ for limited operating frequencies by the used system. The comparison test showed that our new model was in good agreement with the measurement results.

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