



MODELING OF FREQUENCY EFFECTS IN A JILES-ATHERTON MAGNETIC HYSTERESIS MODEL

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Key words: Hysteresis model, Jiles-Atherton theory, Ferromagnetic materials, Frequency dependence.

A frequency-dependent model is necessary, to understand the dynamic behavior of hysteresis phenomenon in ferromagnetic materials. In this study, the hysteresis model based on Jiles-Atherton theory was developed, to simulate the frequency effects on the magnetic hysteresis loop. The frequency effects have been integrated in the model, by introducing the frequency behavior of the parameter k from Jiles-Atherton theory. The proposed model was validated, by comparing the results with those provided by the dynamic Jiles model, and the results are in good agreement.

1. INTRODUCTION

The modeling of the magnetic hysteresis is very important in the design of electromagnetic devices [1]. The hysteresis loop of a ferromagnetic material depends on several factors such as: temperature, shape of the sample, type of the excitation [2] and frequency. However, the magnetic behavior of ferromagnetic materials can be significantly modified by the variation of frequency and, therefore, the hysteresis loop can be changed substantially.

Several models are proposed in literature, in order to analytically describe the hysteretic behavior of the materials such as: the Bertotti model [3], the Bernard model [4] and the dynamic Jiles model [5]. These three models are often quite difficult to implement and they are very expensive regarding the calculation time. In addition, they do not clearly consider the effect of frequency on the hysteresis loop.

In this paper it is suggested a change in the Jiles-Atherton (JA) model, by introducing the frequency effect.

2. THE JILES-ATHERTON MODEL

In the JA model, the magnetization M is decomposed into two parts: the reversible component M_{rev} and the irreversible component M_{irr} [6]. The reversible component represents the translation and the movement of the domain walls (DWs) and the reversible rotation of the magnetization vector in ferromagnetic materials. The irreversible component represents the irreversible displacement of the magnetic domain walls. The relationship between these two components and the anhysteretic magnetization M_{an} (the ideal case is considered without losses) is based on physical considerations of the magnetization processes.

The equations of the JA model are:

$$M = M_{irr} + M_{rev}, \quad (1)$$

$$M_{rev} = c(M_{an} - M_{irr}), \quad (2)$$

$$M_{an} = M_S \left(\coth \frac{H_e}{a} + \frac{a}{H_e} \right), \quad (3)$$

$$\frac{dM_{irr}}{dH_e} = \frac{M_{an} - M_{irr}}{k\delta}, \quad (4)$$

where k is proportional to hysteresis losses, a is the shape parameter for M_{an} , c is the reversibility coefficient and M_S

is the saturation magnetization. All the model parameters are determined from an experimental hysteresis loop and δ is a factor that takes the value $+1$, when $dH \geq 0$, and -1 when $dH < 0$.

The term H_e is the effective field, which is the sum of the applied field H and the molecular field αM as described by eq (5):

$$H_e = H + \alpha M, \quad (5)$$

where the parameter α must be determined experimentally.

Using Eqs. (1–4), and after substitution and simplification, we obtain the following differential equation for JA model.

$$\frac{dM}{dH} = \frac{(1-c) \frac{dM_{irr}}{dH_e} + c \frac{dM_{an}}{dH_e}}{1 - \alpha c \frac{dM_{an}}{dH_e} - \alpha(1-c) \frac{dM_{irr}}{dH_e}}. \quad (6)$$

The JA model has already been extended to include magneto-elastic effects [7–8], anisotropy [9], temperature [10–16]. The previous works on extending the model to include frequency effects [17] were based on the coupling between the JA model and the mathematical model of Chua. On the other hand, a new extension of JA model [6] was developed by Jiles in [5]. This new energy approach, based on the separation of losses, helps one to develop the Jiles dynamic model. The losses in a magnetic material consist of hysteresis, eddy current (eq. 7) and anomalous (excess) losses (eq. 8):

$$\frac{dW_{ec}}{dt} = \frac{(d\mu_0)^2}{2\rho\beta} \left(\frac{dM}{dt} \right)^2, \quad (7)$$

$$\frac{dW_a}{dt} = \left(\frac{GdwH_0}{\rho} \right)^{1/2} \left(\frac{dB}{dt} \right)^{3/2}, \quad (8)$$

where ρ is the resistivity, d is the cross-section of the sample, β is a geometrical factor, $G = 0.1356$, w is the width of the lamination and H_0 is a parameter representing the internal magnetic field, who acts on the domain walls. By using the equations of JA model and adding the two components of losses (eddy current and excess losses) we can deduce the differential equation of the Jiles dynamic model:

$$\frac{\mu_0}{2\rho\beta} \frac{dH}{dt} \left(\frac{dM}{dH} \right)^2 + \left(\frac{\mu_0 G d w H_0}{\rho} \right)^2 \left(\frac{dH}{dt} \right)^2 \left(\frac{dM}{dH} \right)^3 + \left[k\delta - \alpha \left(M_{an} - M + k\delta c \frac{dM_{an}}{dH_e} \right) \right] \left(\frac{dM}{dH} \right) - \left(M_{an} - M + k\delta c \frac{dM_{an}}{dH_e} \right). \quad (9)$$

This equation can be solved with the Newton-Raphson method with $\frac{dM}{dH}$ as unknown parameter.

The present investigation focuses on the integration of the frequency effect on the JA model through the parameter k and comparing the hysteresis loops generated by the JA frequency dependent model with the cycles, generated by the dynamic Jiles model.

3. IMPLEMENTATION OF THE FREQUENCY IN THE JA MODEL

The frequency effects can be taken into account in JA model through the parameter k , which depends on the frequency.

The other JA model parameters (M_s , a , c , and α) are treated as constants, because their variations with frequency are negligible.

Because of the dependence of one parameter with the frequency, it is clear that the frequency dependent JA model is easier to implement numerically. In addition, the resulting model is numerically stable, because it does not solve non-linear system. However, due to the fact that it is time consuming, the dynamic Jiles model is more complex to implement and it has also numerical stability problems.

In soft ferromagnetic materials the parameter k can be approximated to the coercive field H_c ($k \approx H_c$) [18].

The frequency behavior of the parameter k can be expressed, using the evolution curve of the coercive field H_c versus frequency, as shown in the following expression:

$$k_f = k_0(1 + \beta\sqrt{f}), \quad (10)$$

where k_f is the value of k at a given frequency, k_0 and β are two constants that are determined from the evolution curve of the coercive field H_c as function of frequency f . This function is suitable for the studied ferromagnetic sample (non-oriented electrical steel) and it cannot be generalized, because each ferromagnetic sample has its own frequency behavior.

The identification procedures of JA model parameters are well documented in [18–20]. The coercive field H_c is calculated (in the dynamic Jiles model) as a function of frequency and it was used to estimate the k_0 and the β values.

4. RESULTS AND DISCUSSIONS

The evolution curve of the coercive field depending on the calculated frequency (Fig.1), based on the Jiles dynamic model, was used to identify k_0 and β .

To describe the behavior of frequency magnetic hysteresis through the frequency dependent JA model, it is enough to

calculate the parameters M_s , α , c and a of the JA model, then adjusting the analytical model as described in eq. (10).

The simulation of the hysteresis phenomenon, by introducing the frequency behavior of the parameter k , allows a change of the coercive field and consequently of the hysteresis loop area (Fig. 2).

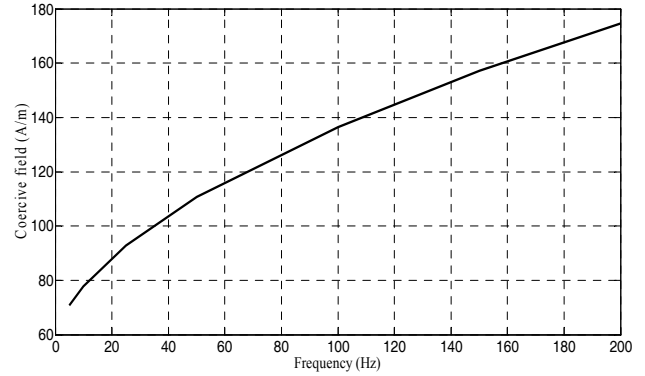


Fig. 1 – The curve of the coercive field versus frequency in the case of a non-oriented FeSi electrical steel .

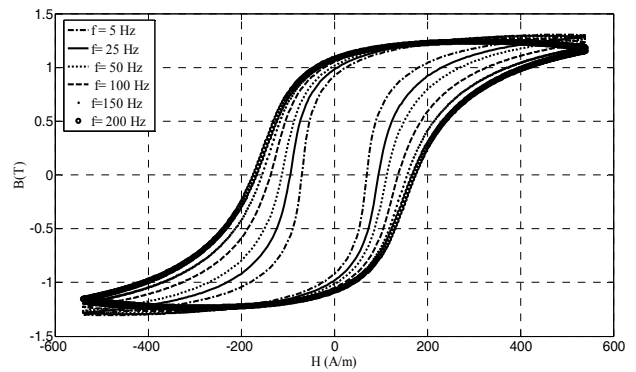


Fig. 2 – The hysteresis loops simulated at $f = \{5 \text{ Hz}, 25 \text{ Hz}, 50 \text{ Hz}, 100 \text{ Hz}, 150 \text{ Hz}, 200 \text{ Hz}\}$. Values of the parameters used in the JA model are: $M_s = 1167880 \text{ A/m}$, $a = 75 \text{ A/m}$, $\alpha = 1.85 \cdot 10^{-4}$, $k_0 = 50.9269 \text{ A/m}$ and $\beta = 0.224$.

The frequency dependent JA model has been validated according to the results, provided by the dynamic Jiles model, applied in the case of electrical steels [21]. The hysteresis loops, calculated with the proposed model, were compared with the simulated cycles, obtained through the dynamic Jiles model. Figure 3 shows that the data are in a good agreement with the results of the other model for the following frequencies: 10 Hz, 25 Hz, 100 Hz and 200 Hz.

The difference between the hysteresis loops, calculated by our approach and those determined through the dynamic Jiles model, increases for high frequencies. This behavior may be due to the hypothesis, which assumes that the reversibility coefficient is independent of the frequency, which is not strictly correct.

Figure 4 shows the dependence of coercive field of a non-oriented FeSi electrical steel versus frequency. It is obvious from the figure that the proposed model is in good agreement with the Jiles dynamic model.

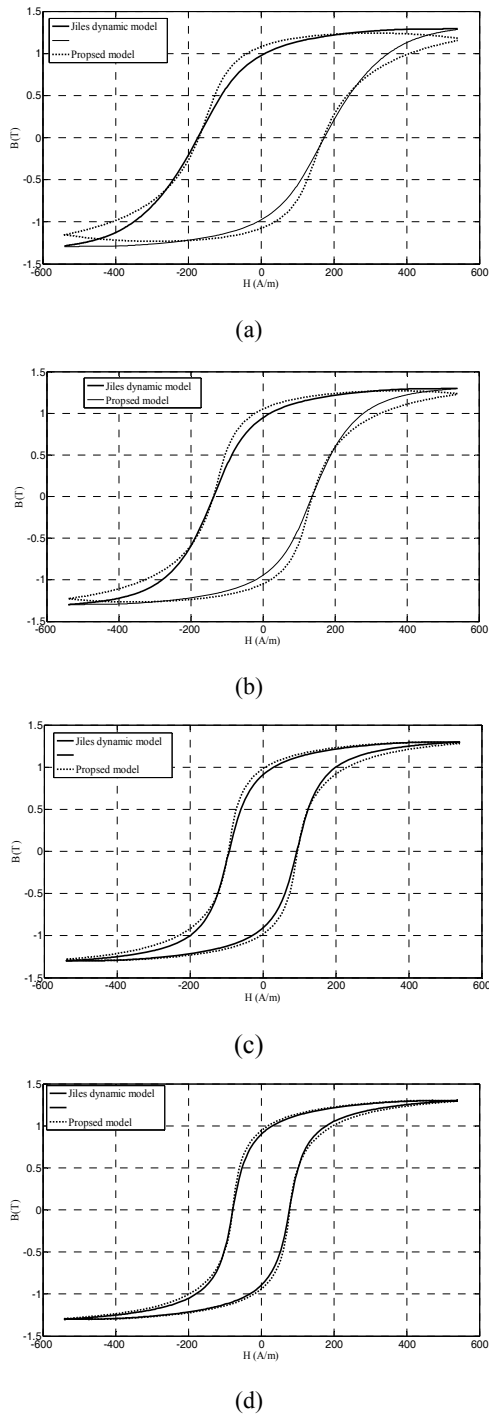


Fig. 3 – Comparison of the numerically determined hysteresis cycles in the case of the two models: (a) $f=200$ Hz, (b) $f=100$ Hz, (c) $f=25$ Hz, (d) $f=10$ Hz.

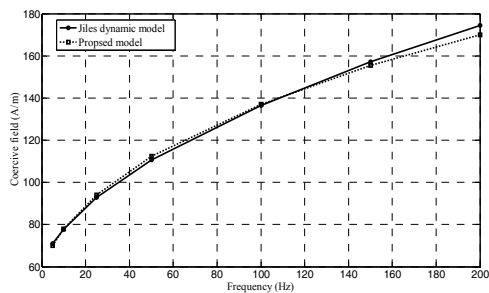


Fig. 4 – The coercive field variation with frequency f in the case of a non-oriented FeSi electrical steel.

5. CONCLUSIONS

In this paper, a frequency-dependent hysteresis model, based on the JA theory, was developed. The frequency effects have been incorporated in the JA model, by considering the parameter k as a function of frequency. The identification of the model parameters a , c , M_s and α , allows us to fix and to find the evolution of the parameter k as a function of the frequency from the dependence of the coercive field versus frequency. The model can be improved if one introduces the effect of frequency on the parameter c . The JA model with the proposed approach to take into account the frequency effects has been validated by comparison with the Jiles dynamic model. The obtained results have shown a good agreement between the two models, especially for low frequencies.

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