Hysteresis Identification Models: A Review

Khaoula Hergli, Haykel Marouani and Mondher Zidi

Abstract Magnetic properties of soft ferromagnetic materials are very sensitive to high mechanical and thermal stresses. In order to characterize its changing magnetic behavior, this chapter deals with the study of the choice of the performant magnetic hysteresis model, which can be able to model perfectly the thermo–magnet–mechanical coupling of a fully processed non-oriented Fe-3 wt%Si steel sheet. Therefore, our study focuses on identifying the model parameters for different static models by application of an appropriate optimization technique. For simple models, a direct identification is used, and the GA technique will be applied for complex ones. The performance of the model depends on the error that it presents with the measurements as well as its ability to reproduce properly the experimental hysteresis studied. Our study is based on the static models of Rayleigh, Potter, Frolich, and Preisach. Identification results show that the Preisach and Frolich static models can model the hysteresis curve of the Fe-3 wt%Si steel sheet more accurately than the other models studied.

Keywords Magnetic hysteresis modeling · Parameter identification
Soft ferromagnetic materials

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M. Haddar et al. (eds.), *Design and Modeling of Mechanical Systems—III*,
Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-3-319-66697-6_19

1 Introduction

Magnetic materials are widely used in various engineering applications and electromechanical systems such as shape memory alloy for seismic dampers and arterial stents, piezoelectric, piezoceramic, electric transformers, and electromechanical actuators which makes the hysteresis modeling one of the most interesting fields of study. The main magnetic properties are defined by the magnetic field H (A/m), the magnetization M (A/m), the magnetic induction B (T), the susceptibility χ (dimensionless), and the permeability μ (H/m). The magnetic behavior and the properties of a material can be learned by studying its hysteresis loop which shows a nonlinear relationship between magnetic induction (B) and magnetic field (H) as shown in Fig. 1.

Several mathematical models have been developed to describe the hysteresis cycle, such as (Rayleigh 1887; Fröhlich 1881; Preisach 1935) models. In fact, in order to produce the magnetization process for a given magnetic material, particularly when studying a complex magnetic system under thermal and mechanical stresses, it is necessary to identify the model parameters and evaluate its performances with regard to experimental data. For some models, the identification of their parameters is achieved by simply reading the measured cycle. Others require the development of an efficient identification technique. Algorithms applied to identify model variable are mainly classified into two groups: Deterministic methods and Stochastic ones. The Deterministic methods are rarely used as they are based on the resolution of the gradient of the objective function. While the stochastic methods can be adapted to different forms of problems, they are based on

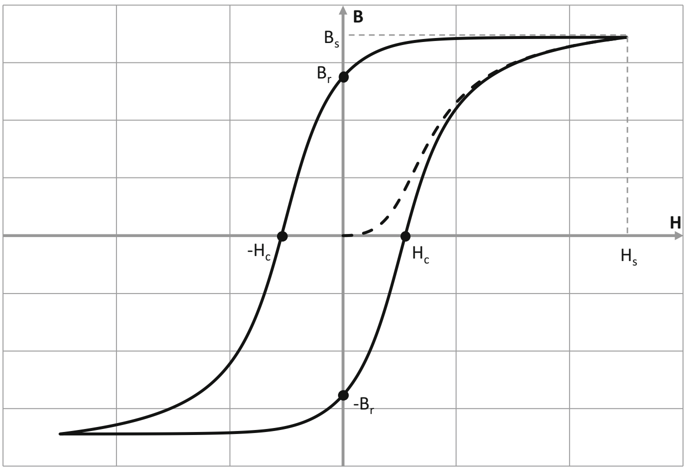

Fig. 1 Hysteresis loop (Bs: saturation flux density; Br: remanence flux; Hs: maximal magnetizing force; Hc: coercivity)

the random evolution and require a lot of evaluation of the objective function to end up guessing the optimum. Among these stochastic methods, the most widely used for magnetic domain are neural network (Zakerzadeh et al. 2011), genetic algorithm (Anh and Kha 2008; Belkebir et al. 2009), PSO (Marion 2008), and nonlinear least squares method (Levenberg 1944; Marquardt 1963; Belkebir et al. 2009).

2 Experimental Hysteresis

Various magnetic measurement systems have been developed for different applications such as magnetic behavior under applied mechanical stress (Sipeky and Ivanyi 2005) and thermal modeling of magnetic components (Quondam et al. 2016).

The experimental setup (Fig. 2) was validated by several experimental studies (Matsubara et al. 1989; Iordache et al. 2003). It consists of two U ferrite cores maintained in contact with the sample. Primary windings are wound on the central limbs of the yokes and the secondary winding surround the specimen. This double-yoke arrangement leads to a better homogeneous distribution of the magnetic field in the measurement zone. Moreover, it minimizes the negative effects of the overhang and of the eddy currents on the measurements accuracy.

The used sample is a fully processed non-oriented Fe-3 wt%Si steel sheet of 0.35 mm thick. The specimen are strips which are 20 mm wide and 250 mm long, cut in the rolling direction, and vacuum annealed at 720 °C for 2 h in order to eliminate the residual stresses which originate from the manufacturing process (Hubert 1998). Figure 3 shows the experimentally obtained hysteresis loop.

From this curve, we extract the reference data in Table 1.

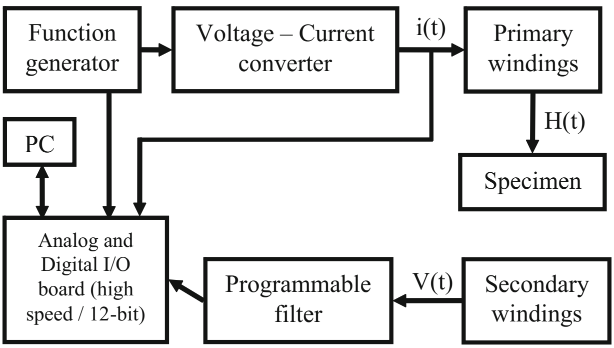

Fig. 2 Block diagram of the magnetic measurement test apparatus

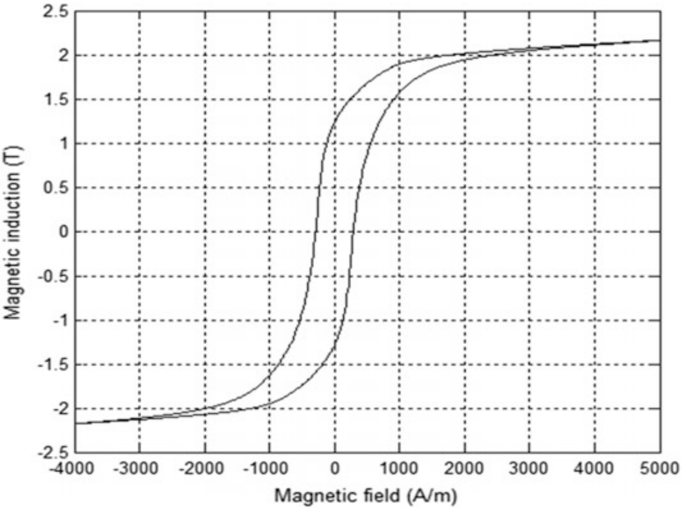

Fig. 3 Experimental hysteresis of a Fe-3 wt%Si steel

Table 1 Experimental reference data

Parameters	Value
H_s (A/m)	5400
H_c (A/m)	300
B_s (T)	2.179
B_r (T)	1.25
f (Hz)	1

3 Static Models

3.1 Rayleigh Model

The classical Rayleigh model of scalar ferromagnetism describes the H-B relation by a Prandtl–Ishlinskii model of play-type. According to the literature (Rayleigh 1887), this model is designed for modeling high-coercivity materials and it is fully determined by four experimental parameters (H_s, B_s, B_r, and frequency f). So, for a field varying between $-H_s$ and $+H_s$, the magnetic density B is expressed by the following expression:

$$B(H) = (\mu_{in} + \eta\, H_s)\, H + \frac{1}{2} sign\,(\alpha)\, \eta\, (H^2 - H_s^2) \tag{1}$$

where, μ_{in} et η are defined, respectively, by the following expressions (2 and 3).

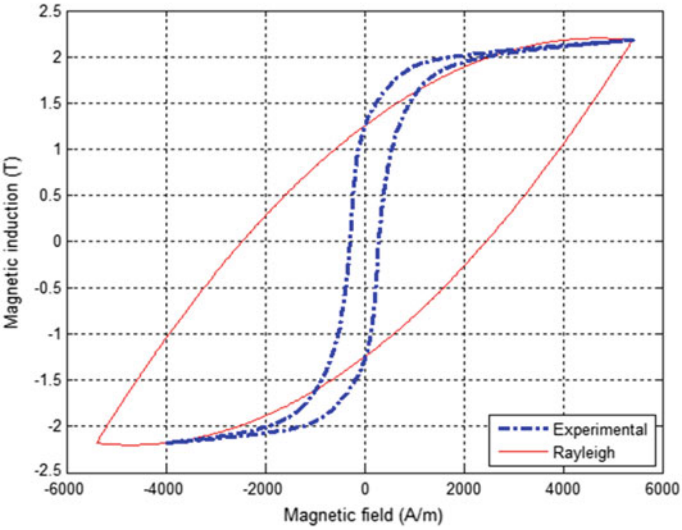

Fig. 4 Comparison of Rayleigh hysteresis and experimental major cycle

$$\mu_{in} = \frac{B_s}{H_s} - \eta H_s \tag{2}$$

$$\eta = \frac{2B_r}{H_s^2} \tag{3}$$

Figure 4 presents a comparison of the resulting curve and the experimental one. The shape of the hysteresis loop provided by Rayleigh model proves that it is adaptable only to magnetic materials with high coercivity (contrary to our used material).

3.2 *Frölich Model*

The Fröhlich model (Fröhlich 1881) is more adapted for the low hysteresis loss materials. The model is fully determined by four experimental parameters (H_s, H_c, B_s, and B_r) which are picked up directly from the experimental cycle.

The relation B (H), defined by the expression (4), allows to create the hysteresis curve as shown in Fig. 5.

$$B = \frac{H - sign\,(\alpha)\ \times\ H_c}{\alpha + \beta|H - sign\,(\alpha)\ \times\ H_c|} \tag{4}$$

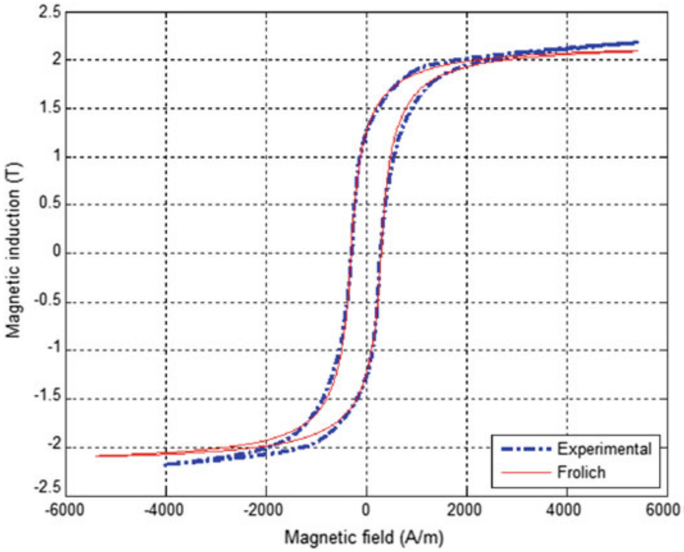

Fig. 5 Comparison of Frölich hysteresis and experimental major cycle

where sign(α) takes the value +1 for the ascending branch of the cycle and the value −1 for the descending branch. Then, α and β are defined, respectively, by Eqs. (5 and 6).

$$\alpha = H_c\left(\frac{1}{B_r} - \frac{1}{B_s}\right) \tag{5}$$

$$\beta = \frac{1}{B_s} \tag{6}$$

The resulting curve and the experimental cycle (Fig. 5) appear superimposable with a minor error which denotes that it is an adequate model for the modeling of the chosen material in this study.

3.3 Potter Model

It is a simple mathematical model that describes the evolution curve of the magnetization M by an analytical equation parametrized in α as follows:

$$B(H,\alpha) = B_s\left[sign\,(\alpha) - \alpha(-\tanh\,(\frac{H_c - H\,sign\,(\alpha)}{H_c}\tanh^{-1}(\frac{B_s}{B_r})))\right] \tag{7}$$

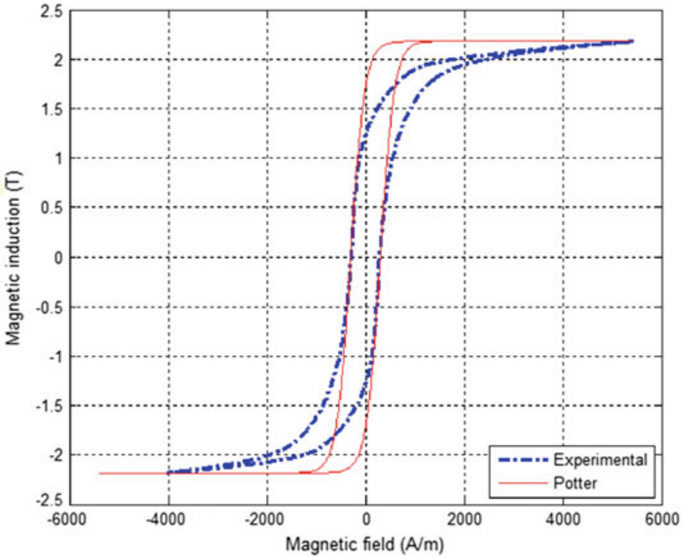

Fig. 6 Comparison of Potter hysteresis and experimental major cycle

where sign(α) takes the value +1 for the ascending branch of the cycle and the value −1 for the descending branch.

Using the parameters on Table 1, the resulting curve compared to the experimental cycle (Fig. 6) shows a moderately significant error. This error is not small enough to consider the Potter model as performant to perfectly model the magnetic behavior of our soft ferromagnetic steel.

3.4 *Preisach Model*

The Preisach analysis (Preisach 1935; Mayergoyz 1991), is mainly designed to describe hysteretic systems with complex behaviors. It is based on decomposing of the system into several elementary hysteretic entities called hysterons. The distribution of the elementary cycles defines the Preisach distribution function which is expressed as follows.

$$M(t) = \iint p(\alpha, \beta)\, \phi_{\alpha\beta}[H(t)]\, d\alpha\, d\beta \tag{8}$$

The distribution function can be identified using analytical approaches like Gaussian function, Lorentz function, and the Lorentz modified function LMF (Preisach 1935).

The LMF is defined by the coercivity H_c, a regulator coefficient k and two parameters a and b. The distribution function by LMF is then given as

$$p(\alpha,\beta) = \frac{ka^2}{(a+(\frac{\alpha}{H_c}-b)^2)(a+(\frac{\beta}{H_c}+b)^2)} \tag{9}$$

Then, the total magnetization M(t) is expressed by (10)

$$M_t = M_{(t-1)} \pm 2 \iint_s \frac{k\,a^2}{(a+(\frac{\alpha}{H_c}-b)^2)(a+(\frac{\beta}{H_c}+b)^2)}\, d\alpha\, d\beta \tag{10}$$

The classical Preisach model is completely determined by five parameters: two of them are experimentally deduced (H_s, H_c) and the remaining ones are numerically identified. The identification is accomplished using the genetic algorithm approach via Matlab.

The comparison of the resulting hysteresis and the experimental cycle (Fig. 7) shows a partial correspondence between the two cycles. According to the literature, this model is adaptable for a variety of hysteresis patterns and it is essentially used for describing static magnetic behavior for ferroelectric and ferromagnetic materials under thermal effects (Quondam et al. 2016).

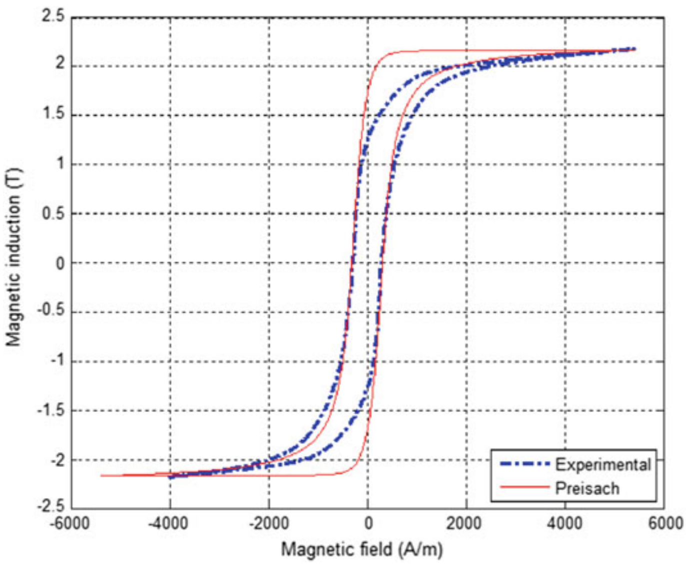

Fig. 7 Comparison of Preisach hysteresis and experimental major cycle

Table 2 Error values

Model	ε (%)
Rayleigh	75.70
Frölich	4.53
Potter	12.37
Preisach	8.41

4 Synthesis

In this section, we resume the results of the error calculation between estimated results and measured data which are listed in Table 2. Taking into account that the hysteresis cycle is symmetrical, the comparison between analytical and experimental models is carried out on a single branch of the major curve (ascending branch). The comparison criteria is the percentage error ε given by the following expression (11)

$$\varepsilon = \frac{\sum \left| \frac{B_{sim}(i) - B_{\exp}(i)}{B_{\exp}(i)} \right|}{N} \times 100 \tag{11}$$

where B_{sim} is the simulated magnetic induction, B_{exp} is the experimental magnetic induction, and N is the number of points.

The error results show that the Frölich model is the best fitting model for the Fe-3 wt%Si steel hysteresis loop. The Preisach model can be also used to reproduce the magnetic behavior.

5 Conclusion

The main objective of this study was to examine the capability of different static hysteresis models for valuing the magnetic behavior of ferromagnetic material Fe3%Si. The results obtained using Frölich model are close to the measured values. Furthermore, both Frölich and Preisach models can be used in magnetic modeling for soft ferromagnetic materials as revealed by the uses statistical criteria. Once the best hysteresis model is identified, further investigations on the modelization of the heat and mechanical stress effects on the magnetic behavior can be conducted.

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