An energy-based vector hysteresis model for ferromagnetic materials

François Henrotte
Institute of Electrical Machines, RWTH-Aachen University, Aachen, Germany
André Nicolet
Institut Fresnel (UMR 6133), Université d'Aix-Marseille III, Marseille, France, and
Kay Hameyer
Institute of Electrical Machines, RWTH-Aachen University, Aachen, Germany

Abstract

Purpose – Proposes a new quasi-static vector hysteresis model based on an energy approach, where dissipation is represented by a friction-like force.

Design/methodology/approach – The start point is the local energy balance of the ferromagnetic material. Dissipation is represented by a friction-like force, which derives from a non-differentiable convex functional. Several elementary hysteresis cells can be combined, in order to increase the number of free parameters in the model, and therefore improve the accuracy.

Findings – A friction-like force is a good way to represent magnetic dissipation at the macroscopic level. The proposed method is easy to implement and non-differentiability amounts in this case to a simple "if" statement.

Research limitations/implications – The next steps are the extension to dynamic hysteresis and the in-depth analysis of the identification process, which is only sketched in this paper.

Practical implications – This vector model, which is based on a reasonable phenomenological description of local magnetic dissipation, enables the numerical analysis of rotational hysteresis losses on a sound theoretical basis.

Originality/value – It proposes a simple, general purpose macroscopic model of hysteresis that is intrinsically a vector one, and not the vectorization of a scalar model.

Keywords Vectors, Modelling, Ferrous metals, Magnetism

Paper type Research paper

1. Introduction

Hysteresis models are generally compared on basis of their ability to reproduce accurately the magnetic curves obtained by measurements. As standard measurements of magnetic characteristics are done along a particular direction (Single sheet tester and Epstein frame), it is not surprising that classical hysteresis models are scalar as well. The model of Preisach (Mayergoyz, 1991) for instance, as it offers a virtually infinite number of parameters, is able to reproduce accurately one-dimensional hysteresis curves of many ferromagnetic materials.

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But when the question of losses and forces in the material arises, the accuracy of the reproduced *b-h* curves is no longer a sufficient proof of a good representation of the material's behaviour. The model must provide in addition an energy balance of the material. As the model of Preisach has no real interpretation in terms of energy, further assumptions are required (Friedman and Mayergoyz, 1998; Delincé *et al.*, 1994) if one wants to use it in coupled problems.

The basic assumptions of the Jiles-Atherton model (Jiles and Atherton, 1986) on the other hand, constitute a real material model with a true interpretation in terms of energy. At a certain point in the development of the model however, algebraic and differential operations are performed, which make loose track of the grounding energy concepts. At the end, the model does not generalise naturally to two or three dimensions of space and provides no energy balance of the material.

This paper presents an alternative hysteresis model which has similarities with the one presented in (Bergqvist, 1997). It is based on the same basic assumptions as the Jiles-Atherton model, but it remains up to the end consistent with the energy interpretation. By this way, a vector hysteresis model for ferromagnetic polycrystals is obtained.

2. Physics of ferromagnetism

2.1 Magnetic polarisation

Paramagnetic materials, in general, are characterised by the existence of permanent atomic magnetic moments of amplitude m_o [Am^2], which are free to rotate, and to orient in space, in function of several external and internal factors (applied field, crystallographic structure, thermal agitation, ...). Without applied magnetic field, the distribution of the orientations is even, and the resultant polarisation is zero.

Let now $\mathbf{H}$ be the local magnetic field along a given direction, say $\mathbf{H} = He_z$. Each individual magnetic moment can be associated an angle θ with respect to that field and an energy $\Psi(\theta) = -\mu_0 m_o H \cos\theta$. This notion of local magnetic field is somewhat vague. It needs to be clarified further. Actually, different theories are based on different definitions of the local field. For instance, the Weiss mean field theory (Jiles and Atherton, 1983) assumes $\mathbf{H} = \mathbf{h} + \alpha M$, with $\mathbf{h}$ the real magnetic field and α a scalar material constant. We shall use $\alpha = 0$ in this paper, but however notice that having $\mathbf{H} \neq \mathbf{h}$ is fundamental to the proposed hysteresis model.

The macroscopic magnetisation M of the sample is obtained by following an approach *à la Boltzmann*. The energy of N moments contained in a volume Ω is given by equation (1) in terms of the Boltzmann distribution (2) of the moments in function of θ (Sablik and Jiles, 1993):

$$\Omega \mathbf{M} \cdot \mathbf{H} = \int_\Omega \Psi(\theta)\varphi(\theta)\, \mathrm{d}\Omega, \tag{1}$$

$$\varphi(\theta) = \exp\left(-\frac{\Psi(\theta)}{k_\mathrm{B} T}\right), \quad \int_\Omega \varphi(\theta)\mathrm{d}\Omega = N. \tag{2}$$

One has then

$$\mathbf{M}(H\mathbf{e}_z) = M_s \frac{\int_0^\pi \cos\theta\, \varphi(\theta) \sin\theta\, \mathrm{d}\theta}{\int_0^\pi \varphi(\theta) \sin\theta\, \mathrm{d}\theta} \mathbf{e}_z \tag{3}$$

with $M_s = \mu_0 m_o N/\Omega\,[T]$ the saturation magnetisation and k_B [J/K] the Boltzmann constant. It can be noted that an increase of H is analogous in this theory to a decrease of the temperature T. Performing the integral in equation (3), one finds

$$\mathbf{M}(\mathbf{H}) = M_s L\left(\frac{H}{h_o}\right)\mathbf{e}_z, \quad L(x) = \coth x - \frac{1}{x} \tag{4}$$

with $h_o = k_B T/(\mu_0 m_o)$ a characteristic field and L the Langevin function. This constitutive relation is scalar and isotropic. It is characterised by a large initial susceptibility and a saturation phenomenon when all moments become parallel to the applied field. The coenergy density is

$$\rho^\Phi(\mathbf{H}) = \int_0^{|\mathbf{H}|} M_s L\left(\frac{x}{h_o}\right)\mathrm{d}x, \quad \mathbf{M} = \partial_{\mathbf{H}}\rho^\Phi, \tag{5}$$

ρ^X denoting in general the density of the quantity X. By definition, the energy density is

$$\rho^\Psi(\mathbf{M}) = \min_H\{\mathbf{M}\cdot\mathbf{H} - \rho^\Phi(\mathbf{H})\}, \quad \mathbf{H} = \partial_{\mathbf{M}}\rho^\Psi. \tag{6}$$

As the developed model is a phenomenological one, any other function with the same characteristics could be used as well. Figure 1 gives, together with the Langevin function, three other candidates. For the sake of comparison, they are all scaled in such a way that $\dot{L}(0) = L(\infty) = 1$. Except for the Langevin function, they are all invertible, which gives practical advantages to express analytically the energy density by equation (6) and to identify the parameters.

2.2 Ferromagnetic materials

The magnetisation of a ferromagnetic material (Fe, Ni, Co, …) is a more complex phenomenon. Due to a strong short-range force of quantum origin, the atomic moments tend also to align with each other. Due to the anisotropy of the crystal structure, they moreover align preferably along a limited set of particular directions, called directions of easy magnetisation of the crystal.

A very intense magnetic field would however be necessary to force all magnetic moments of a ferromagnetic sample oriented in the same direction. In the absence of such a field, the field lines close themselves preferably inside the magnetic material, so

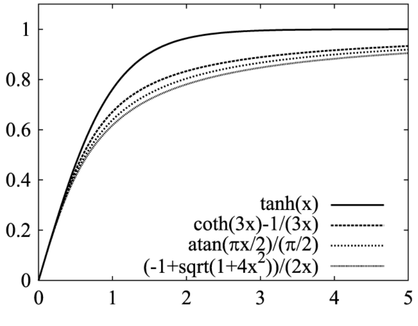


Figure 1. Four candidate functions to represent phenomenologically anhysteretic magnetisation

that the sample divides itself spontaneously at a mesoscopic scale into a large number of small regions called Weiss domains. Inside a domain, the magnetisation is kept homogeneous by the short-range forces, but the orientation of the different regions are distributed over the set of easy-magnetisation directions. If the amplitude of the magnetic field increases, one observes that the domains with $\theta \approx 0$ ($\cos \theta \approx 1$) grow to the expense of the domains with $\cos \theta \ll 1$.

However, isotropic polycrystalline materials, are agglomerates of monocrystals oriented evenly in all directions, which homogenises the anisotropy properties of the individual monocrystals. In such conditions, the approach of the previous section can still be adopted, and the macroscopic magnetisation of the polycrystal is described by equation (4), with an adapted value of the characteristic field h_o.

The induction field is defined by

$$\mathbf{b}(\mathbf{h}) = \mathbf{M}(\mathbf{h}) + \mu_0(1+\chi)\mathbf{h} \qquad (7)$$

assuming for generality the existence of a linear susceptibility of the material, independently of the mechanism described in the previous section. With $\mathbf{H} \equiv \mathbf{h}$, this relation represents the anhysteretic magnetisation curve of the ferromagnetic material. We shall now introduce hysteresis.

2.3 Magnetic hysteresis

Two Weiss domains are separated by a thin transition region, called Bloch wall, where the orientation of the moments changes smoothly from the orientation of the domain on the one side to that of the domain on the other side. Magnetisation of a ferromagnetic material implies the motion of the walls. The reversibility of the magnetisation process is associated with the presence or not of inclusions and impurities in the crystal lattice. Such defects constitute indeed small magnetic voids in the crystal structure. They pin the Bloch walls at fixed positions because the magnetic energy is lower when the wall goes through the void than when the void is inside the domain. In a perfect crystal, i.e. without defects, the motion of the wall is smooth and there is no dissipation associated with a quasi-static variation of the applied field. In a material with defects, each configuration with a pinned wall corresponds with a local minimum of the magnetic energy. When the material is magnetised or demagnetised, the walls jump abruptly from one pinning site to the next one, hence the irreversibility and the hysteresis behaviour.

At the macroscopic scale, the microscopic configuration cannot be represented. The pinning effect can be reasonably represented by a frictional force that impedes the motion of Bloch walls and opposes to any change in magnetisation (Sablik and Jiles, 1993). If the magnitude of that friction force is κ, the associated work $-\kappa|\dot{\mathbf{M}}|$ is entirely converted into heat.

3. Energy balance

All elements required to establish the energy balance of the ferromagnetic material are now available. The first law of thermodynamics $\dot{\rho}^{\Psi} = \dot{\rho}^{W} + \dot{\rho}^{Q}$ writes in this case

$$\dot{\rho}^{\Psi} = \mathbf{h} \cdot \dot{\mathbf{M}} - \kappa|\dot{\mathbf{M}}| \qquad (8)$$

where $\dot{\rho}^{W} = \mathbf{h} \cdot \dot{\mathbf{M}}$ is the rate of work done by the applied field. As this relation must be satisfied for any $\dot{\mathbf{M}}$, equilibrium equations are found by factorising $\dot{\mathbf{M}}$. In order to do so, non-linear functionals must be replaced by a first order linearised expression. Since ρ^{Ψ} is in general differentiable with respect to $\mathbf{M}$, one has simply $\dot{\rho}^{\Psi} = \mathbf{h}_r \cdot \dot{\mathbf{M}}$, with $\mathbf{h}_r \equiv \partial_{\mathbf{M}} \rho^{\Psi}$. On the other hand, the functional $\kappa|\dot{\mathbf{M}}|$ at the right hand side of equation (8) is not differentiable at $\dot{\mathbf{M}} = 0$. But, as it is convex, it has a subgradient G described by

$$G = \{\mathbf{h}_i, |\mathbf{h}_i| \leq \kappa \quad \text{if} \quad \dot{\mathbf{M}} = 0, \mathbf{h}_i = \kappa \mathbf{e}_{\dot{\mathbf{M}}} \quad \text{if} \quad \dot{\mathbf{M}} \neq 0\}. \tag{9}$$

The equilibrium equation

$$\mathbf{h} - \mathbf{h}_r = \boldsymbol{h}_i \in G, \tag{10}$$

is finally obtained. It determines in G (grey circle in Figure 2) the actual value of the "friction force" $\mathbf{h}_i$:

$$\begin{cases} \mathbf{h}_i = \mathbf{h} - \mathbf{h}_r & \text{if} \quad |\mathbf{h} - \mathbf{h}_r| < \kappa \\ \mathbf{h}_i = \kappa \mathbf{e}_{\dot{\mathbf{M}}} & \text{if} \quad |\mathbf{h} - \mathbf{h}_r| = \kappa \end{cases} \tag{11}$$

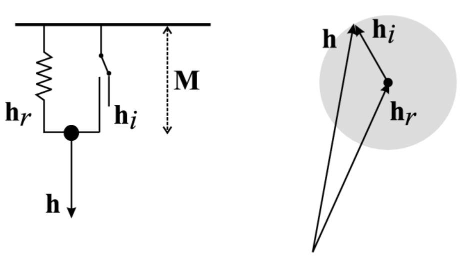
Equation (10) is the fundamental relation of the proposed vector model of hysteresis. The magnetisation $\mathbf{M}$ is obtained by equation (4), with $\mathbf{H} \equiv \mathbf{h}_r$ and the induction is

$$\mathbf{b}(\mathbf{h}) = \mathbf{M}(\mathbf{h}_r) + \mu_0(1 + \chi)\mathbf{h}, \tag{12}$$

to be compared with equation (7). The dissipated power is $\mathbf{h}_i \cdot \dot{\mathbf{M}}$.

This model can be considered through the mechanical analogy of a spring connected in parallel with a friction slider. Unlike the Jiles-Atherton model, which decomposes the magnetisation into a reversible and an irreversible part, the applied field $\mathbf{h}$ is in this model decomposed into the reversible part $\mathbf{h}_r$ (non-linear spring force) and the irreversible part $\mathbf{h}_i$ (friction force), Figure 2.

The memory effect originates from the non-differentiable character of the functional $\dot{\rho}^{Q}$, as the latter implies the non-univocity of the friction force $\mathbf{h}_i$. The subgradient is indeed a whole set of possible gradients, whereas a differentiable functional has one and only one gradient at each point. If $\mathbf{h}$ is inside the circle, one has $\dot{\mathbf{M}} = 0$, which implies $\dot{\mathbf{h}}_r = 0$. The elongation of the spring does not change. In this way, the non-univocity of $\mathbf{h}_i$ makes it possible to maintain a given $\mathbf{h}_r$, and hence a given magnetisation $\mathbf{M}$, even when the magnetic field $\mathbf{h}$ has yet decreased, whence the memory effect.



Note: The grey circle represents the subgradient G

Figure 2.
Mechanical analogy and pictorial representation of the vector model

4. Implementation

Like all hysteresis models, this model fits naturally into any magnetic field formulation. From equations (11) and (10), $\mathbf{e}_{\dot{\mathbf{M}}} = \mathbf{e}_{\dot{\mathbf{h}}_r}$, one can establish that the update rule for $\mathbf{h}_r$ obeys the differential equation in time

$$\mathbf{h}_r + \kappa \mathbf{e}_{\dot{\mathbf{h}}_r} = \mathbf{h}, \tag{13}$$

with the magnetic field $\mathbf{h}$ the input to the model. In practice, a simplified efficient update rule for $\mathbf{h}_r$, as the unknown field $\mathbf{h}$ varies, is

$$|\mathbf{h}^{n+1} - \mathbf{h}_r^n| > \kappa \Rightarrow \mathbf{h}_r^{n+1} = \mathbf{h}^{n+1} - \kappa \frac{\mathbf{h}^{n+1} - \mathbf{h}_r^n}{|\mathbf{h}^{n+1} - \mathbf{h}_r^n|},$$

which ensures $|\mathbf{h}_i| = |\mathbf{h} - \mathbf{h}_r| \leq \kappa$ at all time steps, but verifies only approximately (13).

One sees that the non-differentiable character of the dissipation functional is only a theoretical problem. It amounts to a simple test in the implementation. With first order shape functions, the unknown field $\mathbf{h}$ is constant in each element and the hysteresis algorithm requires to store the value of the vector $\mathbf{h}_r$ for each ferromagnetic element. As the update rule is a vector relation, it gives as such a vector hysteresis model, without making any other assumption.

5. Combined model

In the elementary form presented so far, the model has only four parameters: M_s, h_o and χ to represent the anhysteretic curve, and κ to represent hysteresis. Although it gives yet qualitatively interesting results for the main hysteresis loop (Figure 3), a better representation of the material behaviour could require to dispose of a larger number of free parameters. This can be achieved as follows.

The idea is to decompose the magnetisation $\mathbf{M}$ into different fractions $\mathbf{M}^k$ that are subjected to friction forces of different amplitudes κ^k. Let ω^k, $k = 0, \ldots, n$ with $\sum_{k=0}^{n} \omega^k = 1$ be the fraction coefficients, so that $\mathbf{M}^k \equiv \omega^k \mathbf{M}$. For each fraction, one states that equation (10) remains valid, i.e.

$$\mathbf{h} = \mathbf{h}_r^k + \mathbf{h}_i^k, \quad k = 0, \ldots, n. \tag{14}$$

The energy balance of the fractions writes

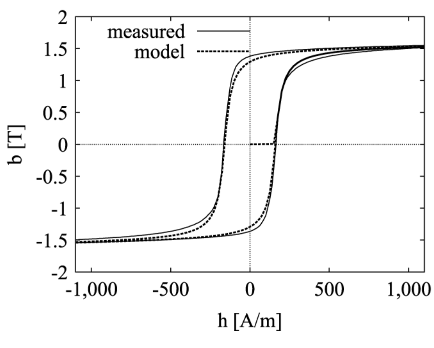


Figure 3.
Measurement and model for steel with the elementary model

$$\mathbf{h}\cdot\dot{\mathbf{M}}^k = \mathbf{h}_r^k\cdot\dot{\mathbf{M}}^k + \mathbf{h}_i^k\cdot\dot{\mathbf{M}}^k \tag{15}$$

and making the sum on k, one obtains the global energy balance

$$\mathbf{h}\cdot\dot{\mathbf{M}} = \left(\sum_{k=0}^{n}\omega^k\mathbf{h}_r^k\right)\cdot\dot{\mathbf{M}} + \left(\sum_{k=0}^{n}\omega^k\mathbf{h}_i^k\right)\cdot\dot{\mathbf{M}}, \tag{16}$$

from which follows

$$\mathbf{h} = \sum_{k=0}^{n}\omega^k\mathbf{h}_r^k + \sum_{k=0}^{n}\omega^k\mathbf{h}_i^k, \quad \mathbf{h}_i^k \in G^k, \tag{17}$$

which is the generalisation of equation (10).

The algorithm of the elementary model is applied to each fraction independently, taking for each fraction the particular value of the friction force $\boldsymbol{\kappa}^k$ into account. Then, the magnetisation $\mathbf{M}$ is obtained by equation (4), with $\mathbf{H} = \sum_{k=0}^{n}\omega^k\mathbf{h}_r^k$. The dissipated power is $(\sum_{k=0}^{n}\omega^k\mathbf{h}_i^k)\cdot\dot{\mathbf{M}}$.

The combined model with $n+1$ fractions has $2n+4$ parameters: M_s, h_o and χ for the anhysteretic curve; $\boldsymbol{\kappa}^k$, $k = 0,\ldots,n$ and $\boldsymbol{\omega}^k$, $k = 1,\ldots,n$. It is relevant to reserve a fraction with a zero friction force, say is $\boldsymbol{\kappa}^0 = 0$. The reversible magnetisation $\omega^0\mathbf{M}$ associated with this fraction represents the bending of the Bloch walls. The combined model requires to store the value of the n vectors h_r^k per element.

6. Identification

As the model is throughout phenomenological, it makes sense to use it in a 3D model, even when the parameter identification is done on basis of 1D measurements.

The identification of the parameters is done in two steps. The parameters M_s, h_o and χ, are first fitted so as to place the anhysteretic curves in the middle of the main hysteresis loop, Figure 4.

The parameters that remain to be identified are the fractions and $\boldsymbol{\omega}^k$ their respective friction forces $\boldsymbol{\kappa}^k$, $\boldsymbol{\kappa}^0 < \cdots < \boldsymbol{\kappa}^n$. As the latter determine essentially the lag of the magnetising field, i.e. $\mathbf{h}_r$, with respect to the magnetic field $\mathbf{h}$, the identification is done by considering the coercivity of the material.

On the one hand, the coercive field h_{coer} of the symmetrical loops is plotted in function of the amplitude h_{peak} of the loops, Figure 5. On the other hand, the coercive field from the model is obtained by setting

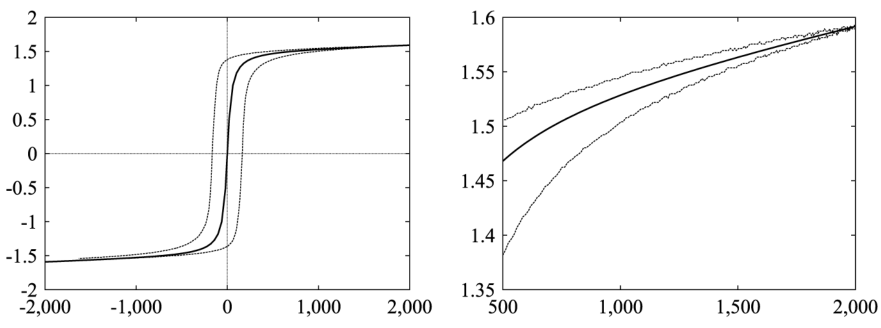


Figure 4. Main hysteresis loop and fitted anhysteretic curve

$$M = 0 \Rightarrow \sum_{k=0}^{n} \omega^k h_r^k = \sum_{k=0}^{n} \omega^k (h - h_i^k) = 0. \tag{18}$$

Let $m(h_{\text{peak}})$ be the higher fraction index for which $\kappa^k < h_{\text{peak}}$, which implies $h_i^k = \kappa^k$, $k \leq m(h_{\text{peak}})$. For the other fractions one has $h_r^k = h - h_i^k = 0, k > m(h_{\text{peak}})$, so that the sum (18) can be limited to:

$$\left(\sum_{k=0}^{m(h_{\text{peak}})} \omega^k \right) h = \sum_{k=0}^{m(h_{\text{peak}})} \omega^k \kappa^k. \tag{19}$$

Finally, isolating $h \equiv h_{\text{coer}}$, one has

$$h_{\text{coer}}(h_{\text{peak}}) = \frac{\sum_{k=0}^{m(h_{\text{peak}})} \omega^k \kappa^k}{\sum_{k=0}^{m(h_{\text{peak}})} \omega^k}. \tag{20}$$

This is a staircase shaped function. It suffices now to choose the parameters so as to match as closely as desired the curve obtained from the measured hysteresis loops. Figure 5 shows the match obtained with five fractions. Figure 6 shows the results obtained in that case.

7. Conclusion

Unlike the models of Preisach and Jiles-Atherton, this model relies consistently on an energy balance, of which all terms (stored magnetic energy and dissipated energy) are known at all times. A material model for a magnetostrictive material with hysteresis could so be obtained directly by substituting to ρ^{Ψ} a magnetostrictive functional.

Unlike the model of Jiles-Atherton, the number of parameters is not limited. The combined model offers an arbitrary number of parameters. However, due to internal constraints in the model, not all hysteresis curves can be matched exactly. Such a limitation is comparable with the congruence property of the Preisach model (Mayergoyz, 1991).

Dynamic effects can be considered by attributing a “mass” to the nodes in the mechanical analogy. Anisotropy can also be considered by adding a weighting function of θ in equation (2).

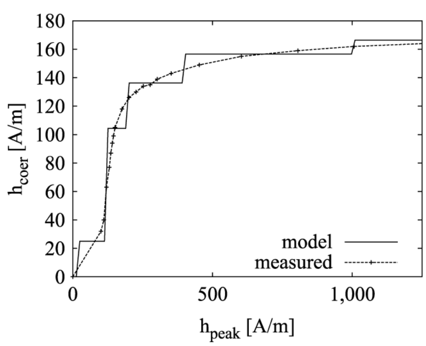


Figure 5.
Coercive field h_{coer} in function of the amplitude h_{peak} of the symmetrical hysteresis loops

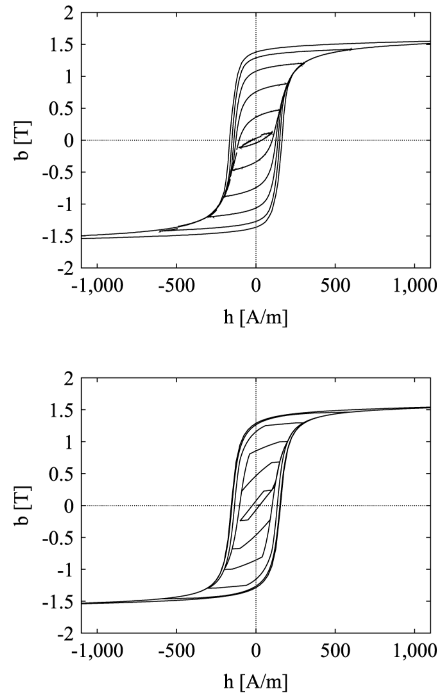


Figure 6.
Measurements (above) and model (below) with five fractions for electrical steel

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About the authors

François Henrotte graduated in engineering (Mechanics-Physics) in 1991 and received the PhD in Applied Sciences in 2000 at the University of Liège, Belgium. In 1991-2000, he was researcher with the Laboratory of Applied Electricity, University of Liège, Belgium. In 2000-2004, he was a postdoctoral researcher with the K.U. Leuven, Belgium. Currently, he is with the Institute of Electrical Machines of the RWTH-Aachen University, Germany. His main research interests are the numerical modelling of electromechanical systems, the theoretical analysis of electromagnetic forces, differential geometry and applied mathematics. He is also active in several projects with industry, for development and optimisation of electrical devices. He is the

author or co-author of about 80 scientific publications. Dr Henrotte is a member of the International Compumag Society, IEM RWTH-Aachen, Schinkelstraße 4, D-52056 Aachen, Germany. He is the corresponding author and can be contacted at: Francois.Henrotte@iem.rwth-aachen.de

André Nicolet has received his engineering degree [Ingénieur Civil Electricien (Electronique)] in 1984 and his PhD in Applied Sciences in 1991 both from the University of Liège (Belgium). From 1984 to 1994, he was a Research Engineer at the Department of Applied Electricity of the University of Liège. From 1994 to 1996, he was Head of the Deparment of Electrotechnics and Power Electronics of the ESIM (Ecole Supérieure des Ingénieurs de Marseille, France). In 1996, he received the “Habilitation à Diriger des Recherches” from the University of Aix-Marseille III. Since 1996, he is Professor at the University of Aix-Marseille III (63rd section: electronics, optronics and systems) and he has joined the Fresnel Institute (UMR CNRS 6133) at his creation in 2000. His main research interests are the numerical computations of electromagnetic fields and he currently focuses on the modelling of micro-structured optical fibres. He is author or co-author of more than 80 papers and of a book entitled ’Foundations of Photonic Crystal Fibres’ (Zolla, Renversez, Nicolet & *et al.*, Imperial College Press, 2005). Université Paul Cézanne, Institut Fresnel (UMR CNRS 6133), Domaine Universitaire de Saint-Jérôme, F-13397 Marseille cedex 20, France. E-mail: andre.nicolet@fresnel.fr

Kay Hameyer received a PhD from the University of Technology Berlin, Germany, 1992. From 1986 to 1988 he worked with the Robert Bosch Gmbh in Stuttgart, Germany, as a design engineer for permanent magnet servo motors. In 1988 he became a member of the staff at the University of Technology Berlin, Germany. Until 2004, he was professor of numerical field computation and electrical machines with the K.U. Leuven and a senior researcher with the FWO-V in Belgium, teaching CAD in electrical engineering and electrical machines. Currently, he is Head of the Institute of Electrical Machines of the RWTH-Aachen, Germany. His research interests are numerical field computation, the design of electrical machines, in particular permanent magnet excited machines, induction machines and numerical optimisation strategies. Professor Hameyer is a member of the International Compumag Society and the IEEE. IEM RWTH-Aachen, Schinkelstraße 4, D-52056 Aachen, Germany. E-mail: Kay.Hameyer@iem.rwth-aachen.de