Anisotropy model for modern grain oriented electrical steel based on orientation distribution function

Fan Jiang, Mathieu Rossi, Guillaume Parent

Anisotropy model for modern grain oriented electrical steel based on orientation distribution function

Cite as: AIP Advances **8**, 056104 (2018); https://doi.org/10.1063/1.5006471
Submitted: 25 September 2017 . Accepted: 13 October 2017 . Published Online: 07 December 2017

Fan Jiang, Mathieu Rossi, and Guillaume Parent

AIP ADVANCES **8**, 056104 (2018)

Anisotropy model for modern grain oriented electrical steel based on orientation distribution function

Fan Jiang, Mathieu Rossi,[a] and Guillaume Parent
Univ. Artois, EA 4025, Laboratoire Systèmes Électrotechniques et Environnement (LSEE), F-62400 Béthune, France

(Presented 8 November 2017; received 25 September 2017; accepted 13 October 2017; published online 7 December 2017)

Accurately modeling the anisotropic behavior of electrical steel is mandatory in order to perform good end simulations. Several approaches can be found in the literature for that purpose but the more often those methods are not able to deal with grain oriented electrical steel. In this paper, a method based on orientation distribution function is applied to modern grain oriented laminations. In particular, two solutions are proposed in order to increase the results accuracy. The first one consists in increasing the decomposition number of the cosine series on which the method is based. The second one consists in modifying the determination method of the terms belonging to this cosine series. https://doi.org/10.1063/1.5006471

I. INTRODUCTION

When modeling an electromagnetic device, either analytically or numerically, the method used to factor in the magnetic behavior of its components is a key point. This is particularly the case when the modeled device is built with Grain Oriented Electrical Steel (GOES) since it presents two distinct of nonlinear properties: a saturation effect on one hand and an anisotropic behavior on the other hand. Several approaches allowing to deal with magnetic anisotropy have been proposed in the literature, each method having its own advantages and limitations. The simplest one consists in using a diagonal magnetic permeability tensor involving the Rolling Direction (RD), the Transverse Direction (TD) and the Orthogonal Direction (OD) $b(h)$ curves,[1] the other directions being taken into account by linear interpolation. Another simple model, called elliptical model,[2] also considers the aforementioned main directions with the addition of nonlinear relationships between them. However due to the interpolation methods used to account for other directions than the RD, TD and OD, both models do not provide a good accuracy, especially in the presence of a rotational field. Another approach consists in using several $b(h)$ curves.[3–7] The main drawback of this approach relies on the number of experimental curves that are to be measured. The Orientation Distribution Function (ODF)[8] based model,[9–13] as for it, allows to account for $b(h)$ curves along any direction from a limited amount of experimental data. So far, neither of those methods allow to properly deal with the behavior of modern GOES since, in this case, the ratio between the magnetic permeabilities along the RD and the TD can be up to 300. Nevertheless, according to the literature,[9–13] the ODF method is a very promising approach for this purpose since it is based on a cosine series it can be mathematically improved, which is the aim of this paper.

In the first part, the ODF model is presented and is applied as presented in Ref. 9 to model modern GOES M11535P. In particular, its failure to properly model the magnetic behavior for low magnetic fields as well as around the saturation knee is highlighted. In the second part, it is shown that the model can easily be improved by simply increasing its decomposition order. Nevertheless, this

[a]Author to whom correspondence should be addressed. Electronic mail: mathieu.rossi@univ-artois.fr

approach suffers from the same drawback than those pointed out in Refs. 3–7 in terms of amount of required experimental data. Then, in the third part, an approach based on FFT, allowing to determine the coefficients of the series leading to good accuracy with a limited number of required experimental data is presented and discussed.

II. ANISOTROPY MODEL BASED ON ORIENTATION DISTRIBUTION FUNCTION

The mathematical theory of ODF[8] can be used to provide an expression of any physical property occurring in a polycrystalline material. This theory was applied to express the magnetic flux density b inside GOES laminations as a 3rd order cosine series,[9,12] leading to (1). Note that in this relation as well as in the following the term order refers to the number of terms occurring in the series.

$$b(h,\theta) = A_1(h) + A_2(h)\cos(2\theta) + A_3(h)\cos(4\theta) \tag{1}$$

where θ is the angle between the magnetic field h and the RD of the lamination. The value of coefficients A_i are determined from Epstein tests from 3 separate arrangements: along the RD, TD and the 45° directions as follows:[9]

$$A_1 = \frac{1}{4}[b(h,0^\circ) + b(h,90^\circ) + 2\,b(h,45^\circ)] \tag{2a}$$

$$A_2 = \frac{1}{2}[b(h,0^\circ) - b(h,90^\circ)] \tag{2b}$$

$$A_3 = \frac{1}{4}[b(h,0^\circ) + b(h,90^\circ) - 2\,b(h,45^\circ)] \tag{2c}$$

In Ref. 9, relation (1) was used to determine $b(h)$ curves along any direction for two different GOES grades: 097-30NS and 111-35S5. The results were promising and quite acceptable overall. Nevertheless, it could be noticed that:

- the area corresponding to low magnetic field values (for $h < 200$ A m^{-1}), was not investigated. This area is a key point because the shape of the $b(h)$ curves highly differs from a direction to another one.
- an error around 12 % remains in the saturated area (for $h > 700$ A m^{-1}),

For the work presented in this paper, M11535P GOES laminations were characterized through Epstein test for 19 different directions, *i.e.* every 5° from the RD (0°) to the TD (90°). Then, (1) and (2) were used to determine $b(h,\theta)$ curves. As an example, Fig. 1a shows the results obtained by the model as well as the experimental curves obtained from Epstein test for comparison for θ = 20°, 40°, 60° and 80°. This figure clearly shows that, as is, the model is totally unable to properly deal with the area corresponding to low magnetic field values. Moreover, as in Ref. 9 a gap between curves from the model and from experiments is also present in the saturated area. As an example, this error is equal to 11 % for the 20° direction. In addition, it can also be noticed that due to a model based on

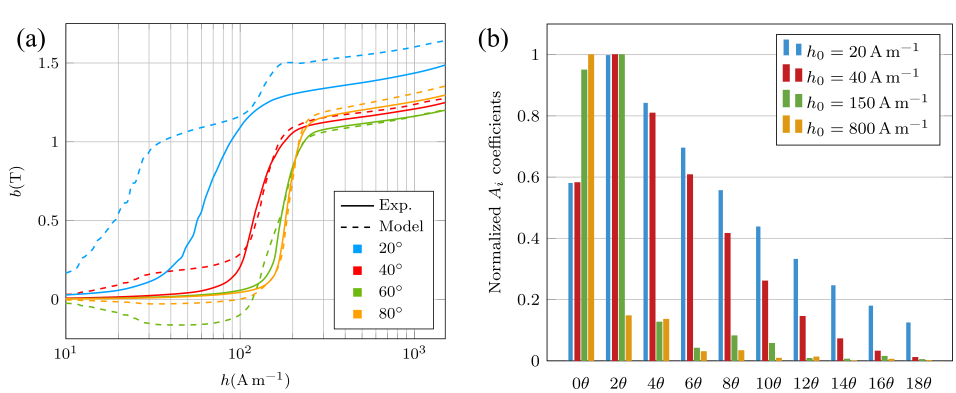

FIG. 1. Application of ODF model from Ref. 9 on GOES M11535P. (a) Comparison between ODF model from Ref. 9 and Epstein test for 4 different angles θ and (b) Values of normalized Fourier coefficients for 4 different values of magnetic fields.

cosine series some oscillations appear, which can even lead to nonsensical results such as a negative magnetic permeability.

Since the ODF theory is based on physical principles,[8] it should perfectly be applied no matter the GOES grade. Then the reasons for such gaps between the model and measurements are to be found on the side of the assumptions made to establish (1) which are the limitation to a 3rd order series on the one hand and the approach used to determine coefficients A_i on the other one.

As for the first point, it can be easily highlighted: for a given value of magnetic field, denoted h_0, the FFT is applied to the curve $b(h_0, \theta)$. Fig. 1b shows the first 10 even normalized Fourier coefficients, the odd ones being equal to zero, for $h_0 = 20$ A m^{-1}, 40 A m^{-1}, 150 A m^{-1} and 800 A m^{-1}. Note that this latter point is in concordance with (1). It clearly shows that the lower the magnetic field values, the richer the harmonic content. Moreover, even for high magnetic field values ($h_0 > 800$ A m^{-1}) the last non negligible coefficient (greater than 1%) is 8θ, which corresponds to a 5th order series. Hence, increasing the decomposition order of (1) is mandatory.

III. ORDER INCREASING

As seen in the previous section, the model governed by (1) can be generalized:

$$b(h, \theta) = \sum_{i=1}^{n} A_i(h) \cos(2(i-1)\theta) \tag{3}$$

where n is the decomposition order. The A_i coefficients are determined from n experimental curves $b(h, \theta_j)\,|_{j=1\,...\,n}$ such that for a given $\theta_j \in [0°, 90°]$ one can write: $b(h, \theta_j) = \sum_{i=1}^{n} A_i(h) \cos(2(i-1)\theta_j)$. Then, for a given magnetic field value denoted h_0, solving system (4) allows to determine a vector $[\, A_1(h_0) \; \cdots \; A_n(h_0) \,]$. Then, the procedure is performed as many times as needed for different values of h_0 in the desired range.

$$\begin{bmatrix} cos\,(2(1-1)\theta_1) & \cdots & cos\,(2(n-1)\theta_1) \\ \vdots & cos\left(2(i-1)\theta_j\right) & \vdots \\ cos\,(2(1-1)\theta_n) & \cdots & cos\,(2(n-1)\theta_n) \end{bmatrix} \cdot \begin{bmatrix} A_1(h_0) \\ \vdots \\ A_n(h_0) \end{bmatrix} = \begin{bmatrix} b(h_0, \theta_1) \\ \vdots \\ b(h_0, \theta_n) \end{bmatrix} \tag{4}$$

The aforementioned procedure was used to model M11535P GOES $b(h, \theta)$ curves for the 7th and 12th order (Fig. 2). As expected, increasing the decomposition order leads to a better accuracy. Moreover, Fig. 2a shows that a reasonable order increase leads to a very good accuracy for high magnetic field values. Nevertheless, it also highlight that a 7th order decomposition is not sufficient to deal with low magnetic field values. In our case, the minimum order to achieve that purpose is 12 (Fig. 2b).

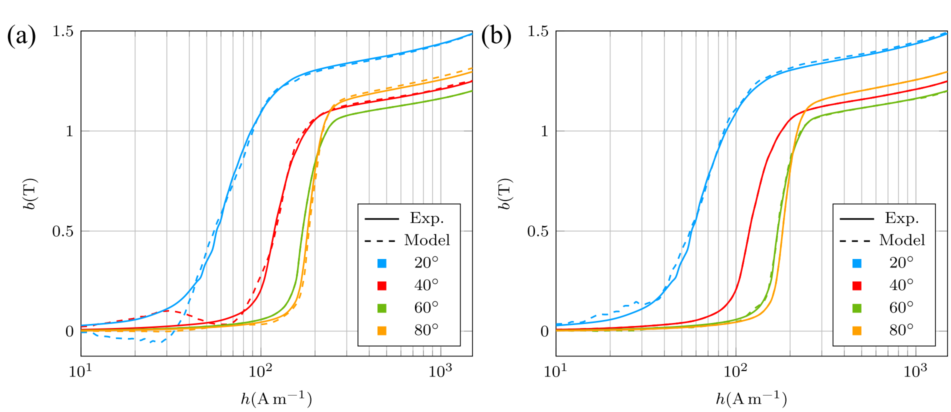

FIG. 2. Comparison between ODF model (7th and 12th orders) and experimental data with A_i coefficients obtained by inverting system (4). (a) 7th order model and (b) 12th order model.

Solving system (4) is actually similar to an identification method, which means that the obtained coefficients A_i values are such that $b(h, \theta_j)$ have an accuracy of 100 % with respect to measured data. Nevertheless, since the model is based on cosine series, this very strong constraint can lead to oscillations as well as important local errors on other directions.

To avoid this drawback we propose to determine coefficients A_i by using a FFT, which allows to share the global error on every curves.

IV. DETERMINATION OF COEFFICIENTS A_i USING FFT METHOD

As in the previous section, a set of n experimental curves $b(h, \theta_j)\,|_{j=1\,...\,n}$ with $\theta_j \in [0°, 90°]$ and $\theta_{j+1} - \theta_j = \frac{90}{n-1}$ is considered. For a given magnetic field value h_0, taking into consideration the symmetries of the anisotropy $b(h, \theta) = b(h, -\theta)$ and $b(h, \pi - \theta) = b(h, \theta)$ as well as the Nyquist–Shannon sampling theorem, FFT can be performed on $b(h_0, \theta)\,|_{\theta \in \{\theta_1 \cdots \theta_n\}}$ curves such that Fourier coefficients thus obtained are taken for coefficients A_i in (3). In these conditions, as in the previous section, the number of required experimental curves is equal to the desired decomposition order.

For comparision, Fig. 3 presents the curves obtained when following this procedure for the same decomposition orders (7 and 12) as in Fig. 2. It can be noticed that the FFT based procedure allows to significantly reduce the oscillations, especially for low magnetic field values, as well as local errors (Fig. 3a). This even leads to a noticeable accuracy for the 12$^{\text{th}}$ order decomposition (Fig. 3b).

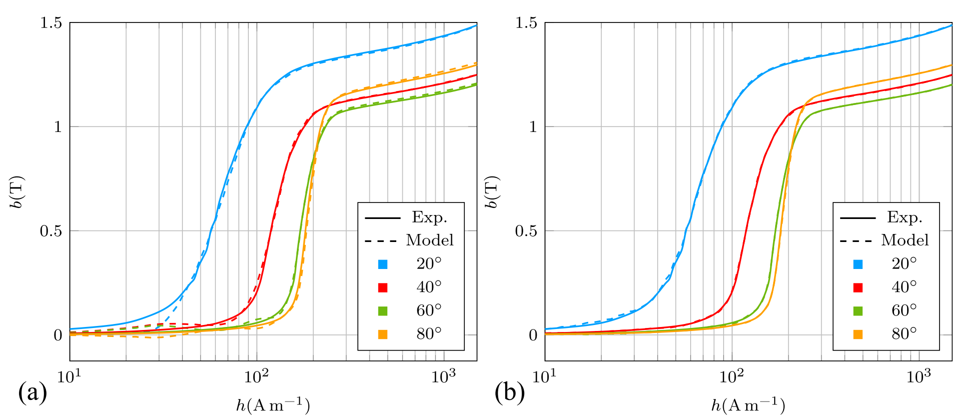

FIG. 3. Comparison between ODF model (7$^{\text{th}}$ and 12$^{\text{th}}$ orders) and experimental data with A_i coefficients obtained using the FFT method. (a) 7$^{\text{th}}$ order model and (b) 12$^{\text{th}}$ order model.

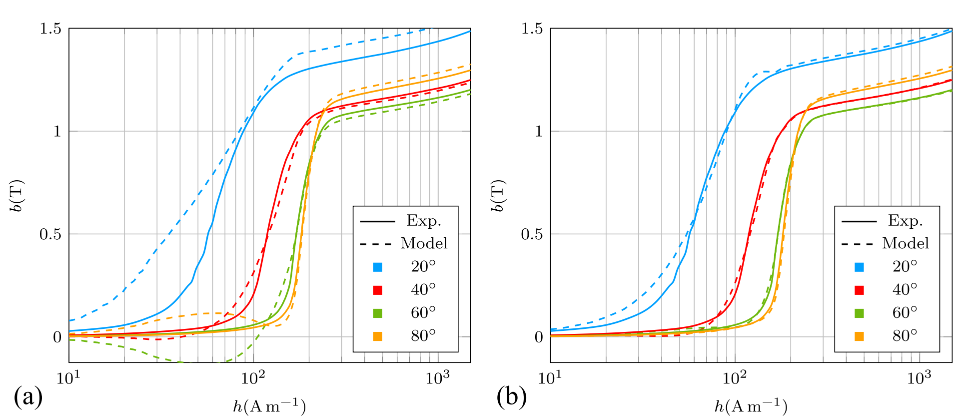

FIG. 4. Comparison between ODF model (3$^{\text{rd}}$ and 5$^{\text{th}}$ orders) and experimental data with A_i coefficients obtained using the FFT method. (a) 3$^{\text{rd}}$ order model, same as model[9] and (b) 5$^{\text{th}}$ order model.

As in section III, this procedure suffers from the number of experimental curves that are to be provided to feed the model, but since the FFT based procedure provides a better accuracy for a given decomposition order it is now possible to decrease the latter. As an illustration, Fig. 4 shows the results obtained for orders 3 and 5. Fig. 4a is to be compared with the results obtained from original model from Ref. 9 presented in Fig. 1a. FFT based method provides slightly better results, especially for 20° and 80° but the obtained curves are still not exploitable. Nevertheless, a 5^{th} order decomposition provides totally acceptable results and requires only 5 experimental curves.

V. CONCLUSION

Anisotropy Model for Modern Grain Oriented Electrical Steel Based on ODF was investigated. It was shown that the original model as presented in the literature can not be applied as is for modern high performance GOES. Two solutions were proposed in order to improve this model. The first one, which consists in increasing the decomposition order of the cosine series, lead to better results but required more experimental data. The second one, which consists in using FFT in order to determine the coefficient involved in the cosine series, allowed to increase the model accuracy while keeping the number of required experimental data to a reasonable number.

ACKNOWLEDGMENTS

The authors wish to acknowledge the support of this work by Thyssenkrupp Electrical Steel.

[1] J. Bastos and G. Quichaud, IEEE Trans. Magn. **21**, 2366 (1985).
[2] J. M. Dedulle, G. Meunier, A. Foggia, J. C. Sabonnadiere, and D. Shen, IEEE Trans. Magn. **26**, 524 (1990).
[3] J. Liu and G. H. Shirkoohi, IEEE Trans. Magn. **29**, 2458 (1993).
[4] T. Nakata, N. Takahashi, K. Fujiwara, and M. Nakano, IEEE Trans. Magn. **29**, 3544 (1993).
[5] J. Liu, A. Basak, A. Moses, and G. Shirkoohi, IEEE Trans. Magn. **30**, 3391 (1994).
[6] G. Shirkoohi and J. Liu, IEEE Trans. Magn. **30**, 1078 (1994).
[7] M. Enokizono and N. Soda, IEEE Trans. Magn. **31**, 1793 (1995).
[8] H.-J. Bunge, *Texture Analysis in Materials Science* (Butterworth-Heinemann, 1982).
[9] M. F. De Campos, in *XVIII IMEKO World Congress* (2006).
[10] M. F. De Campos and F. J. G. Landgraf, in *XVIII IMEKO World Congress* (2006).
[11] K. Chwastek, IET Elec. Power App. **7**, 575 (2013).
[12] K. Chwastek, A. P. S. Baghel, M. F. de Campos, S. V. Kulkarni, and J. Szczygłowski, IEEE Trans. Magn. **51**, 1 (2015).
[13] K. Chwastek, A. Wodzyński, A. P. S. Baghel, and S. V. Kulkarni, in *16th International Conference on Computational Problems of Electrical Engineering (CPEE)* (2015) pp. 21–23.