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THREE EPSTEIN FRAMES TO CHARACTERIZE IRON LOSSES AND MEAN PATH LENGTH OF GRAIN ORIENTED ELECTRICAL STEEL LAMINATION

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Abstract – *This paper proposes a method to characterize the magnetic properties of electrical steel. Three Epstein frames of different lengths are used to identify the iron losses in the core corners and in the straight parts, as well as the mean path length of the flux in the Epstein frames. The experimental results concerning Grain Oriented Electrical Steel are compared to the results given by the standardized Epstein frame.*

Introduction

The Epstein frame is one standardized device used to characterize the electrical steel sheets [1]. Even if it is standardized, two aspects are still regularly reported in the literature. The magnetic path length is set equal to 0.94 m in the standards for the 25 cm Epstein frame but this value is still regularly discussed [2]. It has been shown that the magnetic path length depends on several parameters such as the peak flux density, the frequency and the waveform of the excitation [3] as well as the tested steel, especially the permeability and the anisotropy of the material. In the case of Grain Oriented Electrical Steel (GOES), the differences between the Rolling Direction (RD) and the Transverse Direction (TD) are such that the anisotropy ratio can reach values up to 20000.

Previous studies have proposed the use of various devices based on modified Epstein frames. In [4], a method using 4 frames is proposed. Marketos *et al* use in [3] and [5] two Epstein frames: the standardized 25 cm frame and a shorter (17.5cm) one. Calculating the loss difference enables to access to the specific losses [3] with the hypothesis that the flux is uniform inside the laminations. They conclude that taking a mean path length equal to 0.94 m can lead to an under-estimation of transformer core building factors. In particular, they show that the higher the permeability, the longer the mean path length. In [5], the impacts of the frequency and the magnetization waveform are analyzed. More recently, Wang et al. [6] have used 3 Epstein frames of different sizes. The lengths of all four limbs of their frames are the same and equal, respectively, to 25 cm, 20 cm and 17.5 cm. The mean path length for frequencies between 50 Hz and 200 Hz and for different sampling angles (0°, 55° and 90° to the RD) are calculated. The authors identify different areas: the overlap area and zones of the straight flux parts called uniform zone and impact zone respectively.

This present paper is also focused both on the the determination of the mean path length and the specific loss, using modified Epstein frames. This is the prolongation of [7], which relates to a characterization of GOES with 2 conventional 25cm Epstein frames.

The present paper differentiates from the aforementioned one by the following topics:

- the modified Epstein frames have bigger size than the standard frame. That is important insofar as steel of high performance is analyzed: grains have a big size and that it is better to extend the limb length instead of shorten it,
- the use of 3 frames allows to draw more reliable characteristics concerning the influence of the frame size modifications,
- asymmetrical frames are used and the results will justify that differences of the losses measured in the different frames can be done to find the characteristics of the studied steel,
- different high performance GOES grades of nominal thickness 0.30mm and 0.23mm have been tested (Table 1).

<i>Grade name</i>	<i>Iron losses at 1.7T (W/kg)</i>	<i>IEC denomination</i>
<i>G1</i>	1.027	M105-30P
<i>G2</i>	1.379	M140-30S
<i>G3</i>	0.833	M 085-23P
<i>G4</i>	1.202	H125-35P

Table 1

Why three Epstein frames ?

Frame presentation

The three Epstein frames method proposed in this paper relies on experimental measurements with three magnetic circuits (Fig. 1) similar to those employed in the Epstein frame. They are called “short”, “medium” and “long” frames. The short circuit is a standard Epstein frame whereas the medium and long circuits differ from the latter by the length of two of their four legs. Medium and short frames are obtained by using 2 and 3 standard Epstein frames placed in series.

- two Epstein frames placed in series lead to the medium one which internal limb lengths are 22 cm and 58.4 cm respectively,
 - three Epstein frames give the long one with limb lengths of 22 cm and 94,9 cm.
- Each limbs is composed of $n_s = 7$ GOES laminations, of width l_s and thickness e_s .

All samples have been constituted from the same metallurgical batch. All strips are in neighbouring situations.

Experimental method description

The iron losses P_{iron} are obtained for each frame with a numerical wattmeter YOKOGAWA WT203 which measures the primary current and the secondary voltage. The peak flux density \hat{b} is calculated from a secondary voltage v_2 measured with a secondary coil with N_2 turns ($N_2 = 175$) wound around each limb whose length does not vary. $S = n_s l_s w_s$ is the cross section of the limb, where n_s , w_s and t_s are the number of sheets per limb, the width and the thickness of the samples, respectively.

$$\hat{b} = \frac{\hat{v}_2}{2\pi f N_2 S} \quad (1)$$

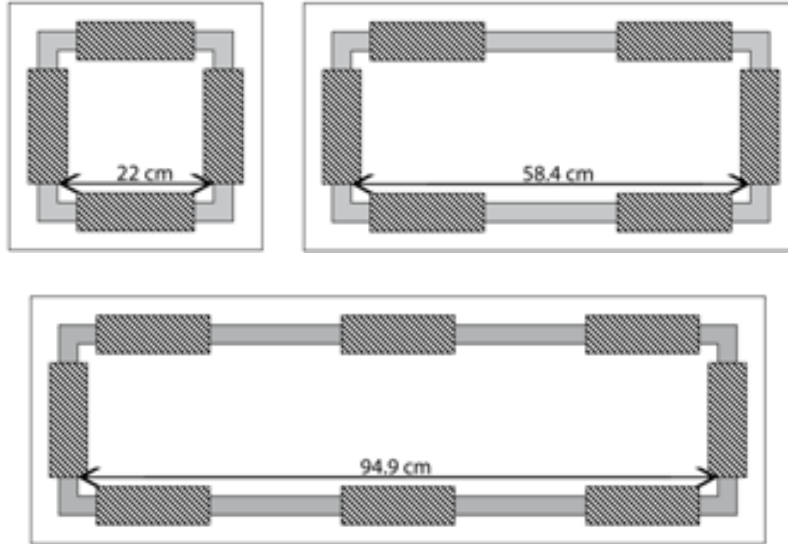


Fig.1 Geometries of the 3 Epstein frames

First experimental results: measurement and magnetic property characterizations

P_{iron} stands for the total iron losses; M_{lim} is the total limb weight, *i.e.* excluding the weight of the corners; and l_{lim} is the total limb length, *i.e.* excluding the corners. The experimentally measured iron losses are given in Fig. 2 for the 3 frames and for G1 steel.

Fig. 3 shows the change of P_{iron} with M_{lim} and with l_{lim} for 3 values of \hat{b} : 0.7T, 1T and 1.5T. The results show a linear trend which enables writing relation (2), where the slope P_{iron}/M_{lim} corresponds to specific iron losses and the nonzero intercept $P_{iron,0}$ corresponds to the losses in the corners:

$$P_{iron} = P_{iron/M_{lim}} M_{lim} + P_{iron,0} \quad (2)$$

The following three characteristics can be extracted from the variation of the losses with the sample weight:

- the slopes of straight lines in Fig. 3 gives access to $P_{iron/M_{lim}}$, without considering the mean path length in the frame, but only with the total limb weight (or with the length increasing the limbs),
- $P_{iron,0}$ depends on the mean path length in the corners and $P_{iron,0}$ changes with the considered frames. The abscissa for which the ordinate is 0 gives the mean path length of the flux in the corners,
- the variations of P_{iron} with M_{lim} are linear, although the medium and long frames are asymmetrical. That proves that the method based on the losses differentiation can be applied. That gives a first answer to the basic hypothesis, which considers that the flux distribution is the same near the corners, regardless the frame geometry for a sufficiently long limb. This hypothesis is more valuable if the short frame dimensions are bigger than the corners size. Simulations performed with a Finite Element software confirm that hypothesis especially for the Grain Electrical Steel (GOES) because the magnetic flux tends to follow the RD as far as possible in the corner before it changes direction towards adjacent laminations [8] [9] [10].

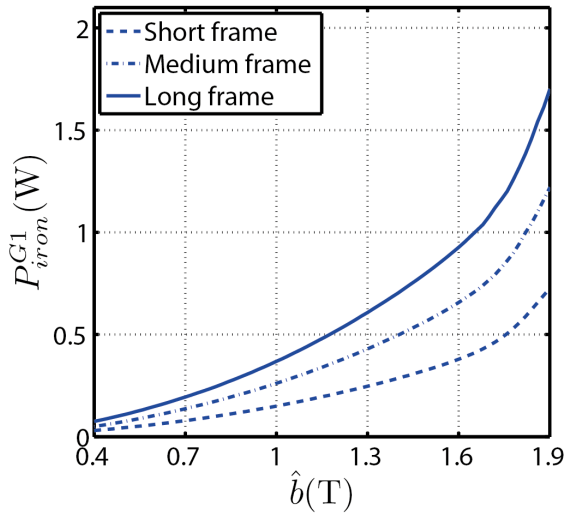


Fig. 2: Variations of P_{iron}^{G1} with \hat{b} for the 3 frames and G1 steel

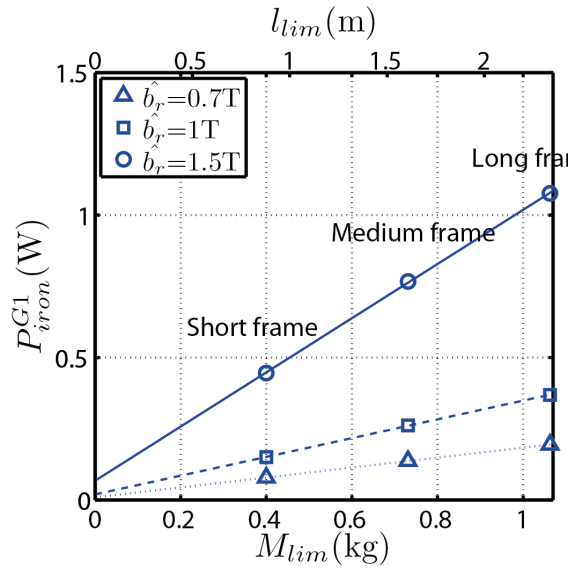


Fig. 3: Variations of P_{iron}^{G1} with M_{lim} for $\hat{b}=0.7T, 1T$ and $1.5T$ for G1 steel

Then, the accuracy of the wattmeter has been estimated concerning the determination of the iron losses and the secondary voltage. Fig. 4 shows the errors, for \hat{b} between $1.5T$ and $1.8T$, with vertical and horizontal bars calculated by considering that the voltage and the power are given by {measured value $\pm 0.1\%$ of the value $\pm 0.1\%$ of the caliber}. The average errors are respectively $\pm 4.47\%$, $\pm 4.4\%$ and $\pm 4.69\%$ for G1 short, middle and long frames.

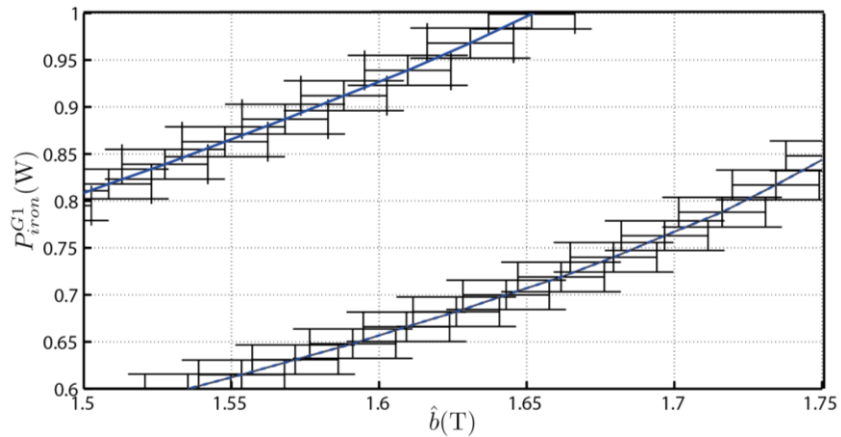


Fig. 4: Errors bars obtained for P_{iron}^{G1} with \hat{b} and for G1 steel

Influence of the frame and sample structure

Additional tests have been done by modifying the geometry of the frames and the number of samples. First, the number of strips per limb have been changed with G4 samples: Fig. 5 shows the variations of P_{iron} with \hat{b} for frames made of 4, 6 and 8 sheets per limb and for 3 flux density values. It shows that the losses vary linearly with the limb thickness increase. The lines are parallel which means that P_{iron}/M_{lim} does not change regardless the limb thickness; that reinforces the validity of the method.

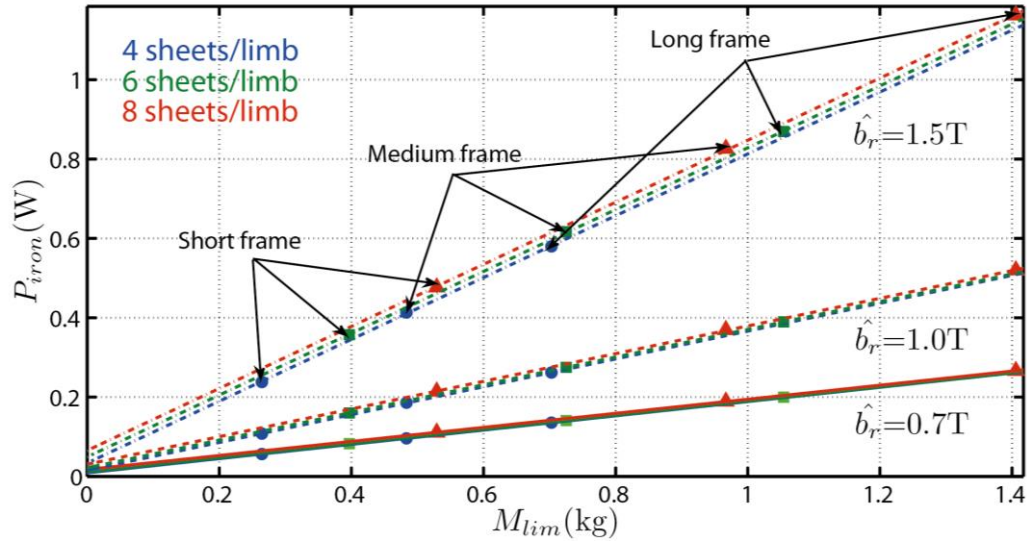


Fig. 5: Variations of P_{iron} with M_{lim} for frame equipped of 4, 6 and 8 samples per limb (G4)

Experimental results for different steel grades

The method has been applied to 4 grades of GOES. $P_{iron/M_{lim}}$, $P_{iron,0}$ and the L_e mean path length has been calculated. L_e results from the sum of the length of the straight parts and the mean path length of the flux in the corners estimated with the proposed method. Fig. 7 shows the variation of $P_{iron/M_{lim}}$ with \hat{b} , for the 4 steel grades, obtained with the Epstein frame and with the 3 frames method. It shows that the Epstein frame overestimates the iron losses. This tendency is already known [MARK1]. The advantage of the method is to estimate the specific iron losses and it shows that the higher the flux density, the higher the difference.

Fig. 8 gives the iron losses in the four corners, with \hat{b} , for the 4 steel grades. The results vary significantly with the steel grades. For $\hat{b} = 1.7$ T, the corners losses are equal to 15%, 16.5%, 15.7% and 13% of the short frame total losses, respectively for G1, G2, G3 and G4.

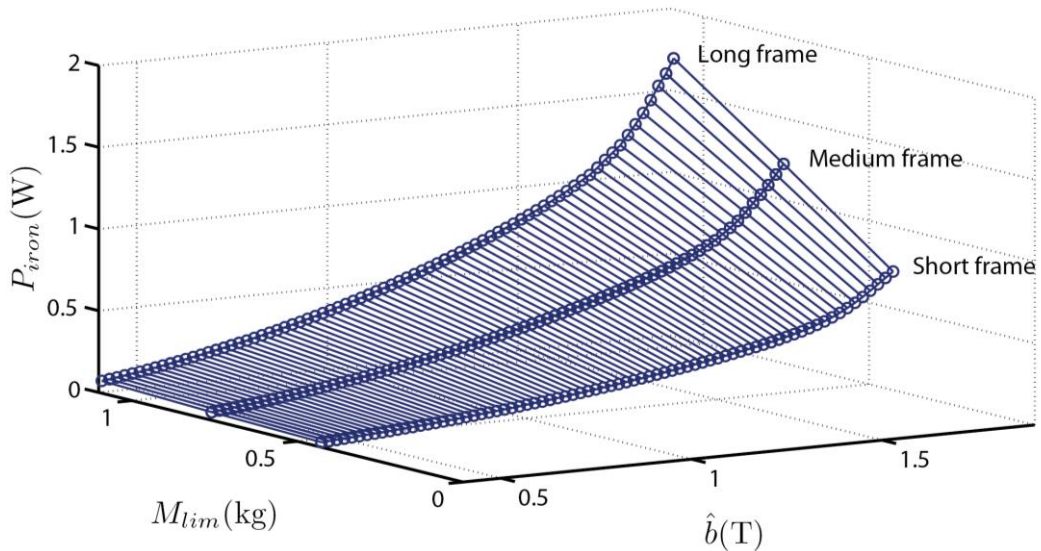


Fig. 6: Variation of P_{iron} with the mass increase of the limbs

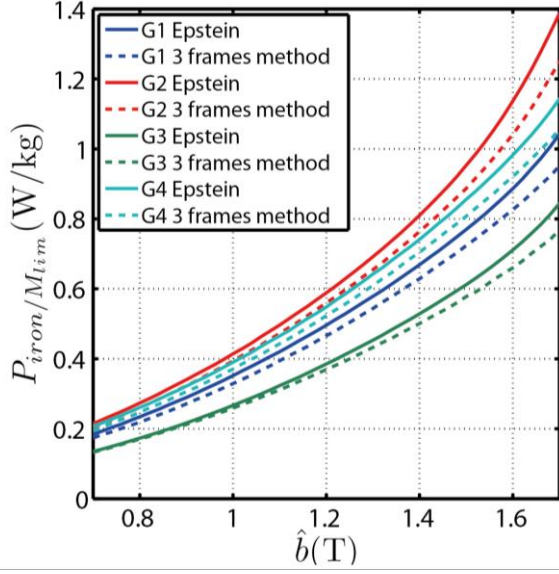


Fig. 7: Variations of P_{iron}/M_{lim} with \hat{b} , for 4 steel grades, measured with the Epstein frame and obtained with the 3 frames method

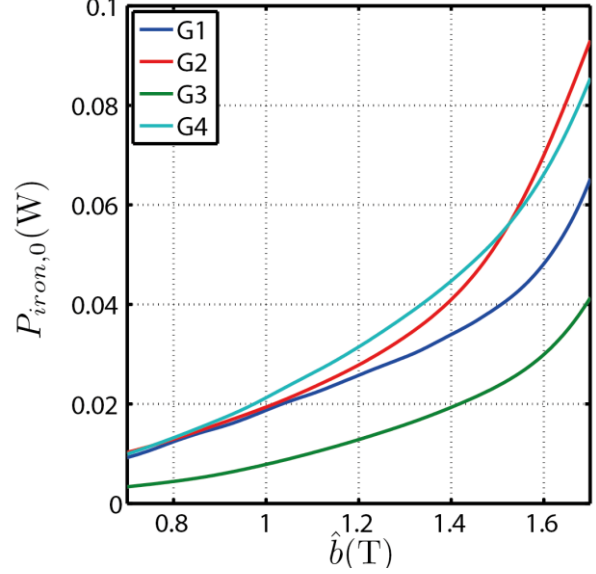


Fig. 8: Variations of $P_{iron,0}$ with \hat{b} for the 4 steel grades and obtained with the 3 frames method

Fig. 9 compares the variations, with \hat{b} and for the 4 steel grades, of the ratio of specific losses in the corner and in the limbs: $P_{iron}/M_{corners}/P_{iron}/M_{lim}$. It shows that the specific losses in the corners are lower than in the limbs even if the width of the corners are doubled with the double overlap joint. Then, whatever \hat{b} , $P_{iron}/M_{lim}^{G_3} < P_{iron}/M_{lim}^{G_1} < P_{iron}/M_{lim}^{G_4} < P_{iron}/M_{lim}^{G_2}$. This is not the case for the corners as the curves of the losses in the corners (Fig. 8) tend to cross. Fig. 9 also shows that the flux distribution in the corners differs in function on the grade and characteristics of the steel.

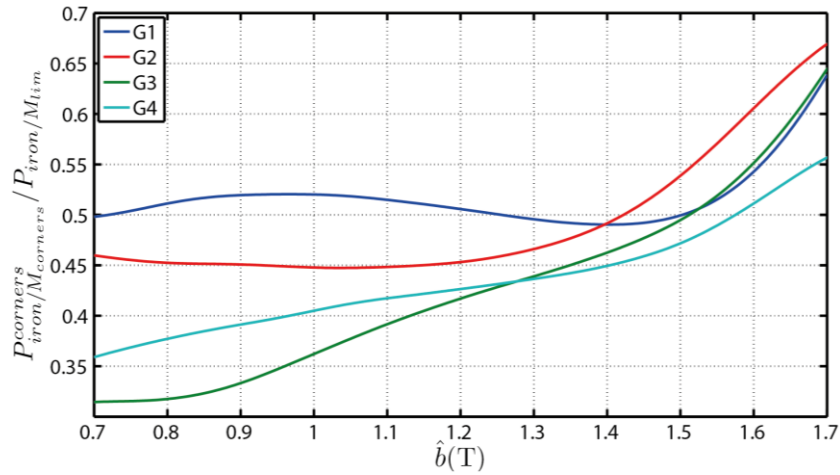


Fig. 9 : Variations of the ratio between the specific losses in the corners and in the limbs with \hat{b}

L_e can be calculated with two methods. The first one, which gives a length noted L_{e1} consists in adding the length of the 4 limbs and the length corresponding to the mean magnetic flux path in the corners. The latter is extracted from Fig.3: as it gives the iron losses with l_{lim} , the length between the origin and the abscissa for which the losses are null gives the mean magnetic flux path in the

corners. The second method [11] uses the relation 3 where P_{iron}^{short} , l and M are the iron losses of the short frame, the length of a strip and the total mass of the laminations.

$$L_{e2} = \left(4 l P_{iron}^{short}\right) / \left(M P_{iron} / M_{lm}\right) \quad (3)$$

Fig. 10 and 11 show respectively the variations of L_{e1} and L_{e2} for the 4 steel grades determined with the 2 methods. It shows that:

- for both methods, L_{e1} and L_{e2} are higher than the standardized length. It can even be superior to 1 m which is the geometrical average length of the frame.
- L_e depends on the peak value of the flux density. The deviation to the standard value is over 6% between 0.5T and 1.8T for L_{e1} . This expresses the fact that at the corner the flux establishes in twice the limb cross section. The local reluctance of the magnetic circuit is thus very different from the one in the limb and influences the overall estimation for the whole magnetic circuit. It also shows that, whatever the grade, this length tends to increase with the flux density peak value. This variation tendency is similar to the curves obtained by Marketos in [MARK2] for a high performance GOES magnetized with an excitation frequency of 50Hz.
- L_e does not depend on a sole identified parameter, as the lamination thickness or the steel grade. L_e is influenced by the flux density peak value, the steel grade but also the anisotropy ratio. The latter impacts the flux distribution in the corners and it may explain the differences on L_e .

The differences between L_{e1} and L_{e2} can be explained by the fact that the straight lines in Fig. 3 results from a linear approximation of the three values.

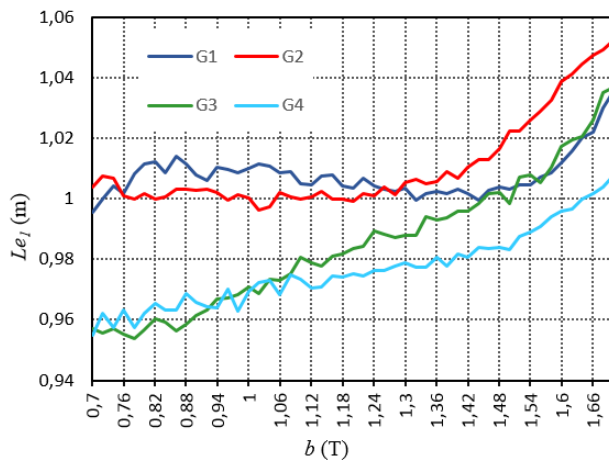


Fig. 10 : Variation of L_{e1} with \hat{b} for 4 steel grades

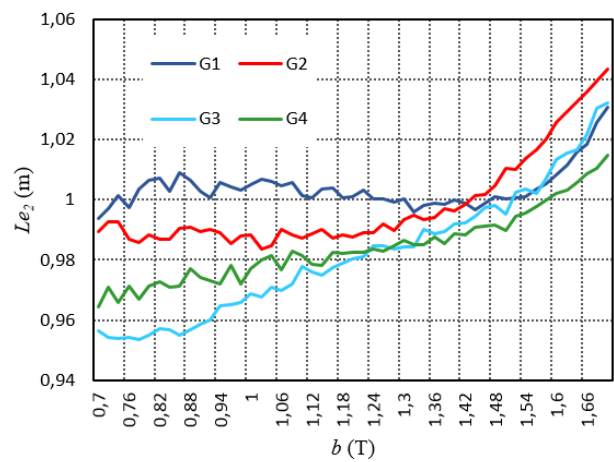


Fig. 11 : Variation of L_{e2} with \hat{b} for 4 steel grades

Conclusion

The proposed method has three advantages.

1. It gives access to the magnetic steel properties without considering the magnetic path length.
2. It makes it possible to separate the corner iron losses and the leg iron losses.
3. It shows that the mean path length of the magnetic flux depends on the steel grade and characteristics, but also on the flux density.

The paper differs from other papers which generally consider two frames of different lengths. Indeed, the chosen frame dimensions and the fact of using three frames make it possible to check that the iron losses are proportional to the frame dimensions and they allow to show that the geometry modifications do not influence the magnetic flux distribution in and near the corners if the frame dimensions are bigger than the corner dimensions.

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