HIGH FREQUENCIES LOSSES PREDICTION IN SOFT MAGNETIC MATERIALS

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Soft magnetic materials are continuously developed and improved in order to minimize their intrinsic operating energy losses. Nowadays, specific nanocrystalline and amorphous alloys are commonly used as magnetic core of different transformers that work at high frequencies and with magnetic flux densities values close to the saturation region. These particular operating conditions make difficult their experimental investigations mainly due to the encountered heating problems. Accordingly, this paper suggests a procedure that predicts the energy losses of a nanocrystalline sample of commercial FINEMET-D using experimental data up to 300 mT and 900 kHz and an elliptical developed model. The latter uses specific parameters evaluated from an searching fitting procedure. The results shows that, comparative to the experimental data (less than 300 mT), the losses prediction (up to 790 mT) estimated with the proposed model are to be considered.

1. INTRODUCTION

Soft magnetic materials are used in a large variety of electromagnetic devices with innumerous applications. Consequently, their magnetic and energetic features are continuously improved. A representative material is FINEMET alloy, which exhibits both good mechanical and magnetic characteristics [1]. Additionally, the nanocrystalline FINEMET alloys advantageously combine the properties of the cobalt-based metallic glasses (high permeability, low coercivity, and low magnetostriction) and conventional crystalline material (high flux density)[2]. FINEMET alloys are used in the constructions of many commercial applications: switching-mode power supplies, data communication interface components, solenoid valves, high frequency transformers or magnetic sensors. Thus, is taken benefit of their low coercivity, large saturation induction, large resistivity and good thermal stability [3–5].

One of the most common material known as FINEMET is an alloy with the chemical formula Fe_{73.5}Cu_{1}Nb_{3}Si_{13.5}B_{9}, containing Mo easily from amorphous phase [6]. In order to minimize the core losses, a percentage of Al instead of Si.
(1, 3, 5 or 7 parts) was introduced in the FINEMET compositions. Thus, for instance, Fe\textsubscript{73.5}Cu\textsubscript{1}Nb\textsubscript{3}Si\textsubscript{10.5}Al\textsubscript{3}B\textsubscript{9} has core losses at 100 kHz with 50% less than the initial material [7].

Magnetic properties of these nanocrystalline alloys can be controlled by applying a magnetic field during the annealing. Accordingly, three different magnetic material types can be manufactured: H–Type alloys when a magnetic field is applied in a circumferential direction during annealing, M–Type – no magnetic field is applied during annealing, L–Type – a magnetic field is applied vertically to the core plane during annealing. The latter sample exhibits a bigger anisotropy from H–Type to L–Type [8].

In our further investigations a FIMEMET sample was used with the following properties: saturation flux density 1.2–1.23 T (depending on the work temperature), crystallization temperature \( T_c = 5700 \, ^\circ\text{C} \), mass density \( \delta = 7205 \, \text{kg/m}^3 \), electrical resistivity \( \rho < 120 \, \mu\Omega \, \text{cm} \) and 19 \( \mu\text{m} \) thickness. Fig. 1 illustrates the first magnetization curve and the major loop for this sample obtained at a frequency of 500 Hz [9, 10].

![Fig. 1 – First magnetization curve and major loop obtained for 500 Hz.](image)

### 2. ELIPTICAL MODEL

The elliptical model was already reported by the authors in [11]. The model idea mainly came from the experimental loops obtained on several nanocrystalline and amorphous materials in high frequencies. The hysteresis loop looks like a rotate
ellipse in low magnetic field region. Thus, the model equations mainly rotate the
original axes with the angle $\alpha$ due following relations:

$$\begin{cases}
h = X \cos \alpha + Y \sin \alpha \\
b = X \cos \alpha - Y \sin \alpha.
\end{cases}$$  \hspace{1cm} (1)

The resulting equation for the ellipse became in this case:

$$A \cdot X^2 + B \cdot Y^2 + C \cdot XY + D = 0,$$  \hspace{1cm} (2)

where the above coefficients are calculating with the following expressions:

$$\begin{align*}
A &= \left(u^2 + v^2\right) \cos^2 \alpha \\
B &= \left(u^2 + v^2\right) \sin^2 \alpha \\
C &= 2\left(v^2 - u^2\right) \cos \alpha \sin \alpha \\
D &= -u^2 v^2,
\end{align*}$$  \hspace{1cm} (3)

where $u$ and $v$ are the semi axis of the ellipse and $\alpha$ is the rotating angle.

In Fig. 2 is represented the rotate ellipse and the next step is to identify the
generic parameters from (2) regarding the magnetic aspects. The original
experimental data must be normalizing to the highest values for both axes, because
magnetic field strength and magnetic flux density are measured in different units
i.e. $B$ in [T] and $H$ in [A/m].

![Fig. 2 – Representation of the ellipse in normalized coordinates.](image-url)
Thus, using normalizing relations: \[ h = \frac{H}{H_m}; \quad b = \frac{B}{B_m}; \quad h_c = \frac{H_c}{H_m}; \quad b_t = \frac{B_t}{B_m}, \]
the identification of the parameters from (3) can be performed:

\[ u = \sqrt{2}; \quad v = \frac{h_c \cdot h}{\sqrt{h^2 + h_c^2}}; \]
\[ \cos \alpha = \frac{b_t}{b}; \quad \sin \alpha = \frac{b}{\sqrt{b^2 + b_t^2}}. \] (4)

It can be concluding that the model requires the following experimental data: coordinates of the saturation point \((B_m, H_m)\), coercive field \((H_c)\) and remanent magnetic flux density \((B_r)\).

### 3. MODEL PARAMETER FITTING

Different sets of experimental data were used in order to determine the model parameters fitting. The hysteresis loops were obtained at a certain value of the peak magnetic flux density: \(B_m\). Using Matlab© fitting tool there was carried out an searching procedure of mathematical fitting the remain three coefficients for four values of the \(B_m\) (10 mT, 50 mT, 100 mT and 300 mT). The objective of the fitting procedure was to determine a function with the minimum amount of parameters and the fitting curve to be very close to most of the measure coefficient variations (using minimum average relative error, equation (7)). Also, some of the parameters of the fitting function were determined after searching fitting procedure, some of them were able to be identified with some magnetic values from the 5 Hz hysteresis loops, and other had only mathematical values [12, 13].

All coefficients were fitted as a function of the frequency, which varied from 5 Hz to 900 kHz (identify as \(f_{\text{max}}\)). From the experimental data we conclude that after this value of the frequency, the parameters entered in a “saturation” zone. In the following fitting formula there can be identified next values: \(B_m(5)\) is the value of the peak magnetic flux density at 5 Hz, \(B_r(5)\) is the value of the remanent flux density at 5 Hz, \(H_m(5)\) is the value of the peak magnetic field strength at 5 Hz and \(H_c(5)\) is the value of the coercive field at 5 Hz. First coefficient fitted was remanent magnetic flux density using a ratio of two polynomial functions:

\[ B_r(f) = \frac{p_1 \cdot f + p_2}{f + q_1}, \] (5)

where the three parameters had the following meaning:

\[ p_1 = \log(B_m(5))^{0.25} + 8 \quad [T]; \quad p_2 = f_{\text{max}} \cdot B_r(5) / 16 \quad [T \cdot \text{Hz}]; \quad q_1 = f_{\text{max}} / 16 \quad [\text{Hz}]. \] (6)
Parameters $p_1$, $p_2$ and $q_1$ are determined for a minimum of the average relative error between the experimental and modeled curves for $B_r$:

$$e_r(B_r) = \frac{1}{n} \sum_{k=1}^{n} \left| \frac{B_r,\text{exp}(f_k) - B_r,\text{mod}(f_k)}{B_r,\text{exp}(f_k)} \right| 100\%,$$

(7)

where $n$ is the total number of frequencies used in the modeling.

For fitting peak and coercive value of the magnetic field the following exponential-logarithmic function with three parameters was adopted:

$$H_m(f) = a \cdot \lg(f)^b + c,$$

(8)

where:

$$a = \frac{B_m(5)}{2.5 \cdot 10^7} \quad [\text{A/m}]; \quad b = 11; \quad c = H_m(5) \quad [\text{A/m}],$$

(9)

and

$$H_c(f) = m \cdot \lg(f)^n + t,$$

(10)

where

$$m = \frac{B_c(5)}{7.14 \cdot 10^7} \quad [\text{A/m}]; \quad n = 9; \quad t = H_c(5) \quad [\text{A/m}].$$

(11)

Parameters $a$, $b$, $c$, $m$, $n$ and $t$ are obtained after similar procedure of minimizing the relative errors like equation (7) for $H_m$ and $H_c$.

Using these fitting procedures the next two figures depicts the experimental loop (red curve) and ellipse model with fitted parameters (black curve) for a peak value of 300 mT at 1 kHz (Fig. 3) and 200 kHz (Fig. 4) respectively.

Fig. 3 – Experimental (red) and model (black) for $B_p=300$ mT and $f=1$ kHz.
Fig. 4 – Experimental (red) and model (black) for $B_p=300$ mT and $f = 200$ kHz.

Obviously, with higher frequency, the difference between the experimental loop and the modeled one are more evident, but through the energetic point of view the relative errors are not so significant (as the following section will illustrate).

4. POWER LOSSES PREDICTION

The experimental set-up offers the opportunity of calculating the total hysteresis losses for each measurement and in Table 1 are presented the total magnetic losses at different values of the peak magnetic flux density and different frequencies.

<table>
<thead>
<tr>
<th>$B_m$ [mT]</th>
<th>$f = 50$ Hz</th>
<th>$f = 10$ kHz</th>
<th>$f = 200$ kHz</th>
<th>$f = 500$ kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.56E-04</td>
<td>2.69E-04</td>
<td>1.44E-02</td>
<td>2.77E-02</td>
</tr>
<tr>
<td>50</td>
<td>9.60E-03</td>
<td>1.25E-02</td>
<td>3.59E-01</td>
<td>6.83E-01</td>
</tr>
<tr>
<td>100</td>
<td>4.88E-02</td>
<td>5.86E-02</td>
<td>1.42E+00</td>
<td>2.67E+00</td>
</tr>
<tr>
<td>300</td>
<td>5.62E-01</td>
<td>7.32E-01</td>
<td>1.24E+01</td>
<td>2.76E+01</td>
</tr>
</tbody>
</table>

Considering the modeled loop to be an ellipse a general formula for determining the area of this geometric figure (eq. (12)) was used. Consequently the values obtained from the modeled loop are presented in Table 2.
\[ P_{\text{mod}} = \pi \cdot a \cdot b \cdot B_{m} \cdot H_{m}. \]  
\( (12) \)

**Table 2**

Total magnetic losses modeled at different magnetic flux density and different frequency

<table>
<thead>
<tr>
<th>Elliptic model losses [J/m³]</th>
<th>( B_{m} ) [mT]</th>
<th>( f = 50 \text{ Hz} )</th>
<th>( f = 10 \text{ kHz} )</th>
<th>( f = 200 \text{ kHz} )</th>
<th>( f = 500 \text{ kHz} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
<td>1.67E-04</td>
<td>2.78E-04</td>
<td>1.45E-02</td>
<td>2.78E-02</td>
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<tr>
<td></td>
<td>50</td>
<td>1.02E-02</td>
<td>1.26E-02</td>
<td>3.26E-01</td>
<td>6.24E-01</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>5.33E-02</td>
<td>6.34E-02</td>
<td>1.43E+00</td>
<td>2.70E+00</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>5.19E-01</td>
<td>6.49E-01</td>
<td>1.34E+01</td>
<td>2.63E+01</td>
</tr>
</tbody>
</table>

In order to emphasize the difference between experimental data and those modeled Table 3 shows the relative errors computed with the relation for each point of the measurements:

\[ \varepsilon_{r} = \left| \frac{P_{\text{exp}} - P_{\text{mod}}}{P_{\text{exp}}} \right| \cdot 100 \% . \]  
\( (13) \)

**Table 3**

Relative errors between the measured and modeled losses obtained

<table>
<thead>
<tr>
<th>Relative errors [%]</th>
<th>( B_{m} ) [mT]</th>
<th>( f = 50 \text{ Hz} )</th>
<th>( f = 10 \text{ kHz} )</th>
<th>( f = 200 \text{ kHz} )</th>
<th>( f = 500 \text{ kHz} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
<td>7.36 %</td>
<td>3.38 %</td>
<td>0.49 %</td>
<td>0.52 %</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>6.76 %</td>
<td>0.65 %</td>
<td>9.11 %</td>
<td>8.60 %</td>
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<tr>
<td></td>
<td>100</td>
<td>9.41 %</td>
<td>8.19 %</td>
<td>0.54 %</td>
<td>1.21 %</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>7.72 %</td>
<td>11.33 %</td>
<td>7.99 %</td>
<td>4.57 %</td>
</tr>
</tbody>
</table>

One can notice that the relative errors vary from less than one percentage to 11%. Anyway, the average relative errors we can consider it less than 5%, an admissible value in this case.

The main objective of this paper was to use this model with its fitted parameter to predict the losses for higher values of the flux density. The experimental set-up was able to give experimental result for higher value than 300 mT and frequencies up to MHz, because of the heating problems. So, using the elliptical model with fitting parameters we were able to predict the total losses in the sample for magnetic flux densities up to 790 mT, corresponding to the linear area of the first magnetization curve (Fig. 1). In Fig. 5 are represented the variation of the total magnetic losses with the frequency for different values of the magnetic flux density: with solid lines are the experimental values and with dot lines are the modeled values.

It can be observed that the modeled values are not so different from the experimental ones and from an engineering point of view they can be accepted.

In Fig. 6 is a representation of the variation of total losses modeled with magnetic flux density for different values of the frequency.
Fig. 5 – Experimental (solid line) and model (dot line) total magnetic losses for different values of the magnetic flux density.

Fig. 6 – Total magnetic losses modeled for different values of the frequency.
5. CONCLUSIONS

The aim of this paper was to predict the total magnetic losses for a commercial FINEMET nanocrystalline magnetic material used in a wide range of frequencies. The experimental set-up prevent the measurements in high frequencies and high values of the magnetic flux density due the heating problems. Using an analytical model we were able to determine and compare the total magnetic losses between the experimental results and the developed model. The elliptical model proposed here had tree fitted parameters.

The comparison between the experimental loops and the model ones (using the elliptical model) provided very good results for frequencies up to 50 kHz and satisfactory result for higher frequencies (up to 900 kHz). In the range of 100–900 kHz, there was difficult to obtained a fix value of the remanent magnetic flux density and coercive field (two of the model fitted parameters) and this may be one of the cause of the higher relative errors obtained. In spite of the fact that the experimental and modeled loops are quite different (Fig. 4), relative error for the total magnetic losses is only 8%. The results obtained for lower values of the magnetic flux density (less than 300 mT) encourage us to use the model up to 800 mT, corresponding to the linear region of the first magnetization curve.

The work will be continued for other amorphous magnetic materials.

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