Electrical and caloricimetric power loss measurements of practically ideal soft magnetic cores

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In this paper we demonstrate two methods for measuring power losses of soft magnetic cores made of nanocrystalline (Fe₁₀₀₋₃₅Co₉₋₆₅Ni₉₆₋₉₀₃Cu₃₋₅₁Nb₃₋₅₁Bi₃₋₅₁) alloys at the magnetic induction level Bₘₐₓ=300mT and at the measurement frequency f=100kHz. We investigated the possible sources and consequences of measurement errors both for the electronic and for the simplified calorimetric method. While the electrical core loss measurement showed more than a factor of 2 higher value for µ₂=300 sample than for µ₂=2600, the calorimetric method proved that it is not the case, it is only about 30% higher. The result is interpreted with significantly higher measurement uncertainty of the electrical measurement when the phase angle φ is very close to 90°, i.e. when the magnetic core behaves like an almost ideal inductor. The calorimetric measurement error is also gradually increasing as µ₂ is lowered, due to the increasing fraction of the copper wire’s Joule heating. The measured data are consistent with the eddy current loss component. It has been demonstrated that the tape thickness plays the most important role for the power loss of these soft magnetic cores.

Index Terms—Calorimetric methods, core losses, eddy current, Fe-based nanocrystalline alloys.

I. INTRODUCTION

In the world of growing energy needs the efficiency of electronic equipments must be continuously improved. It means that the power losses of passive inductive components have to be reduced. Nanocrystalline soft magnetic cores made of (Fe₁₀₀₋₃₅Co₉₋₆₅Ni₉₆₋₉₀₃Cu₃₋₅₁Nb₃₋₅₁Bi₃₋₅₁) alloys are used in electromagnetic compatibility (EMC) applications, most often in conjunction to electrical drive systems (EDS). Such applications can be found in all kinds of transportation, chiller facilities, paper industry and wind turbines. The magnetic cores are absorbing high frequency conducted noises and transforming them into heat. The more the power losses are the higher the overheating of the core is. Therefore power losses cannot be considered only as the measure of the efficiency, but it plays an important role in designing a suitable filtering application, too. [1]

FIGURE 1

Nanocrystalline cores, especially the ones with lower permeabilities (µ₂<10000) can have phase shift very close to the ideal 90°. In this condition measuring power losses with flux metric method can be affected with large errors, because of the current probe delay, leakage inductances and parasitic capacitances. Figure 1 shows a block diagram of such kind of instrument. The core is excited on N₁ number of primary turns with Iₙ effective current, whereas U₂ secondary voltage is monitored on N₂ number of secondary turns. The dissipated power is given as

\[ P_D = I_n U_2 \frac{N_1}{N_2} \cos \phi \tag{1} \]

where \( \phi \) is the phase shift between the current and the voltage signals. We note here that the specific core loss measured by this electronic method is defined as

\[ P_{sh} = P_D / m_{core} \tag{2} \]

where \( m_{core} \) is the mass of the core.

Let us suppose that the real phase shift of the inductor is (90°–β), and the phase shift introduced by the measuring system is ψ. For small angles the following approximation is valid:

\[ P_D = I_n U_2 \frac{N_1}{N_2} \cos(\pi / 2 - \beta - \psi) = \]

\[ = I_n U_2 \frac{N_1}{N_2} \sin(\beta + \psi) = I_n U_2 \frac{N_1}{N_2} (\beta + \psi) \tag{3} \]

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FIGURE 2

Figure 2 shows how huge measurement error in the value of the core loss can occur. Despite of the phase correction algorithms used in the most sophisticated equipments, one cannot reach \( \psi << 0.1° \). It is clear that for \( \phi \leq 88° \) the core loss can be measured reasonably well with this kind of method. It is not surprising that in some cases measurements performed with various power meters were giving awfully different results, e.g. we managed to observe 50% power loss value compared to a reference instrument, on a core with \( \phi = 30° \times \phi = 10° \times \phi = 50° \), \( N_1 = 3 \), \( N_2 = 1 \), at \( f = 100 \) kHz. These findings gave the motivation for us to develop an independent measurement method for the core losses in this regime.

II. EXPERIMENTAL TECHNIQUE

A simplified calorimetric measurement method has been developed. Small sized samples, \( 30 mm \times 25 mm \times 6 mm \) were prepared with various permeability levels. They were placed into half cases, and wound with insulated primary and secondary copper wires, where the primary is made turn-by-turn, each turn soldered onto a PCB as shown in Figure 3.

FIGURE 3

\( \phi = \phi = 6 \) configuration was chosen in order to ensure homogenous magnetic field generation and to reduce the stray field effects as much as possible. The 4-probe d.c. resistance of the primary side was between 1.22 and 1.29 mΩ for all

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samples. Special care was taken to have exactly the same mechanical configuration for all samples, and one sample was created only with an empty case for calibration purpose as described later. A platinum resistor as a temperature sensor was attached to the surface of the core. This construction was placed into a plastic cup filled with always 100 g transformer oil. In order to establish quasi-adiabatic condition for the experiment, first we waited at least 30 minutes in order to stabilize the system at the ambient temperature. Stirring of the oil was done by a wooden chopstick and it has been checked that stirring did not introduce temperature rise in the system.

Instead of making extra efforts for better heat insulation or trying to figure out and calculate with all the various heat capacities in the system, we calibrated the system by introducing a very small resistive heater with negligible heat capacity. The heat capacity $C$ of the total system was calculated then as

$$C = \frac{P_{DC}}{dT/dt} = 200 \pm 15\%$$

where $P_{DC}$ is the dissipated power on the heater, measured very easily and accurately with standard instruments (Hameg HM8143 function generator and zes-Zimmer LMG95 power meter), and $dT/dt$ is calculated from the recorded time trace of the temperature $T$ by numerical differentiation. The total measurement time was over 11 minutes in all experiments, and the maximum temperature variation was 5 K. This is a small change compared to the ambient environment, therefore the influence of heat transfer to the surrounding due to not perfect heat insulation is negligible.

In order to measure the iron loss of the cores, we still have to do a second calibration step. We have to measure the temperature rise due to the Joule heating of the primary coil, also called copper loss of the inductor. For this purpose we used the already mentioned empty sample, but placed a similar bare core inside the measurement setup in order to keep the same total heat capacity. Feeding $I_0=5.6$ A current into the system, the dissipated power on the primary conductor with $R_{\text{in}}$, resistance at 100 kHz can be calculated from the measured $dT/dt=1.23K/615s=2mK/s$ as follows:

$$P_0 = I_0^2 R_{\text{in}} = C \left( \frac{dT}{dt} \right)_{\text{empty}} = 0.40 \text{ W} \pm 3\%$$

(5)

The error bar is taken from the overall variation of the primary conductor’s resistances among the different samples.

**FIGURE 4**

At the end, we measure the temperature-time trace of the sample core at a given exciting current $I$ (Figure 4), and the calorimetrically measured specific iron loss of the core can be calculated as

$$P_{\text{corr}} = \frac{C \left( \frac{dT}{dt} \right)_{\text{sample}} - P_0 \left( \frac{I}{I_0} \right)^2}{m_{\text{core}}}$$

(6)

**III. RESULTS AND DISCUSSION**

In this section, in order to make an easy comparison of the results, we always select $f=100$ kHz measurement frequency and $B_{\text{max}}=300$ mT magnetic induction. At this frequency the signal waveforms are nice sinusoidal, therefore the following formula connects the excitation current $I$ and the magnetic induction $B$:

$$I = \frac{l_{Fe} B}{N_1 \mu_0 \mu_r}$$

(7)

where $l_{Fe}$ is the mean magnetic path length of the core, $\mu_0$ is the vacuum permeability.

**FIGURE 5**

First of all, we would like to demonstrate that the electronic and calorimetric measurement methods give the same result when $\phi \leq 88^\circ$. This condition is easily fulfilled with standard $\mu_r=30000$ products. Figure 5 shows the magnetic hysteresis loop obtained by the Brockhaus MPG200 equipment. During the measurement, the device controls the signal levels in such a way that the preset $B_{\text{max}}=300$ mT would be reached, and the associated primary current, and the secondary voltage waveforms are recorded. By using the geometric factors, the software transforms these waveforms into $H$ and $B$ fields, and at the end calculates $\mu_r$ and $P_{\text{core}}$. After having all these details available about the core, we can move to the calorimetric measurement and all parameters are known to set the excitation current according to (7).

An alternative way to find out $\mu_r$ is by using an inductance analyzer, e.g. Wayne-Kerr 3260B [2]. This type of device can measure the inductivity of our samples with the accuracy of 0.5% at $f=100$ kHz, and $\mu_r$ can be easily calculated. Both ways are easy and straightforward for $\mu_r=30000$ cores, but as $\mu_r$ decreases below ~2000, leakage inductance starts to play an important role and can potentially cause significant measurement error and often irreproducible or at least setup dependent results. Without discussing possible alternative workarounds here in detail, we note that the configuration with the equally distributed 4 or 6 windings (as shown on Figure 3) eliminates all these leakage related problems. The trade off is the increased winding capacitance and other parasitic capacitances that also evolves into the measurement system error $\psi$

**TABLE 1**

Table 1 shows the experimental results for the power losses for both electrical and calorimetrical methods. The results are according to the expectations stated in Section I. For samples with $\mu_r \geq 2600$, the electrical power loss measurement is giving an accurate result and so is the calorimetric experiment. But the increased (even doubled) power loss value for the lowest permeability core is clearly not verified by the calorimetric method.

At this point, we have to comment on the measurement error level of this calorimetric method. The biggest source of error is the subtraction of the copper losses. In order to evaluate it more carefully, we performed the empty core measurements for each current levels used for the real samples with $\mu_r \leq 1000$. The lower the permeability is, the more
important the copper loss part is. By assuming 10% error for the copper loss part, we can conclude from the data shown in Table 1 that the maximum value for the core loss of sample #6 with \( \mu_r \sim 300 \) is about 125 W/kg. The overall comparison of our electrical and calorimetric results are presented in Figure 6.

**FIGURE 6**

In order to demonstrate how close the core loss is for an ideal inductor, we would like to estimate the minimum feasible value for the power loss at \( B_{\text{max}} = 300 \text{mT} \) and \( f = 100 \text{kHz} \). In the loss separation method, the various components of the losses per unit volume \( (P_V) \) can be written as follows [3]:

\[
P_V = P_{V,\text{eddy}} + P_{V,\text{hysteresis}} + P_{V,\text{anomalous}} =
\]

\[
\frac{(2\pi f)^2 B^2 d\delta}{8} \left( \frac{\sin \frac{d}{\delta} - \sin \frac{d}{\delta}}{\cosh \frac{d}{\delta} - \cos \frac{d}{\delta}} \right) + \frac{fA_{\text{hyst}} d}{2\delta} \left( \frac{\sin \frac{d}{\delta} + \sin \frac{d}{\delta}}{\cosh \frac{d}{\delta} - \cos \frac{d}{\delta}} \right) + A^\frac{1}{5}
\]

where \( d \) is the tape thickness, \( \sigma \) is the conductivity of the tape, \( \delta = 1/\sqrt{2\pi f \mu \sigma} \) is the skin depth, \( A_{\text{hyst}} \) is the area of the quasi-static hysteresis curve, \( A \) is a constant. At \( f = 100 \text{kHz} \) frequency, the major component is the eddy current loss due to its strongest frequency dependence.

**FIGURE 7**

Figure 7 demonstrates that the calculated eddy current loss component gives us alone a nearly constant value of \( \sim 70 \text{ W/kg} \) for the nominal tape thickness of \( d = 20 \mu\text{m} \), and for permeability levels between \( \mu_r = 300 \) and \( \mu_r = 20000 \). This value is nearly the same as the observed power loss of our samples, showing that the influence of the hysteresis loss and anomalous loss are negligible. We note that the eddy current loss is strongly and linearly depending on the tape thickness in this regime, therefore the tape thickness plays the most important role for the power loss of our soft magnetic cores.

**IV. CONCLUSION**

Two methods for measuring power losses of soft magnetic cores were presented and compared. Both methods show significant measurement errors for the samples with the lowest permeability level \( \mu_r \sim 300 \). The sources of the errors were analyzed. While the electrical method gave substantially higher loss value for the sample with \( \mu_r = 300 \) than for the others, the calorimetric method proved that it is not the case. Most remarkably, the power losses of all these samples are indeed very close to each other and to the theoretical value of the eddy current loss at the measured frequency \( f = 100 \text{kHz} \). It has been found that the tape thickness plays the most important role for the power loss of our soft magnetic cores. These cores behave as nearly ideal inductors with a phase shift very close to 90°, at least when \( \mu_r \leq 1000 \).

**ACKNOWLEDGMENT**

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**REFERENCES**


Fig. 1. Block diagram of a standard power loss measuring equipment.

Fig. 2. The relative error of the core losses value calculated for various levels of measuring system related phase shifts $\psi = 0.1^\circ, 0.2^\circ$ and $0.3^\circ$.

Fig. 3. Sample configuration.

Fig. 4. Examples of recorded temperature-time traces. Blue, red and green traces are for cores with $\mu_r = 2616, 1461, 994$, respectively. Solid lines are linear fits.

Fig. 5. B-H hysteresis loop measured on various samples. The legend shows the permeability level of each core measured at $f = 100$ kHz.
Fig. 6. Electrical and calorimetric core loss measurements performed on tape-wound toroid soft magnetic cores made of \((\text{Fe}_{100-a-b}\text{Co}_a\text{Ni}_b\text{Cu}_1\text{Nb}_3\text{Si}_y\text{B}_z)\) alloys as a function of permeability.

Fig. 7. Calculated eddy current loss component at \(B_{\text{max}}=300\text{mT}, f=100\text{kHz}\), for various tape thicknesses and permeability levels.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>COMPARISON OF ELECTRICAL AND CALORIMETRIC RESULTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>#1</td>
</tr>
<tr>
<td>(\mu_r)</td>
<td>20281</td>
</tr>
<tr>
<td>(m_{\text{core}}) (g)</td>
<td>7,1</td>
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<tr>
<td>(I_1) (A)</td>
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<tr>
<td>(P_{E1}) (W/kg)</td>
<td>69,0</td>
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<td></td>
<td>±2%</td>
</tr>
<tr>
<td>(\phi) (°)</td>
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<tr>
<td>(\Delta t) (sec)</td>
<td>600</td>
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<tr>
<td>(C(\Delta T/\Delta t)_{\text{sample}}) (W)</td>
<td>0,408</td>
</tr>
<tr>
<td>(P_{E1}/I_1) (W)</td>
<td>0,0002</td>
</tr>
<tr>
<td>(P_{E2}) (W/kg)</td>
<td>57,7</td>
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<td></td>
<td>±10%</td>
</tr>
<tr>
<td>(P_{E2}/P_{E1})</td>
<td>83,6%</td>
</tr>
</tbody>
</table>

The electronically measured \((P_{E1})\) and calorimetrically measured \((P_{E2})\) specific power losses of various cores are shown here. The error bars for the electronic measurement are assumptions with measuring system related phase shift value of \(\psi=0.3°\). For the calorimetric results, the elapsed time \((\Delta t)\) is given for \(\Delta T=1.23\text{K}\) temperature change.