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Study of magnetic losses in Mn-Zn ferrites under biased and asymmetric excitation waveforms

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***Abstract*—We present magnetic loss measurements performed on Mn-Zn ferrite samples using an original experimental setup recently developed and described elsewhere [1]. Measurements have been performed on small amplitude loops (100 mT peak to peak induction amplitude) under excitation frequencies ranging from 20 kHz up to 200 kHz. Loss characteristic is explored under non conventional excitation reproducing typical working conditions of power electronics integrated devices. We present measurements performed under triangular symmetric and biased excitations with offset field in the interval: $0 \leq H_{off} \leq 110$ Am^{-1}. A second set of measurements has been performed under triangular asymmetric excitation where the field change rate was different between the ascending and the descending branch of the cycle.**

***Index Terms*—Magnetic losses, soft ferrites, Mn-Zn sintered ferrites, magnetic losses measurement.**

I. Introduction

New applications in power electronics and integration, generated an increasing request for extremely detailed knowledge of magnetic materials loss characteristic. While most of the loss characteristics of commercial materials are measured on symmetric loops (e.g. low induction cycles centred on the demagnetised state) and under sinusoidal excitation, the conception of new integrated components needs characterizations performed in working conditions (i.e. under non conventional excitation). As a matter of fact in most of the applications (e.g. in a typical switched-mode power supply), materials can be subjected to field biased triangular waveform and to triangular asymmetric waveforms. These excitation conditions involve three major departures from the standard under which magnetic losses are generally characterized and modelized:

i. Most of the characterizations on industrial materials are performed under sinusoidal excitation waveform. Moreover, most of the model of losses (e.g. the very often used statistical approach due to Bertotti [2]) have been conceived to be applied to this case. Nevertheless departure from sinusoidal excitation has been the object of proper generalisations of power losses models (see for instance [3], [4] and references within).

ii. Power losses are generally measured on symmetric hysteresis loops,this means that the loops are centred on the origin and that the measurement takes place after that a proper demagnetization of the sample has been performed. In the case of small amplitude polarizations

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the loops can be considered as Rayleigh cycles. Loops measured in presence of a field offset under small amplitude excitations, as the ones we study in this work, are asymmetric both with respect to the B axis, and with respect to the H one. If the loops are measured on the first magnetisation curve (i.e. the bias field is applied after an AC demagnetization) their shape should not be very different from the one of cycles measured in the Rayleigh region. Nevertheless departure from a symmetric position with respect to the origin of the (BH) plane is expected to affect the balance between reversible and irreversible contributions to the magnetization process and therefore the associated loss.

iii. Finally, the measurement of power losses on small amplitude loops where the ascending and descending branches of the cycle are swept with different field rates $\dot{H} = dH/dt$ introduces a further reduction of symmetry. In this case the shape of the loop is expected to be asymmetric and, particularly when the duty cycle η (the ratio between the time length of the ascending and of the descending branch of the cycle) is far from 0.5 (corresponding to the symmetric loop) the precision of classical flux-metric measurements can be dramatically reduced due to phase lags introduced by voltage and current probe. Moreover this is a case where power losses can be hardly modelized without using an approach able to describe statical and dynamical hysteresis features in detail like the one described in [6]

In this paper we present power loss measurements performed on a sample of industrial Mn-Zn ferrite using an original experimental setup that we described in detail in a recent paper [1]. In the next section the main features of the measurement method will be recalled. The third section will be devoted to present loss measurements performed under triangular field biased excitation (with offset field in the range $0 \leq H_{off} \leq 110 Am^{-1}$), and triangular asymmetric (with duty cycle varying in the interval $0.2 \leq \eta \leq 0.8$) biased excitation in a frequency interval ranging from 20 kHz up to 200 kHz.

II. Experimental setup

The most widespread experimental technique used to measure power losses in soft magnetic materials is based on the flux metric method. The main difficulty challenging the precision of power loss measurements performed with a typical hysteresisgraph-wattmeter equipment, when excitation frequencies are above 10 kHz, are due to the spurious phase contributions arising from stray capacitances and inductances. Particularly when characterizing low-loss materials under small amplitude excitation the spurious phase shift can be of the order of magnitude of the measured loss. In this case phase shift correction systems, provided with commercial voltage and current probes, become highly ineffective and reliable measurements can be obtained only using suitably designed equipment where extreme attention is devoted to the arrangement of windings, leads, cables, and components.

Here, besides the frequencies involved, we are facing additional difficulties arising when non-sinusoidal excitation waveforms are used. For this reason we follow a fairly different experimental approach based on the calorimetric method.

A. General principles of the calorimetric method

The method is based on the possibility to relate the power dissipated in the magnetic material with the temperature increase of the sample, so that loss measurement reduces to the measurement of a temperature ramp. Now, let us consider the mean electrical power $\langle P' \rangle$ (in watts) dissipated by a coil, wound around a sample in a closed magnetic circuit, when a periodic voltage V_{in} is applied:

$$\langle P' \rangle = \langle V_{in} I_{in} \rangle \tag{1}$$

This power loss is the results of all the dissipative processes involved, from the electrical resistivity in the coil to whatever irreversible phenomena associated with core magnetisation (Barkhausen jumps, eddy currents, domain wall resonance, spin dumping, magnetoacustic emission etc..). Under suitably controlled isolation condition of the sample, all the magnetisation process related effects should eventually convert into heat, producing a temperature increase of the magnetic material. For a magnetic core with an average length, not too far from its maximum and minimum path length, we can reasonably assume to have an homogeneous magnetic induction through the section of the sample. Thus, the power can be considered to be uniformly dissipated all through the core. The thermal source density p_s (in Wm^3) is then,

$$p_s = \frac{\langle P \rangle}{v} \tag{2}$$

where $\langle P \rangle$ is the mean power dissipated in the magnetic material and v is the volume of the core. When the electrical resistivity loss in the coil can be neglected we can write: $\langle P' \rangle = \langle P \rangle$. When thermal isolation of the sample is properly achieved, as discussed in detail in [1], the lapse of time when the heat equation can be linearised can be extended as much as possible and the temperature field $T(x, y, z, t)$ rate of change is expressed as:

$$\frac{\partial T}{\partial t} \simeq \frac{1}{\rho c_p} p_s \tag{3}$$

where c_p is the specific heat of the sample and ρ its density. Combining Eq. 2 and 3, we obtain:

$$\langle P \rangle \simeq C_p \frac{\partial T}{\partial t} \tag{4}$$

where C_p is the heat capacity of the sample.

Once C_p is known (its measurement using a setup very similar to the one used to determine power losses is described in [1]), the loss measurement reduces to the measurement of the temperature increase of the sample.

B. Temperature measurement

Sample temperature measurement is the central issue of our power losses measurement method. Different temperature methods can be envisaged. The main advantage of infrared method is the fact that it is contactless. However the precision of this technique is drastically affected by infrared radiations due to the environment. Contact method requires a thermoelectric couple or a platinum probe. In this case it is very important to avoid thermal leakage by reducing as much as possible the size of the probe. It is worth noting that, when the sample is a ferrite, its temperature can be measured with high precision by screening the material resistivity. This method will be discussed in detail elsewhere [7]. As thermocouples can be quite small but can hardly attain an accuracy better than 0.1 K we used, to determine the temperature of the sample, a platinum probe. A detailed description of the calibration of the probe is given in [1].

All the measurements presented here have been performed using a *Pt 500* (TRFD501B, Murata) probe with a volume of the active part ($\sim 3 \times 2 \times 0.7 mm^3$) small compared with the volume of the sample. The sensibility of the probe is of 5 mK.

C. Magnetic circuit

Experiments have been performed on a square section *U/I* commercial soft ferrite (*U* $25/16/6$, *I* $26/6/6$, Ferroxcube). The material is a Mn-Zn ferrite $3E27$. The effective length of the circuit is 69.8 mm.

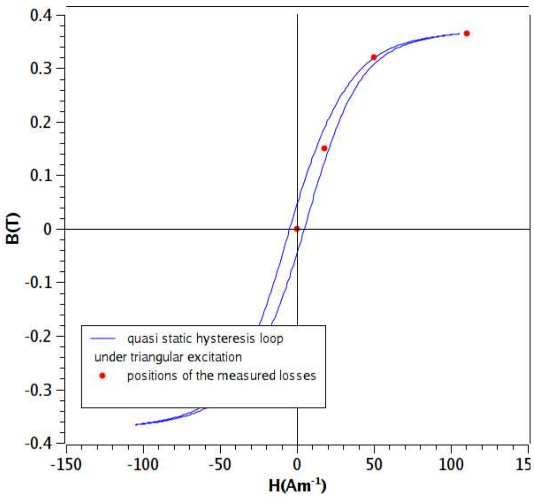

Fig. 1. Quasistatic hysteresis loop measured with fluxmetric method. The points represent the position where losses have been measured. Starting from the demagnetised state the points correspond respectively to the following bias field: $H_{off} = 0, 17.9, 50, 110.3$ Am^{-1}

The primary and secondary 10 spires windings are wrapped around the U part of the magnetic circuit, far enough from the platinum probe, to avoid any thermal influence on the measurement of temperature. A Krohn-Hite 7500 amplifier, driven by a TTi TGA 1230 wave form generator, is used to apply the voltage to the primary winding. Measurement and adjustment of the level of the induction B in the circuit are performed using a Lecroy $PP006$ (500 MHz) voltage probe and a Lecroy 9304 A scope connected respectively to the secondary and primary windings. The magnetic circuit has been set in a vacuum chamber with a pressure of 267 Pa ($O.263\%$ of an atmosphere) held by a vacuum pump during all the measurements. The measured specific heat of the sample is $c_p = 760$ Jk^{-1}, a value in agreement with the values given in the literature [8].

III. Loss measurements

Measurements have been performed applying to the primary coil a controlled rectangular voltage signal. The shape and the field bias of the resulting triangular current excitation have been obtained by adjusting the dc offset and the duty cycle of the voltage signal. Losses measured under sinusoidal excitation have been measured too and are plotted, as a reference, in Fig. 2 and 3. All the measurements have been performed under 100 mT peak to peak induction amplitude.

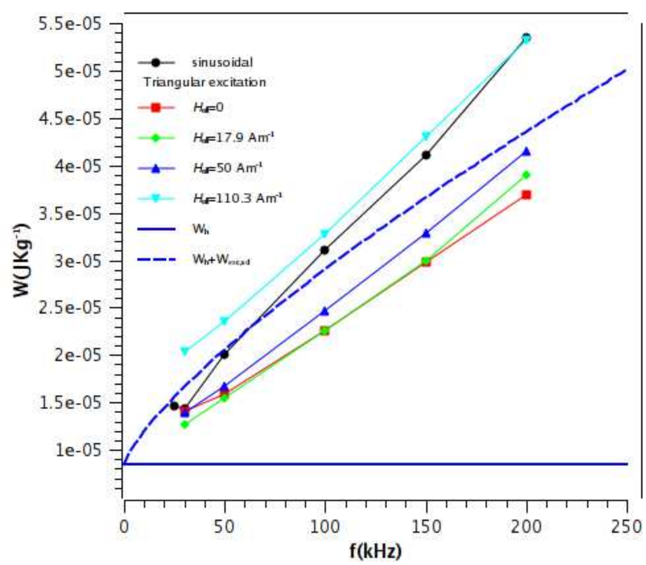

Fig. 2. Total losses measured under sinusoidal excitation (full circular black points), triangular unbiased (full red square points), triangular biased with offset field $Hoff = 17.9$ Am^{-1} (full diamond green point), 50 Am^{-1} (upward full triangle), 110.3 Am^{-1} (downward full triangle). The dashed line represents the sum of the hysteresis losses W_h and the spin dumping excess losses $W_{exc,sd}$ calculated using expression (5) with $n = 0.3$, $\alpha_{LL} = 0.06$ and $k_{irr} = 0.18$. The full line represents the hysteresis losses extrapolated from the measurements

Fig. 2 shows the total losses measured under sinusoidal excitation (black full circles) and under triangular unbiased (empty circles) and biased under the three values of H_{off}. The positions on the BH plane where measurements have been performed are represented by the full circular red points in Fig. 1. As expected triangular excitation reduces total losses of about 25%. Also biased triangular excitation generates losses lower

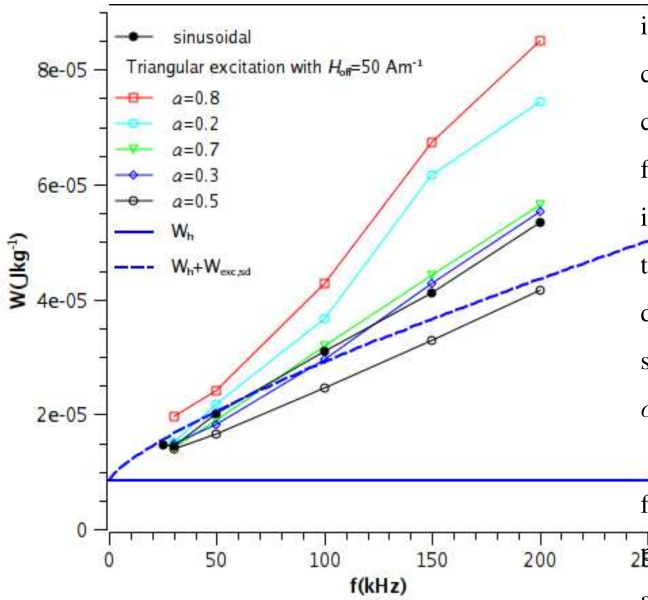

Fig. 3. Total losses measured under sinusoidal excitation (full circular black points), triangular biased ($H_{off} = 50Am^{-1}$), with different degrees of asymmetry. The lines represents the same curves plotted in Fig. 2

than the sinusoidal one but for the case of $H_{off} = 110.3$ Am^{-1} where the permeability of the material is reduced and quite elevated peak field are necessary to attain the $100mT$ peak to peak induction. It is worth noting that the $H_{off} = 50$ Am^{-1} case represents a typical working point of many power electronic devices (i.e. with the induction minimum at $B = 0$ and the maximum at $B_{max} = 2B_p$ where B_p is the peak induction). The measurements show that, in this case, the presence of the offset produce a quite small increase of the total loss with respect to the unbiased triangular one. This is also due to the small peak to peak amplitude that we applied.

In Fig. 3 we show the losses measured under a fixed $H = 50$ Am^{-1} field offset with different degrees of asymmetry of the triangular excitation waveform. The duty cycle α (i.e. the ratio between the time length of the ascending and of the descending branch of the loop) is varied between 0.2 and 0.8 ($\alpha = 0.5$ is the symmetric case). A first result that is worth noting is that loss characteristic depends on the departure of the duty cycle from the $\alpha = 0.5$ symmetric case but not on the sense in which this asymmetry is applied. Doesn't matter if the steeper branch of the loop is the ascending or the descending one. Hence measured losses are about the same when $\alpha = 0.3$ and $\alpha = 0.7$ or when $\alpha = 0.2$ and $\alpha = 0.8$.

A second result that deserves some discussion, is the fact that the more distorted excitations ($\alpha = 0.8, 0.2$) produce an important increase of the total loss and a change of slope of the loss curve that becomes steeper above about $100kHz$. So, while there is a nearly negligible change of the total loss when passing from symmetric triangular excitation to an asymmetric one with $\alpha = 0.3, 0.7$, the losses increase of about 40% when $\alpha = 0.2, 0.8$ and the frequency is above $100kHz$.

IV. Discussion

Many works have been devoted to the physical explanation of dissipation in soft magnetic ferrites. In the 90's important advancements have been achieved by relating different dissipation regimes to the domain wall configuration induced by the texture of the material [9], [11] and [10]. More recently, the frequency dependence of the contribution of different processes to the total losses was discussed using a generalisation of the statistical model presented in [2].

In [10] a two regimes loss behaviour was related to the transition between a monodomain configuration, where grains are saturated and the magnetisation process is dominated by rotations, and a much more dissipative intra-granular domain wall configuration. Neutron depolarisation analysis has given its experimental foundation to this approach (see [11], [10] and references therein).

Because of the grain size of our material and the range of frequencies explored the losses we measured are expected to be mainly lead by intra-granular domain wall dissipation. In this frame, the dependence of the loss characteristic slope on the field bias and on the excitation distortion suggests a particular sensibility of intra-granular domain wall movement to field offset and to asymmetric excitations. To verify this interpretation a further study is needed based on the comparison between the present data and measurements performed, with the same method, on samples with grain size well below the monodomain limit.

We can also try to qualitatively explain our observations using the model proposed in [12] where the authors discuss the contribution of different processes to the total losses as a function of frequency. A generalisation of the statistical model of losses presented in [2] is proposed to apply loss separation approach to ferrites. It is shown that for soft ferrites in the frequency range spanned in this paper (i.e. between 10 and 200 kHz), excess losses due to eddy currents and classical losses give a nearly negligible contribution to the total loss. On the contrary, the main frequency dependent contribution to total losses is due to two distinct processes. One, that we call spin dumping excess loss $W_{exc,sd}$, is associated with domain walls motion and is due to the precession of the spin moments around a direction perpendicular to the wall plane. The spin damping associated to this motion can be described by a parameter β_{sd} related to the Landau-Lifshitz damping constant α_{LL} as: $\beta_{sd} = 2B_s\alpha_{LL}/(\mu_0\gamma\delta_w)$, where μ_0 is the magnetic constant, γ is the electron gyromagnetic ratio, B_s is the saturation polarisation, and δ_w is the domain wall thickness. The other, that we call $W_{exc,rot}$, is associated with the damping of the global precessional spin motion (i.e. rotations). In Mn-Zn ferrites this second component overcomes the first at frequencies of the order of 100 kHz.

Now, the statistical theory of losses, originally elaborated to describe the viscous response of a 180 domain wall in a metallic material, is based on a dw equation of motion where the damping associated with eddy currents is described by a single parameter β_{ec}. In [12] it was shown that the very same equation of motion is still valid when the damping process changes and that consequently we can describe spin damping excess losses by using the same model substituting β_{ec} with β_{sd}. In this case spin damping losses are given by the following expression:

$$W_{exc,sd}(B_p, f) = 4\{\beta_{sd}[W_h(B_p)\delta]^n \langle s\rangle k_{irr}(B_p/B_s)f\}^{1/(n+1)} \tag{5}$$

where $W_h(B_p)$ is the hysteresis loss, B_p is the peak polarisation, δ is the density of the material, $\langle s\rangle$ is the average size of the grains, k_{irr} is the fractional irreversible contribution to B_p obtained from the Rayleigh parameters, and $0 \leq n \leq 1$.

The measurements that we discuss here are expected to fall in the crossover region between the spin damping lead regime and the rotation lead one. We do not have enough points in the low frequency range to be able to adjust the two free parameters, n and α_{LL}, of Eq. (5) using our data. However we can use some typical value from literature on Mn-Zn ferrites (see for instance [12] and [13]) to have at least a qualitative comparison between measurements and the model.

In our case $B_p = 50$ mT, $B_s = 0.5$ T, $\langle s\rangle \simeq 20$ μm, $\delta = 5000$ Kgm^{-3}, $k_{irr} = 0.18$, $n = 0.3$ and $\alpha_{LL} = 0.06$. The sum of W_h and $W_{exc,sd}$ is plotted as a dashed line in Fig. 2 and 3. In spite of the coarse determination of the parameters α_{LL} and n the calculated loss shows a good agreement with the total loss measured with sinusoidal excitation below $f = 100$ kHz. This fact seems to confirm that above 100 kHz the contribution of global precessional damping becomes dominant. This fact might also represent a clue to understand the loss characteristic under highly distorted excitations ($\alpha = 0.2, 0.8$). As in this case the steeper branch of the loop involves very high filed rates $\dot{H}$, we can reasonably expect an increasing importance of the contribution of $W_{exc,rot}$ to the total loss originating the observed change of slope of the loss characteristic observed above $f = 100$ kHz.

Further studies, extending the range of frequencies explored and performed on samples with different average grain sizes, will be devoted to check which of the two explanations can possibly describe our observations.

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