A Study on the Use of Specific Points on the Complex Permeability Frequency Curves of Ferrites for Presentation of Magnetic Loss

J. Jankovskis, V. Yurshevich, V. Scavinskis
Department of Electronics Equipment, Riga Technical University,
Azenes str. 12, LV-1048, Riga, Latvia; e-mail: jankovsk@rsf.rtu.lv

Introduction

Polycrystalline ferrites (PF) are the best suited magnetic materials for electronics in high frequency application areas (from low level signal ones to switched-mode power supply practice). In the design of magnetic components with PF (reactors and transformers) several common trends usually dominate: a desire to optimize their functionality (e.g., to obtain for signal inductors the maximal quality factor for given inductance and sizes), a need to increase maximum operation frequency f_{op} (in order to occupy smaller size), a.o. But fulfillment of the trends is met with serious problems: there are a lack of appropriate analytic presentations of magnetic loss against frequency f and PF material basic specifications; in addition, the nature of magnetism places specific restrictions (e.g., on f_{op}, and several others).

Let us consider in greater detail the restriction mentioned – between two important for applications parameters, namely the static initial magnetic permeability (IMP) μ_{st} (which controls, e.g., the value of inductance) and the limiting frequency of operation $f_{op.l}$ (specified on the reach of the level of impermissible loss) – they are inversely proportional ($\mu_{st} \cdot f_{op.l} \approx const$). This clearly is demonstrated in Fig. 1 (carried out by use of the data from [1]) where typical experimental magnetic spectra (MS) – the real and the imaginary parts of complex IMP $\dot{\mu}_i(f) = \mu_i'(f) - j\mu_i''(f)$, are shown for NiZn-ferrites in a broad frequency range. Even though $f_{op.l}$ is not strictly defined here, the curves bring out clearly that rapid increase of loss tangent $\tan\delta(f) = \mu_i''(f)/\mu_i'(f)$ comes at frequencies $f \propto 1/\mu_{st}$; at the characteristic frequency f_u, at which the absorption curve $\mu_i''(f)$ peaks, $\tan\delta(f_u) \approx 1$. These high values of loss in the vicinity of peak frequencies usually calls for $f_{op} << f_u$. In the cases when MS of PF are available it is an easy matter to find f_{op} for allowed loss level. But such a procedure is not appropriate in the analytic optimization process which as a rule calls for mathematical presentation of MS or magnetic loss in a broad frequency range.

Today's MS theory may be thought of as a branch that is still in its developmental stage. A certain progress in the modeling of MS is related also with the model that accounts for grain size distribution effects (GSDE) in PF [2,3]. In this study we mainly use the results

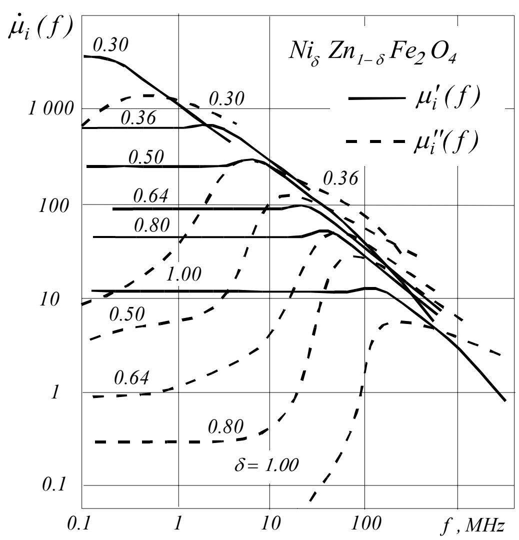

Fig. 1. Magnetic spectra of NiZn-ferrites (according to data from [1])

from mentioned GSDE model on an attempt to create an approximate but a handy analytic presentation of magnetic loss in frequency range bounded by f_u (thus the range of interest enters into the region that is known also as resonance/relaxation one [8]). The handiness means that in the presentation as little as possible number of parameters are included – just ones directly available (or simply calculable) from usual technical guides.

Specific points; relaxation loss

IMP $\dot{\mu}_i(f)$ (or initial magnetic susceptibility (IMS) $\dot{\chi}_i(f) = \dot{\mu}_i(f) - 1$) curves in general can show several types of dispersion if examined over a broad frequency range (Fig.2). In line with this IMS may have several components [4]:

$$\dot{\chi}_i(f) = \dot{\chi}_{i\,dif}(f) + \dot{\chi}_{i\,DW}(f) + \dot{\chi}_{i\,NSR}(f)\,, \qquad (1)$$

where $\dot{\chi}_{i\,dif}(f)$ is the low frequency component attributed to the diffusion aftereffect (not always presented, e.g., in Fig.1, hence not shown also in Fig.2 and not included in the subsequent analysis); $\dot{\chi}_{i\,DW}(f)$ represents the high frequency IMS related to domain wall (DW) processes that give rise to large amplitude dispersion (responsible among other things for already mentioned resonance/relaxation loss on the hole, and, specifically, for maximum absorption at some specific frequency f_u); $\dot{\chi}_{i\,NSR}(f)$ is the very high frequency IMS appearing as the small amplitude dispersion in a consequence of natural spin resonance (NSR).

It should be also noted that dispersion and absorption curves of MS are interrelated by Kramers-Kronig relations [1] (valid both for total MS as well as for its particular Eq.(1) components):

$$\chi_i'(f) = \frac{2}{\pi}\int_0^{\infty} \frac{z\chi_i''(z)}{z^2 - f^2}\,dz\,; \qquad (2,a)$$

$$\chi_i''(f) = -\frac{2}{\pi} f \int_0^{\infty} \frac{\chi_i'(z)}{z^2 - f^2}\,dz\,, \qquad (2,b)$$

where z is the variable frequency of integration.

The applications of PF most commonly are related with the call for high value of magnetic part of quality factor $Q_{mag} = 1/\tan\delta(f) = \mu_i'(f)/\mu_i''(f)$ which cause to make chose of $f_{op} << f_u$. Thus the frequency range of actual interest $0 < f_{op} < f_u$ (with some degree of underestimation) in fact is DW process region, for which as the specific points of MS can be used the parameters: μ_{st}, $\mu''_{\max}$, f_u (Fig.2). The first, μ_{st} is a principle parameter of PF (obviously as the sum of $\mu_{st\,DW} + \mu_{st\,NSR}$, but usually $\mu_{st\,DW} >> \mu_{st\,NSR}$ at least in the cases when $\mu_{st\,DW}$ have values beginning with tens). The another one, f_u can be only estimated by the order from a well-know Snoek's Law [1]: $(\mu_{st} - 1)f_{res} = (4/3)\gamma M_s$, which actually was derived for NSR process and as a such still gives a rough estimate of $f_u \approx f_{res}$ for DW processes (herein f_{res} is NSR frequency; γ is the gyromagnetic ratio, and M_s - the saturation magnetization). Analysis of experimental data from great quantity of known MS revealed [5] that it is more appropriate for DW processes in Snoek's Law instead of $(4/3)\gamma$ to use the value 4π (in the cases when $f_u\,[MHz]$, $M_s\,[G]$; let's also note here that more extended analysis results in yet another relation that more closer approximates the data but it needs extra characteristics of PF: the average, or effective grain size D_a and σ which represents the scattering of grain sizes):

$$(\mu_{st} - 1)f_u = 4\pi M_s\,; \qquad (3,a)$$

$$(\mu_{st} - 1)f_u = 4\pi M_s / D_a\,\sigma\,. \qquad (3,b)$$

In effect, Eq.(3,a) makes only rough estimate (in a like manner as the known Snoek's Limit or the rule of thumb $\mu_{st} \cdot f_g = 5000 \ldots 10\,000\ MHz$ [9] where f_g is defined as the frequency at which $\mu_i'(f_g) = \mu_i''(f_g)$). In spite of this, Eq.(3,b) claims to be more correct in principle but it can be rarely used because of lack of typical characteristics of PF microstructure. Even so the use of only estimating Eq.(3,a) is proving its worth since the parameters of PF generally have a rather loose tolerance as well [10].

If MS is approximated by simple relaxation relation (with only one relaxation time $\tau = 1/f_u$), then

$$\dot{\chi}_i(f) =$$
$$= \chi_{st}/[1 + (f/f_u)^2] - j\chi_{st}(f/f_u)/[1 + (f/f_u)^2] \qquad (4)$$

and relaxation loss $\tan\delta(f) = f/f_u$; this and the use of Eq.(3,a) allows to obtain:

$$\tan\delta(f) = (\mu_{st} - 1)f/(4\pi M_s)\,. \qquad (5)$$

In the case when Eq.(5) is used for particular material and there is known also its $\tan\delta(f_x)$ on some fixed frequency f_x, it is possible to modify the equation by use of these data: $\tan\delta(f) = (f/f_x)\tan\delta(f_x)$.

Despite the fact that practically no MS are pure relaxation type, even so Eq.(5) as an evaluating approximation is rather appropriate for high IMP (low frequency) PF loss presentation (even in the case when both f and μ_{st} are variables and M_s as an averaged is used).

Resonance/relaxation loss

The majority of actual MS nevertheless are of resonance character. Mathematical presentation of these MS is more complicated (in fact, there is no generally accepted theory). In the case of symmetrical MS (unsymmetrical ones create only negligible corrections) GSDE model [2] allows to represent the absorption curve of MS as:

$$\mu_i''(f) = \mu''_{\max}\exp[-(\log f/f_u)^2 / 2\sigma^2]\,, \qquad (6)$$

where σ is the measure of the width of log-normal distribution of domain wall resonance frequencies (closely related to analogous grain size distribution). Accordingly σ is included in the list of parameters for modeling.

The value of σ is available from absorption curve $\mu_i''(f)$ of experimental MS [2]:

$$\sigma = (\log f_u/f_i) \Big/ \sqrt{2\ln \mu''_{\max}/\mu_i''(f_i)}\,, \qquad (7)$$

where f_i is the frequency sufficiently well away from f_u. If $f_i = f_{0.5}$ is defined by half-value absorption condition, i.e., $\mu_i''(f_{0.5}) = 0.5\mu''_{\max}$, and $f_{0.5} < f_u$ (Fig.2), then $\sigma = 0.849\log f_u/f_{0.5}$.

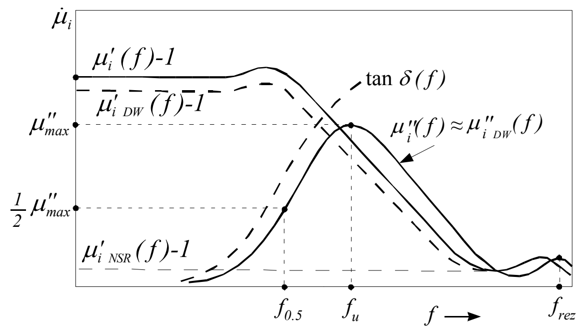

Fig.2. Typical MS and its specific points

It is particularly remarkable that variations of σ values allow to change MS character from relaxation type ($\sigma > 0.5$) to resonance one ($\sigma < 0.5$). Unfortunately, presentation of the dispersion curve of MS currently is possible only by integral type Eq.(2,a). But for all that the static value of μ_{st} (when $f = 0$) is readily available from Eq.(2,a) if in its integrand Eq.(5) is used:

$$\mu_{st} - 1 = \frac{2}{\pi}\int_0^{\infty} \frac{\mu''_{\max}}{z} \exp[-(\log z/f_u)^2 / 2\sigma^2]dz\ . \quad (8)$$

The integration performed results in the relation:

$$\mu_{st} - 1 = 3.67\sigma\, \mu''_{\max}\ . \quad (9)$$

It can be seen graphically in Fig.1 that for frequencies f only several times less than f_u the dispersion curve of MS $\mu_i'(f) \approx const = \mu_{st}$. This relation as well as Eqs. (6), (9) allow to obtain

$$\tan\delta(f) \approx (0.27/\sigma)\exp[-(\log f/f_u)^2 / 2\sigma^2]\,, \quad (10)$$

which has a reasonable accuracy in the frequency range $0 < f/f_u < (0.4\ldots0.5)$ predominantly for resonance type MS. But Eq.(6), as already noted above, is universal – appropriate both for resonance and relaxation MS. This allows to improve Eq. (10) for relaxation loss by the use of typical relaxation dependence for μ_i':

$$\mu_i'(f) - 1 = (\mu_{st} - 1)/[1 + (f/f_u)^2]\,, \quad (11)$$

which results in relation apt also for relaxation loss ($\sigma > 0.5$) in an extended frequency range:

$$\tan\delta(f) \approx (0.27/\sigma)[1 + (f/f_u)^2]\times$$
$$\times\exp[-(\log f/f_u)^2 / 2\sigma^2]\,. \quad (12)$$

Similarly as in the case of relaxation loss, the known reference parameters $\tan\delta(f_x)$ and f_x allow for

$$\tan\delta(f) \approx \tan\delta(f_x)\exp[(-1/2\sigma^2)\log(f/f_x)\times$$
$$\times\log(f\cdot f_x/f_u^2)]\,. \quad (13)$$

In practice Eqs.(10), (11) need only two specific parameters: f_u, which is possible to determine from Eq.(3,a), and σ, which has typical values $0.4\ldots0.6$ for high μ_{st} (low frequency) ferrites and $0.2\ldots0.3$ for low μ_{st} (high frequency) ones.

Results and conclusions

The potential of relations, derived for magnetic loss presentation by the use of only several specific parameters of PF, is demonstrated by correspondence degree between $\tan\delta(f)$ theoretical values gained from Eq.(10) and calculated ones from experimental data. As the experimental data there were used MS (which seemingly adequately obey Kramers-Kronig relations) taken by chance from different sources: [1] – Fig.1 in this study, [6], [7]. These MS allow to determine $\tan\delta(f)$ curves (in the following referred to as "experimental"), normalized in relation to known f_u and specified by σ (estimated directly from MS by the use of above noted procedure); the corresponding set of curves (*A*, *B*, *C*, *D*, *E*, *F*) are shown in Fig.3 and several their characteristics are listed in Table 1. It is seen from Fig.3 that in the region of higher f/f_u steepness of experimental curves and that of theoretical ones (Eq.7), as a rule, correlates well. On the other hand, in the region of smaller f/f_u significant difference appears: experimental curves tend to some limit – obviously to the residual loss (details of which at the present state of the art are still obscure; in fact there are also samples of current

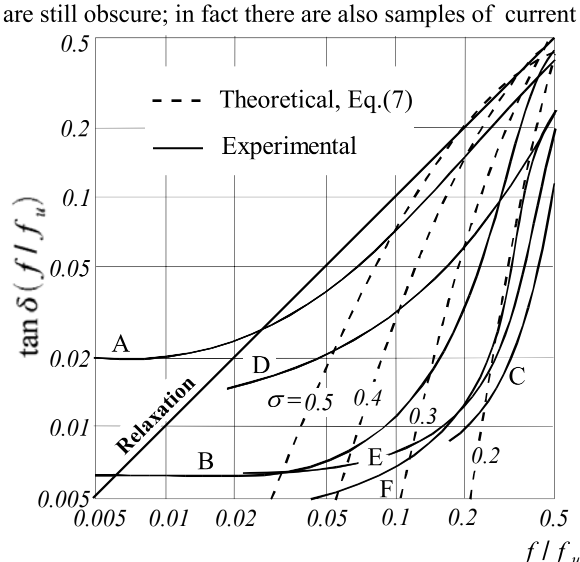

Fig.3. A correlation between theoretical (Eq.10) and experimental curves of $\tan\delta(f/f_u)$

ferrites which MS show practically no residual loss [8]). But within this approximated analysis it is possible to assume that to sufficient accuracy the residual loss is *const* and sets limit for quality factor at low frequencies.

Table 1. Data for magnetic loss curves in Fig. 3

Fig.3:	Ferrite, [source]	Experimental			Estimations	
		μ_{st} - 1	M_s [G]	f_u [MHz]	σ	f_u [MHz]
A	MnZn, 76 material [6]	10 000	320	0.17	0.42	0.39
B	MnZn, 78 material [6]	2 300	380	2.3	0.32	2.1
C	NiZn, 61 material [6]	125	190	35	0.18	20
D	NiZn, $\delta = 0.36$ [1]	630	290	5.5	0.26	5.8
E	NiZn, $\delta = 0.80$ [1]	43	280	70	0.26	82
F	NiZn, KN120 material [7]	120	340	45	0.23	36

From the practical point of view the proposed approximations for resonance/relaxation loss of PF on the whole are rather useful in the first iteration cycles in deciding on a particular ferrite material for magnetic component under design.

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J. Jankovskis, V. Jurševič, V. Ščavinskis. Polikristalinių feritų kompleksinės magnetinės skverbties nuostolių analizė įvertinant dažninių charakteristikų ypatinguosius taškus // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2005. – Nr. 5(61). – P.5–8.

Polikristaliniams feritams pradinės magnetinės skverbties stipriai išreikštos dispersijos srityje, (taip pat žinoma kaip domenų ribų rezonansinės/relaksacinės dispersijos sritis), siūlomos aproksimuojančios išraiškos dažninės priklausomybės magnetinių nuostolių kampo tangentui nustatyti. Čia naudojami tik keli pagrindiniai šių feritų parametrai: statinė magnetinė skverbtis, įsotinimo magnetiškumas, ir bendruoju atveju, parametras, susijęs su ferito grūdelių dydžio išbarstymu. Ill. 3, bibl. 10 (anglų kalba; santraukos lietuvių, anglų ir rusų k.).

J. Jankovskis, V. Yurshevich, V. Scavinskis. A Study on the Use of Specific Points on the Complex Permeability Frequency Curves of Ferrites for Presentation of Magnetic Loss // Electronics and Electrical Engineering. – Kaunas: Technologija, 2005. – No. 5(61). – P. 5–8.

For polycrystalline ferrites in the frequency range of large amplitude dispersion of complex initial magnetic permeability (known also as domain wall resonance/relaxation region) approximating relations for frequency dependence of magnetic loss tangent are proposed. The distinctive feature of approaches is the use of only several basic parameters of the ferrites: the static magnetic permeability, the saturation magnetization, and, in more general cases, the parameter that is related with grain size distribution scattering. Ill. 3, bibl. 10 (in English; summaries in Lithuanian, English and Russian).

Я. Янковский, В. Юршевич, В. Щавинский. Использование характерных точек на частотных зависимостях комплексной магнитной проницаемости поликристаллических ферритов для представления их магнитных потерь // Электроника и электротехника.– Каунас: Технология, 2005. – № 5(61). – С. 5–8.

Для поликристаллических ферритов в области сильно выраженной дисперсии начальной магнитной проницаемости (известной также как область резонансно/релаксационной дисперсии доменных границ) предлагаются аппроксимирующие выражения для частотной зависимости тангенса угла магнитных потерь. Отличительная особенность подхода заключается в том, что при этом используются всего лишь несколько основных параметров этих ферритов: статическая магнитная проницаемость, намагниченность насыщения и, в обобщающем случае, параметр, связанный с разбросом размеров зерен феррита. Ил. 3, библ. 10 (на английском языке; рефераты на литовском, английском и русском яз.).

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