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Application of Scaling Algorithms in the Analysis of Energy Losses Under Non-sinusoidal Excitations

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The paper presents the measurements of the hysteresis loops and energy losses in a nanocrystalline composite core, obtained for sinusoidal and triangular waveforms of magnetic flux density. The influence of flux density waveforms on the shapes of hysteresis loops and energy losses, as well as the corresponding coefficients in the scaling-based loss model, are investigated. The scaling-based modelling of energy losses is validated for both types of the analysed flux density waveforms.

topics: energy losses, soft magnetic composite, non-sinusoidal excitation, scaling algorithms

1. Introduction

Energy dissipation in soft magnetic materials is a complex phenomenon due to the specific structure of these materials, the eddy current flow, and the nonlinearity of magnetisation processes. The phenomenon of energy losses in magnetic materials has been the subject of analyses since the end of the 19th century, starting from the Steinmetz hysteresis model [1], through the descriptions of eddy current loss proposed by H.J. Williams, W. Shockley, C. Kittel [2] and R.H. Pry, C.P. Bean [3], to the statistical loss model developed by G. Bertotti [4–6]. The last approach assumes the presence of interactions between the so-called magnetic objects (MOs) existing in the material, as well as the validity of loss separation into three components (hysteresis, eddy current and excess). Currently, Bertotti's model is most commonly used. On the other hand, it does not provide acceptable accuracy in the low-frequency range for non-standard excitations, as well as in the case of magnetic materials with amorphous and nanocrystalline structure [7–13]. Moreover, "magnetic objects" are not precisely defined (depending on a magnetic material, they may correspond to a single domain wall or to the entire domain structure inside a single grain), which causes additional problems in the interpretation of Bertotti's model. The three-term loss separation scheme anticipated from Bertotti's model has been questioned in the textbook [14], which pointed out that "*A physical approach to core losses not only rejects the "anomalous loss" as a fiction, but it also rejects the conventional separation of the total loss into hysteresis and eddy-current components as artificial.*"

Taking into account the above-given remark, Sokalski et al. [15] proposed an alternative approach to loss analysis in soft magnetic materials, based on the Widom scaling theory. Such scaling-based approach to the loss analysis was developed and verified by Najgebauer et al. [16–20], proving its effectiveness in loss modelling for a wide class of magnetic materials. The scaling-based loss analyses were carried out only for sinusoidal waveforms of magnetic flux density, as required by international standards for magnetic measurements. However, electrical and electronic devices very often operate under distorted excitation conditions, and thus, the flux density waveform is not sinusoidal. In the present paper, the application of scaling algorithms in the analysis of energy losses under the triangular flux density waveform is validated.

2. Sample, measurements and scaling-based loss model

The sample under examination was a composite core made of nanocrystalline powder and epoxy resin, compacted under a pressure of 800 Pa and cured at a temperature of 530°C. Magnetic

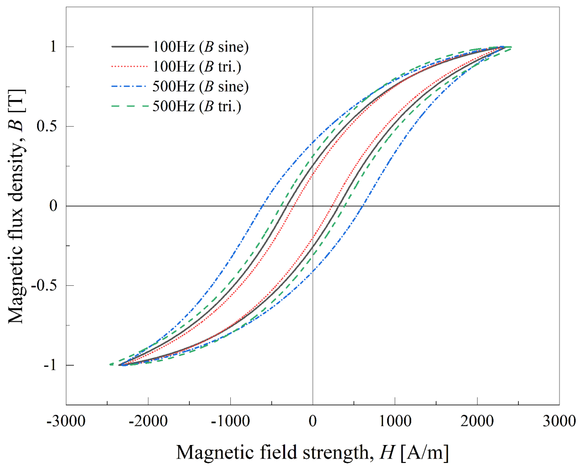

Fig. 1. Hysteresis loops measured at sinusoidal and triangular flux density waveforms.

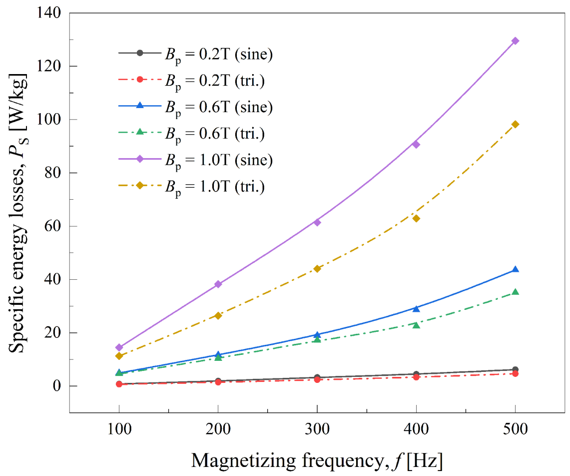

Fig. 2. Energy loss curves measured at sinusoidal and triangular flux density waveforms.

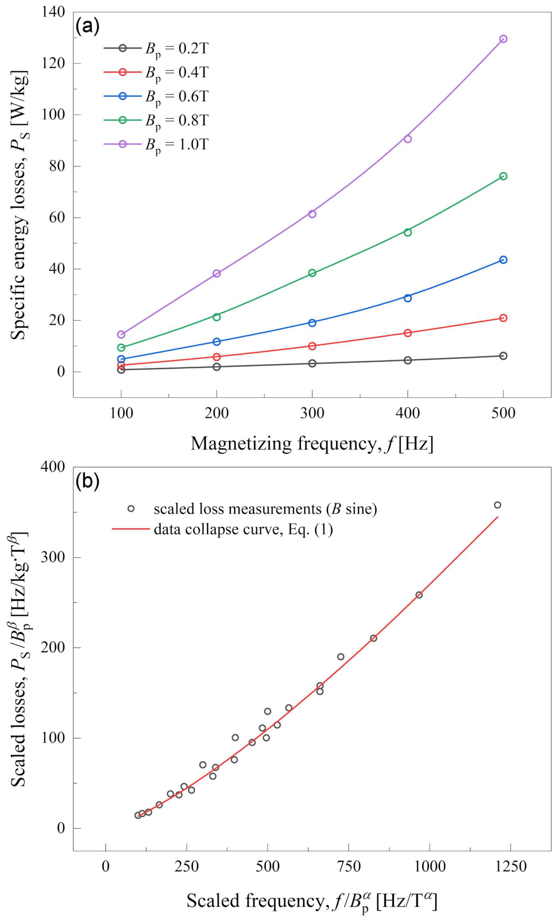

Fig. 3. Energy loss scaling for a sinusoidal flux density waveform: (a) measured loss curves, (b) data collapse curve.

properties were measured using the Brockhaus Measurements MPG-200 system with sinusoidal and triangular magnetic flux density waveforms that were shaped and controlled by digital feedback. Hysteresis loops and energy loss curves were measured at peak flux density $B_{\mathrm{p}} = 0.2$, 0.4, 0.6, 0.8, 1.0 T and magnetizing frequency $f = 100$, 200, 300, 400, 500 Hz.

In the conducted research, the fractional scaling procedure described in detail in [16] was used. Briefly explained, the scaling procedure allows one to reduce the set of loss curves to a single loss curve given in scaled coordinates and described by the following equation

$$P_{\mathrm{S}}/B_{\mathrm{p}}^{\beta} = p\left(f/B_{\mathrm{p}}^{\alpha}\right)^{x}, \qquad (1)$$

where P_{S} denotes specific energy losses, B_{p} — peak flux density, f — magnetizing frequency, p — the amplitude coefficient, α and β — scaling exponents, x — a fractional exponent. The scaling parameters α, β, p, and x are estimated using all the measurement loss data of the magnetic material tested, therefore, their values can be considered universal.

3. Results and discussion

Exemplary hysteresis loops measured at sinusoidal and triangular flux density waveforms are depicted in Fig. 1, whereas the corresponding loss curves are compared in Fig. 2. These figures depict that the specific energy losses are lower for triangular excitation, which is particularly noticeable at higher values of the magnetic flux density.

As mentioned previously, all measured loss curves were used in the scaling analysis. The set of loss curves measured for sinusoidal and triangular flux density waveforms are depicted in Fig. 3a and Fig. 4a, respectively. The loss scaling results obtained using (1) are depicted in Fig. 3b and Fig. 4b. In both cases, the set of loss curves is collapsed onto a single curve. This confirms that the scaling algorithms are effective also for non-sinusoidal flux density waveforms.

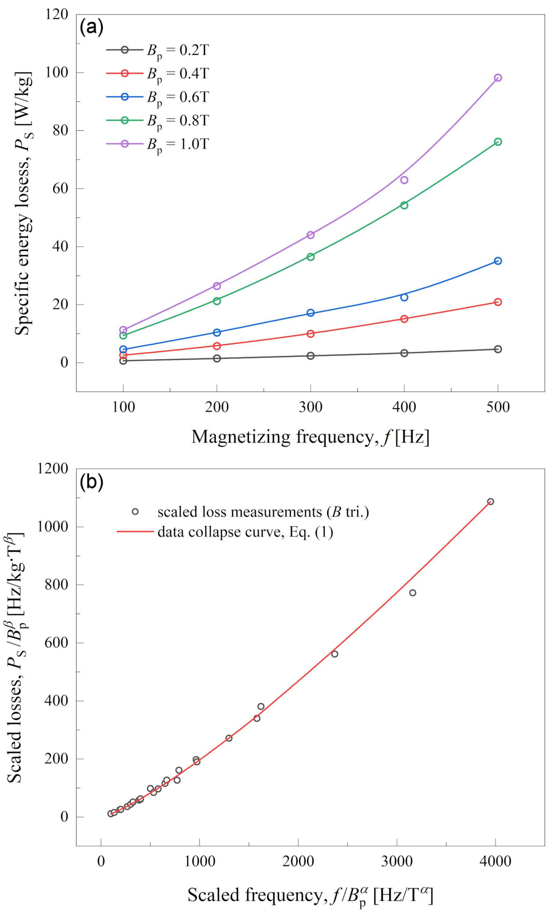

Fig. 4. Energy loss scaling for a triangular flux density waveform: (a) measured loss curves, (b) data collapse curve.

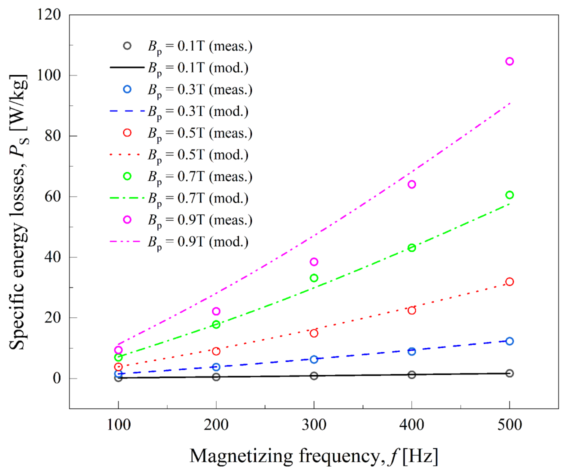

Fig. 5. Scaling-based modelling of energy losses for a composite core under a sinusoidal flux density waveform: circles — measurements, solid line — modelled losses.

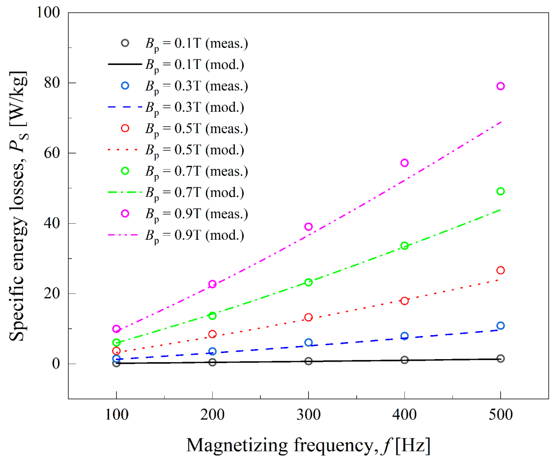

Fig. 6. Scaling-based modelling of energy losses for a composite core under a triangular flux density waveform: circles — measurements, solid line — modelled losses.

TABLE I

The scaling parameters estimated for different waveforms of magnetic flux density.

B waveform	α	β	x	p
sinusoidal	0.54	2.52	1.30	0.0350
triangular	1.28	3.39	1.24	0.0365

The estimated values of the scaling parameters are compared in Table I. It should be noted that the scaling exponents α and β have significantly different values in both analysed cases, while the values of the remaining scaling parameters are similar. This may indicate that the parameters α and β are correlated with the flux density waveform, while the parameters p and x are characteristic quantities for the type of magnetic material.

The scaling analysis can also be used to predict energy losses. After transforming (1) to a form that directly describes specific energy losses, i.e.,

$$P_S = p\, f^x\, B_p^{(\beta-\alpha x)}, \tag{2}$$

and inserting the estimated values of the scaling parameters α, β, p, and x (see Table I), one obtains formulas describing the specific energy losses for sinusoidal

$$P_{S(\sin)} = 0.035\, f^{1.30} B_p^{1.81}, \tag{3}$$

and triangular

$$P_{S(\mathrm{tri})} = 0.0365\, f^{1.24} B_p^{1.79}, \tag{4}$$

flux density waveforms. It is worth noting that despite different values of the scaling parameters α and β, the exponent at the peak flux density B_p in the formulas directly describing energy losses has almost the same value in both analysed cases. The results of scaling loss modelling based on (3) and (4) are depicted in Figs. 5 and 6, respectively. The mean modelling errors are 6.44% and 7.99%, respectively. It can therefore be concluded that the scaling-based modelling of energy losses provides satisfactory results for sinusoidal and non-standardised (triangular) flux density waveforms.

4. Conclusions

This paper presents the results of the scaling-based analysis of energy losses in a composite core, excited with sinusoidal and triangular flux density waveforms. A strong correlation between the scaling exponents α, β and the flux density waveforms was revealed, and it was also indicated that the parameters p and x can be characteristic quantities for soft magnetic materials. The scaling-based modelling of energy loss was validated for sinusoidal and triangular flux density waveforms, providing satisfactory agreement with loss measurements. The results indicated above require further research for a wide class of soft magnetic materials and other non-standard magnetic flux density waveforms.

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