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ABSTRACT

Nanocrystalline core is widely used in the design process of high-frequency transformers and inductors due to the attractive magnetic properties of nanocrystalline material. However, the flux density distribution is nonuniform in the core because the reluctance is closely related to its geometric shape. The nonuniformity of flux density distribution may cause huge calculation errors of core losses. In this paper, Finite Element Method (FEM) is used to justify taking into account nonuniform distribution of flux density during the process of core loss calculation. An improved loss separation equation considering nonuniform distribution of flux density is proposed, and the improved equation is verified through calculating and analyzing the losses of nanocrystalline cores with different wound thicknesses. Compared with the traditional loss separation equation, the accuracy is improved, and the average error of improved equation is confined in 10%.

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I. INTRODUCTION

Nanocrystalline alloy has high saturation flux density, high initial permeability, and low high-frequency loss.[1] The working frequency of iron-based nanocrystalline can reach up to 100kHz.[2] The permeability of nanocrystalline alloy has better temperature stability than that of ferrite.[3] For high-frequency transformers with the same voltage output level, nanocrystalline core is lighter (about 1/3 lighter) and cheaper than permalloy core.[4] Therefore, nanocrystalline alloy is more suitable for making high-frequency transformer cores. With the minimization and high-frequency development of electronic devices, nanocrystalline alloy will play a significant role in power electronic devices due to its excellent high-frequency soft magnetic properties.[5]

To calculate the core loss, the corresponding loss equation is essential in the electromagnetic finite element analysis. In Ref. 6, the relative permeability related to the air gap is introduced into the Steinmetz formula for the loss calculation of the magnetic core with different air gap lengths. For the loss calculation of cores with various wound thicknesses, the Steinmetz equation and the Bertotti's loss separation method both use average flux density.[7] However, due to the different reluctance inside and outside the core, the flux density is nonuniformly distributed in the core.[8] Since the height of the core does not affect the loss density, only the influence of other shape parameters on the loss is considered.[9,10] The calculation method of iron core with different dimension sizes considering the nonuniform distribution of the flux density is proposed, and proved its effectiveness through simulation.[11] Therefore, there is a lack of experimental analysis when considering the nonuniform distribution of flux density.

In this paper, the U-shape nanocrystalline cores with various wound thicknesses are measured and analyzed in a wide range of frequency under sinusoidal excitation. Through finite element analysis, it is found that when the average flux density is the same, the difference in flux density between the inner and outer sides of the nanocrystalline core becomes larger as the wound thickness increase.

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An improved loss separation equation considering the nonuniform distribution of flux density in the cores is obtained. Compared with the traditional loss separation equation proposed by Bertotti which doesn't consider the actual flux density distribution inside the core, the error of the improved loss separation equation is significantly reduced.

II. TEST SYSTEM FOR MAGNETIC PROPERTIES

The schematic diagram of experimental setup and the model parameters of the nanocrystalline core are shown in Fig. 1. The sinusoidal excitation waveform from 5kHz to 20kHz is generated by the arbitrary function generator. The power amplifier is used to amplify the signal to simulate the magnetization state at working condition. The current probe is used to acquire the excitation current of the primary winding. The voltage probe is used to acquire the open circuit voltage of the secondary winding. The digital oscilloscope is used to store voltage and current signals in real time. In theoretical design, the thickness difference between two adjacent cores is 1mm, the actual size and weight of nanocrystalline cores are provided in Table I.

The total core loss can be calculated by the voltage and current as follows:

$$P = \frac{N_1}{N_2}\int_0^T u_2(t)i_1(t)dt \tag{1}$$

TABLE I. Dimensions of nanocrystalline cores with various wound thickness.

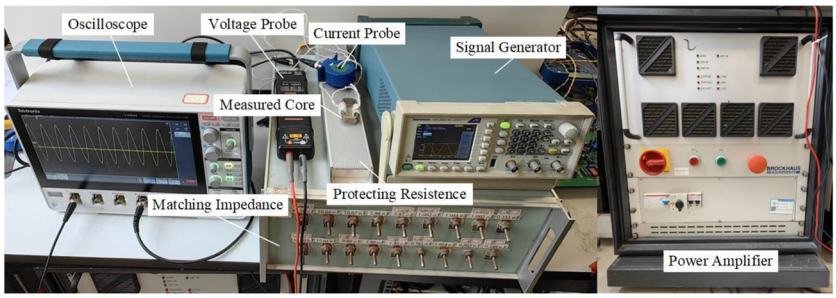
Type	a(mm)	b(mm)	d(mm)	r(mm)	h(mm)	m(g)
5033	7.4	31.1	2.15	9	10	15.4
5034	7.1	31.5	3.15	9	9.9	21.7
5035	7.8	31.9	4.3	9	9.9	28.7
5036	7.3	30.8	5.15	9	9.9	34.2
5037	7.9	31.9	6.1	9	10.2	40.4
5038	7.4	32.7	7.2	9	10.2	47

Fux density B and magnetic field strength H can be calculated by (2) and (3)

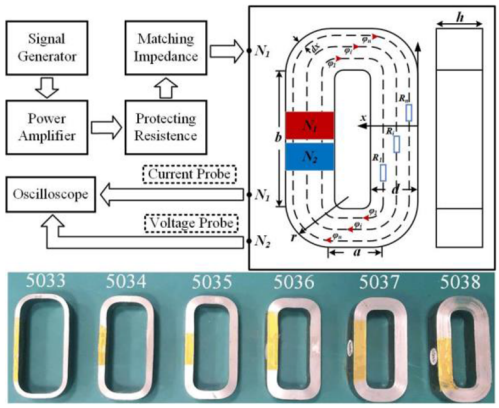
$$H(t) = \frac{N_1 i_1(t)}{l} \tag{2}$$

$$B(t) = \frac{1}{N_2 S}\int_0^t u_2(t)dt \tag{3}$$

where N_1 and N_2 are the number of turns on the primary winding and the secondary winding, respectively, i_1 is the primary winding current, l is the average magnetic circuit length of the U-shape core, u_2 is the voltage of the secondary winding, and S is the cross-sectional area.



(a)

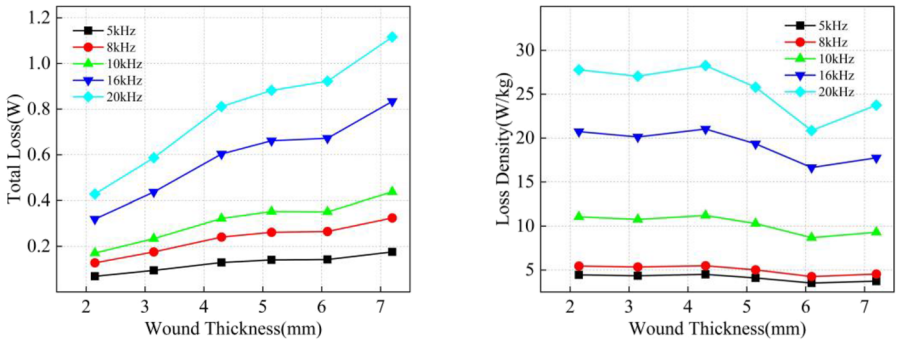


(b)

FIG. 1. Experimental circuit diagram (a) Physical experimental circuit (b) Experimental circuit diagram.

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(a) (b)

FIG. 2. The variation of loss with stack thickness, B_{avg} = 0.5T (a) Total loss (b) Loss density.

III. EXPERIMENTAL AND SIMULATION DATA ANALYSIS

Figure 2(a) shows the variation of total losses with frequency and wound thickness. B_{avg} is the average flux density flowing across the core cross section. As the frequency increases, the slope of the total loss gradually increases with increasing wound thickness. Especially when the frequency is 16kHz or 20kHz, its slope is significantly larger than that when the frequency is 10kHz or lower. This is because with the frequency increases, the dynamic loss increases rapidly, causing the slope to increase. The corresponding variation of loss densities are shown in Fig. 2(b). It can be seen from Table I that the core mass increases linearly with the wound thickness. When the wound thickness is less than 4.3mm, the total loss increases linearly, so the loss density fluctuates slightly. When the wound thickness is larger than 4.3mm and less than 6.1mm, the increase rate of total loss decreases, resulting in a decrease in loss density. When the wound thickness is larger than 6.1mm, the total loss increases faster, causing the loss density to increase.

Figure 3 shows the distribution of flux density in the core obtained by FEM simulation. In Fig. 3(a), since the excitation coil is on the left limb, which makes the flux density around the coil is slightly higher than other parts. The two figures show that under the same average flux density, as the wound thickness increases, the difference of flux density between the inside and outside of the core increases. Therefore, it is necessary to consider the nonuniform distribution of flux density in the loss calculation.

IV. MODELING OF NANOCRYSTALLINE CORE LOSS

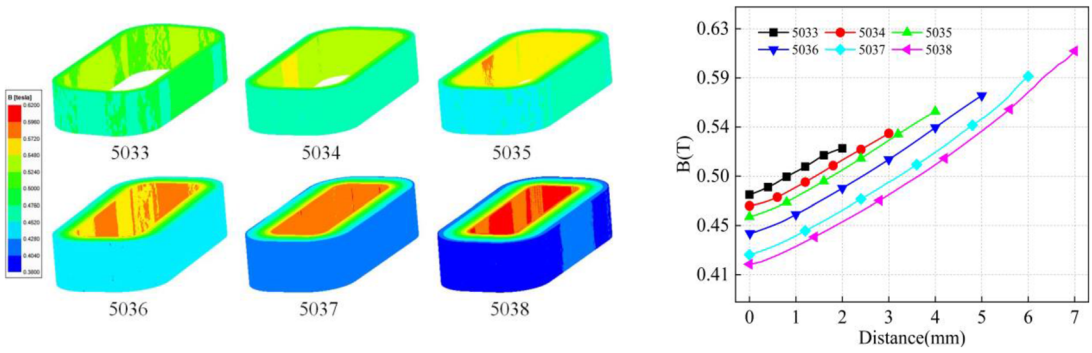
According to Ampere's loop law, the magnetomotive force F generated in the core can be expressed as[12]

$$F = R_m\varphi = N_1 i_1 = Hl \tag{4}$$

where R_m is the total reluctance of the core, φ is the magnetic flux across the core.

As shown in Fig. 1, the core is divided into several parts from outside to inside, the magnetic path length and the reluctance of each part are shown in equation (1) and (2) [13]

$$l(x) = 2(a+b) + 2\pi(r-x) \tag{5}$$



(a) (b)

FIG. 3. The simulation of nanocrystalline cores with different wound thicknesses, B_{avg} = 0.5T (a) Cloud map of flux density distribution in the core (b) Flux density distribution from outside to inside of the core.

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$$dR = \frac{l(x)}{\mu h dx} \tag{6}$$

where a, b, r and h are illustrated in Fig. 1, μ is the permeability of the nanocrystalline material. From equation (5) and (6), the total reluctance is expressed as the line integral from the outside to the inside

$$R_{\mathrm{m}} = \frac{1}{\int_l \frac{1}{dR}} = \frac{1}{\int_0^d \frac{\mu h}{2(a+b)+2\pi(r-x)} dx} \tag{7}$$

where d is the wound thickness of the core.

Combining equation (5) and (6) with Ampere's loop law, the distribution function of flux density can be obtained.

$$B(x) = \frac{\mu \varphi R_{\mathrm{m}}}{2(a+b)+2\pi(r-x)} \tag{8}$$

According to the loss separation theory, the loss density can be decomposed into hysteresis loss and dynamic loss[14]

$$p = p_{\mathrm{h}} + p_{\mathrm{d}} = c_{\mathrm{h}} B_{avg}^{\alpha} f + c_{\mathrm{d}} B_{avg}^{2} f^2 \tag{9}$$

Where c_h and c_d are the hysteresis loss coefficient and dynamic loss coefficient of the loss density, respectively. And α is the fitting coefficient.

Inserting the distribution function of flux density into equation (9), and then perform volume integration on the loss density equation to obtain the total loss.

$$P_{\mathrm{non}} = \int_V p(x) dV = \int_0^d p(x) l(x) h dx \tag{10}$$

Finally, the total hysteresis and dynamic loss considering nonuniform distribution of flux density is derived

$$P_{\mathrm{non-h}} = \frac{C_{h1} h f R_{\mathrm{m}} (\mu N_1 i_1)^{\alpha_1}}{2\pi(2-\alpha_1)} \times \left[[2(a+b+\pi r)]^{2-\alpha_1} - [2(a+b+\pi r-\pi d)]^{2-\alpha_1} \right] \tag{11}$$

$$P_{\mathrm{non-d}} = \frac{C_{\mathrm{d1}} h f^2 R_{\mathrm{m}} (\mu N_1 i_1)^2}{2\pi} \ln\left(1 + \frac{\pi d}{a+b+\pi r-\pi d}\right) \tag{12}$$

TABLE II. The coefficients of improved equation.

Coefficient	C_{h1}	α_1	C_{d1} ($\times 10^{-4}$)
value	12.04	1.876	$7.14 - 1.3e^{-\frac{(d-6.1)^2}{0.8}}$

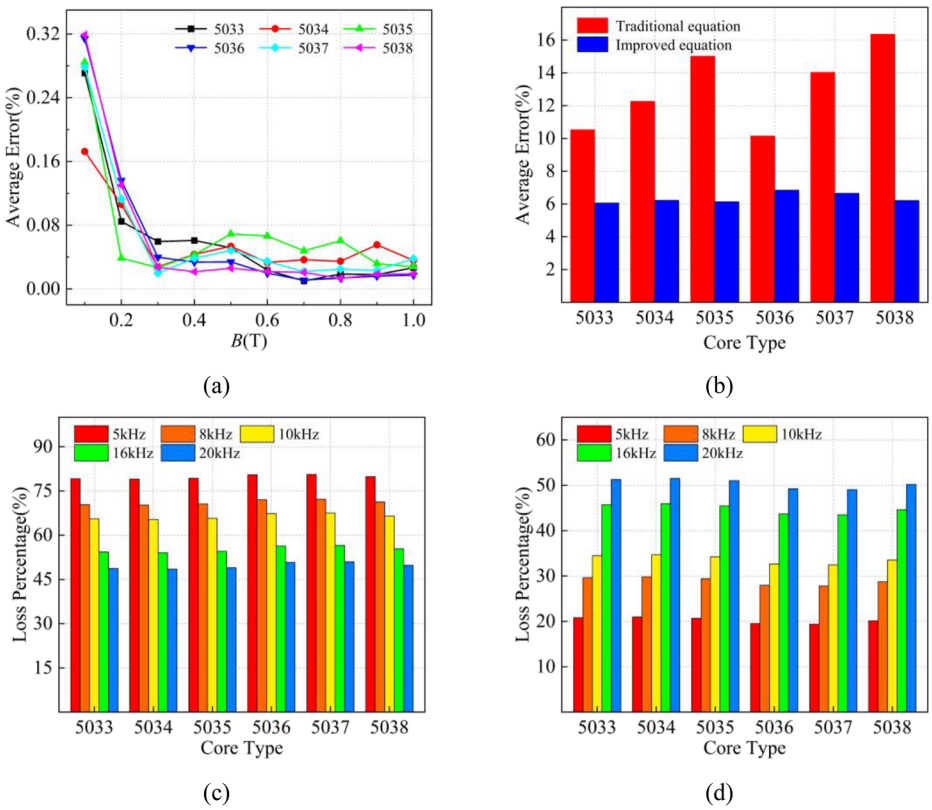


FIG. 4. Improved equation calculation data analysis (a) average calculation error under different flux densities (b) average error comparison between the improved equation and the traditional equation, f = 10kHz (c) and (d) are the hysteresis loss percentages and dynamic loss percentages respectively.

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Where C_{h1} and C_{d1} are the hysteresis loss coefficient and dynamic loss coefficient of the total loss, α_1 is the fitting coefficient.

When the distribution of flux density is assumed to be uniform, the total loss P_{uni} is the production of loss density p and the volume V.

$$P_{uni} = p \cdot V \tag{13}$$

The shape parameters of each core and its total loss measured at different frequencies and flux densities are brought into the equation (11) and (12). Three unknown coefficients can be determined by the Levenberg-Marquardt(L-M) algorithm based on nonlinear least square method. The hysteresis loss coefficient C_{h1} and fitting coefficient α_1 remain constant with the changes in wound thickness, flux density and frequency. The dynamic loss coefficient C_{d1} only changes with the wound thickness. Table II lists each coefficient of the improved model.

The average percentage error between the calculated and measured core loss values for the five frequencies in each average flux densities is shown in Fig. 4(a). Since the difference between the inner and outer sides of each core is small when the flux density is low, the calculation error of the improved equation is large. With the increase of the flux density, the superiority of the improved equation begins to emerge. The average percentage errors of the improved model are within 10% for different wound thickness cores.

Figure 4(b) depicts the average error comparison between the improved equation and the traditional equation when f = 10kHz. Since the average flux density is used in the traditional loss separation equation, the average error is large and the fluctuation is serious. The improved equation takes the nonuniform distribution of flux density into account, the average error decreases significantly and remains stable compared with the traditional equation.

Figure 4(c) and (d) depicts the variation of hysteresis loss percentage and dynamic loss percentage with different frequencies when B_{avg} = 0.5T. With the increase of excitation frequency, the proportion of hysteresis loss of each core gradually decreases, and the proportion of dynamic loss gradually increases. When the frequency is not higher than 10kHz, the hysteresis loss dominates in the total loss. When the frequency is higher than 10kHz, the proportion of dynamic loss is almost the same as that of hysteresis loss. Especially at 20kHz, the proportion of dynamic loss exceeds that of hysteresis loss.

V. CONCLUSION

The losses of U-shape cores with various wound thicknesses are measured and analyzed. The necessity of considering nonuniform distribution in loss calculation is proved through the FEM simulation. An improved loss separation equation considering nonuniform distribution of the flux density is proposed. The calculation accuracy is improved significantly compared with the traditional equation. The relative errors of the improved equation are within 10% for all frequencies. And the variation of hysteresis loss and dynamic loss with the wound thicknesses and frequencies can be obtained precisely by using this improved model. This study would be beneficial to the design of high-frequency converters and transformer cores.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Wenbin Meng: Formal analysis (equal); Writing – original draft (lead). **Changgeng Zhang**: Funding acquisition (lead); Supervision (equal); Writing – review & editing (equal). **Yongjian Li**: Funding acquisition (lead); Resources (equal). **He Sun**: Writing – review & editing (equal). **Zhenyu Wan**: Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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