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EFFECTS OF TEMPERATURE, FREQUENCY, FLUX DENSITY, AND EXCITATION WAVEFORM ON THE CORE LOSS AND DYNAMIC B-H LOOPS OF SUPERMALLOY

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ABSTRACT

The availability of experimental data which characterize the performance of soft magnetic materials for the combined conditions of temperature and frequency over a wide flux density range for different types of excitation is almost non-existent. An experimental investigation of an 80-20 Ni-Fe alloy (Supermalloy) was conducted over the temperature (T) range of 23 to 300 C, frequency (f) range of 1 to 50 kHz, and maximum flux densities (B_M) from 0.1 T up to 0.7 T for both sine and square wave voltage excitation. The investigation focused on the effects of B_M , f, T, and excitation waveform on the specific core loss (SCL) and dynamic B-H loops. The results show that the ratio (R) of sine to square wave excitation specific core loss was always greater than unity for a given f and T and identical values of B_M . The values of R ranged from 1.07 to 1.34. The classical theory of core loss separation into a hysteresis and eddy current loss component was used to theoretically determine the lower and upper bounds on R, against which the experimental R-values were compared. The experimental R-values were also used to make a comparison of the core loss of a sine and square wave voltage driven transformer.

INTRODUCTION

Almost all power electronic circuits, such as inverters and converters, require power magnetic components such as transformers and inductors. These magnetic components function as either power transfer or energy storage devices, and in some cases fulfill both needs. Increasing the operating frequency of the power magnetic components will reduce their mass and size and increasing their operating temperature will cause the cooling radiator or heatsinks to decrease in size and mass. In terrestrial ac power distribution systems, the generator's output is a sine wave voltage and thus, this same waveform is the excitation source for the transmission and distribution transformers used to transform the voltage levels between power source and load. In most power electronic circuits such as switched mode power supplies, the excitation voltage impressed on the converter's transformer is non-sinusoidal, and in DC-DC converters such as the push-pull and bridge converters, this excitation waveform is a square wave.

A very essential element in the design of magnetic components is a knowledge of the properties and characteristics

of available soft magnetic core materials. Properties such as saturation induction, Curie temperature, and thermal conductivity can generally be obtained from the product literature provided by the manufacturers and fabricators of soft magnetic materials. However, experimental characterization data such as the effects of temperature, frequency, flux density, and excitation waveform on the core loss (i.e., power loss due to hysteresis, eddy current, and other effects) and dynamic B-H loops are not always readily available. In many instances neither the manufacturer's product literature nor the technical literature provides this essential information. This almost total lack of information is particularly true for non-sinusoidal excitation core loss data. When faced with this situation, the only alternative for the magnetic's designer is to use core loss data obtained for sine wave voltage excitation, assuming that even this data exists.

Because of this lack of design data, the NASA Lewis Research Center (LeRC) initiated an experimental program to investigate the electrical and magnetic characteristics of candidate soft magnetic materials for temperatures up to 300 C and frequencies up to 50 kHz for both sine and square wave voltage excitation. Five crystalline and two amorphous soft magnetic materials were investigated previously for sine wave voltage excitation over the temperature range of 23-300 C and depending on material, frequencies from 0.1 to 50 kHz (Wieserman, et al., 1990, 1991a, 1991b, 1992). In that previous work, a Ni-Fe alloy, known in the industry as Supermalloy, was found in most instances to have the lowest core loss relative to the other materials investigated. In this paper the effects of temperature (T), frequency (f), and maximum flux density (B_M), on the core loss and dynamic B-H loops for a 0.001-inch thick tape Supermalloy toroid are investigated for both sine and square wave voltage excitation over the temperature range of 23-300 C, frequency range of 1-50 kHz, and maximum flux density range of 0.1 to 0.7 T. A comparison of results for sine and square wave voltage excitation is also given for like conditions of B_M , f, and T.

The differences in core loss and B-H loop behavior resulting from either a sine or square wave voltage excitation were previously investigated by C. H. Chen (1978) and by T. Sato and Y. Sakaki (1988). Chen investigated several materials and depending on material and flux density, the test frequencies

ranged between 10 and 100 kHz. Chen found for like conditions of B_M and f that the core loss was larger for sine than for square wave voltage excitation. Sato and Sakaki tested materials similar to those investigated by Chen but extended the test frequency to 1 MHz. Their results were similar to those reported by Chen. In both of these papers there is no indication that their tests were conducted for temperatures beyond 50 C.

EXPERIMENT DESCRIPTION

The Supermalloy test cores were wound by Magnetics in the form of toroids from 0.001-inch thick by 0.25 inch wide tape with nominal dimensions of OD = 1.25 inches and ID = 1.0 inch. The manufacturer's literature (Magnetics, 1992) for Supermalloy gives a mass composition of 79% Ni, 17% Fe, and 4 Mo; a saturation flux density range of 0.65 to 0.82 T; and a Curie temperature of 460 C.

The experimental setup used to measure, compute, plot, and display the electrical and magnetic characteristics of the test core, and the means to obtain the specific core loss (SCL) and dynamic B-H loops from the exciting current and induced voltage waveforms, were previously described and discussed by Wieserman, et al., (1990). A key element in the measuring system is the power amplifier used for core excitation. The introduction of amplitude distortion by the amplifier will produce erroneous core loss and B-H loops. The commercial power amplifier previously used for sinusoidal voltage excitation performed satisfactorily to 50 kHz, but this amplifier's risetime limited square wave voltage excitation to frequencies below 10 kHz. To overcome this limitation and make square wave excitation possible to greater than 50 kHz, a cost-effective, low output impedance amplifier was built around the Apex, Inc. Model PA19 operational amplifier and operated in a non-inverting gain of 20 configuration. This driving amplifier could provide a voltage swing of ± 30 V, a 300 ns risetime, and a peak current up to 4A.

Room temperature data over the frequency range of 1-50 kHz was taken on three Supermalloy test cores. Because of time constraints, and also because the room temperature data were consistent for all three cores, a single representative core was chosen for all additional tests. Current and voltage waveforms for this test core were obtained for both sine and square wave voltage excitation for frequencies of 1, 5, 10, 20, and 50 kHz at 23 C and thereafter in 50 C increments from 50 to 300 C and then again at 23 C after 300 C. The maximum flux density test levels were in increments of 0.1 T to either the saturation flux density of 0.7 T (applicable at the lower frequencies) or to a flux density for which the SCL did not greatly exceed 100 W/lb.

EXPERIMENTAL RESULTS

A considerable amount of test data was taken on the Supermalloy material to characterize the combined effects of flux density, frequency, temperature, and excitation waveform on the core loss and dynamic B-H loops. Representative plots for specific core loss for sine excitation are given in Figures 1 and 2 and for square excitation in Figures 4 and 5. Figure 3 gives representative B-H loops for sine wave excitation and Figure 6 for square wave excitation.

The effects of B_M and f on the SCL at fixed temperatures of 23 C and 300 C for sine and square wave excitation are given in Figures 1 and 4, respectively. These plots show that for a given f , the SCL tends to increase nearly linearly with B_M on a log-log scale; and for a given B_M , the SCL increases with increasing f . A comparison of Figure 1 (sine excitation) with Figure 4 (square excitation) for identical temperatures shows that the SCL is larger for sine than for square wave excitation.

Figure 2 (sine excitation) and Figure 5 (square excitation) plot the SCL as a function of temperature for fixed values of B_M of 0.4 and 0.6 T with f as the parameter. The almost flat SCL versus T curves shown in these plots would indicate that the SCL for Supermalloy is not a strong function of T over the range of 23-300 C. Close inspection of the curves shows that a slight dip in SCL occurs in the neighborhood of 150 C. Although not shown in these plots, it was found that the SCL at 23 C after 300 C showed an increase of between 6 and 12% for both excitations. This increase in SCL would indicate that a slight degradation did occur in the core loss characteristics due to temperature exposures up to 300 C. Additional tests would be required to determine if subsequent runs up to 300 C would have adverse effects on SCL.

Figure 3 (sine excitation) and Figure 6 (square excitation) give a family of B-H loops for 50 kHz at 23 C and 300 C. A comparison of these plots shows that the shape of the loop is very dependent on the type of excitation. Square wave excitation tends to give loops with tails such that the peak magnetizing field is greater for square than for sine excitation for the same B_M . However, an inspection of the loops shows that the ac coercive force is less for square than for sine excitation for the same B_M . An examination of the B-H loops also reveals that some of the loops are non-symmetrical with respect to the origin, and this behavior is much more pronounced for square than for sine excitation. For both types of excitation, the loops tend to become symmetrical as B_M approaches saturation. It is readily demonstrated that the application of a dc bias across the exciting winding will cause non-symmetry in the B-H loop. To prevent dc offset effects from occurring in our measuring system, a blocking capacitor was inserted between the amplifier's output and the exciting winding. Thus, in the absence of a dc offset it is not completely clear what causes the B-H loops to behave non-symmetrically. Magnetic materials with a high remanence, i.e., square loop type materials such as Supermalloy, have a higher tendency to behave in a non-symmetrical manner than materials with low remanence. A plausible explanation for non-symmetrical loops with no dc bias present is that a minor loop tends to ratchet toward saturation due to a dynamic instability related to loop shape and driving source impedance.

COMPARISON OF SINE TO SQUARE SCL

A comparison of the sine to square wave experimental SCL data shows that $(SCL)_{SINE}$ is always greater than $(SCL)_{SQ}$ for comparable values of B_M , f , and T. A representative sample of the test data is given in Table 1 for 23, 150, and 300 C for $B_M = 0.4$ T over the frequency range of 1-50 kHz. Included in this table is the ratio, R, of sine to square wave SCL and the results show that R is not a constant. A possible reason as to why R is not a constant is discussed later. For the total SCL data set of 225 points, R varied from 1.07 to 1.34. The only pattern observed in the experimental data was that the R values for low B_M tended to be larger than those for high B_M . No clearly discernible patterns or trends were observed in the SCL data set for the dependence of R on either f or T.

The classical theory of core loss separates the total loss into a hysteresis and eddy current component so that R can be defined as

$$R = \frac{(SCL)_{SINE}}{(SCL)_{SQ}} = \frac{(W_c)_{SINE} + (W_h)_{SINE}}{(W_c)_{SQ} + (W_h)_{SQ}} = H + \frac{K-H}{1+r} \quad (1)$$

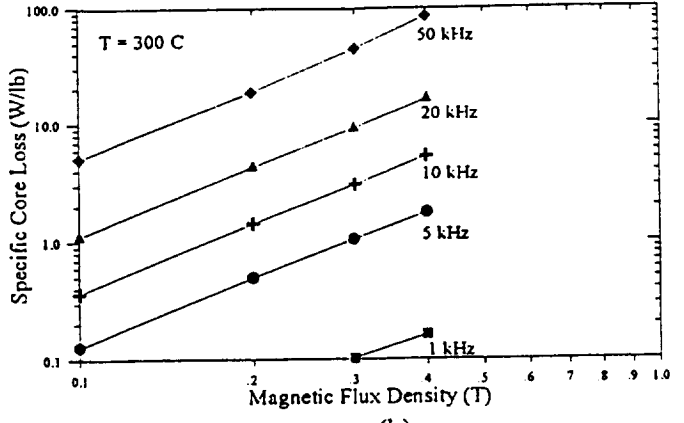
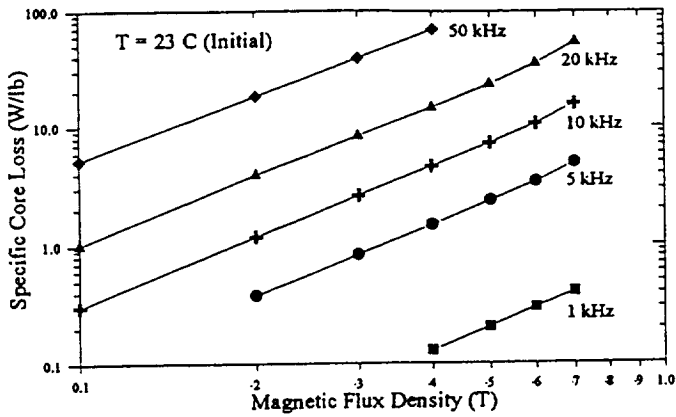


FIGURE 1. SUPERMALLOY SPECIFIC CORE LOSS FOR SINE WAVE VOLTAGE EXCITATION VERSUS MAXIMUM FLUX DENSITY WITH FREQUENCY AS PARAMETER FOR 0.001 INCH THICK TAPE TOROID (IF20). (a) T = 23 C (INITIAL), (b) T = 300 C

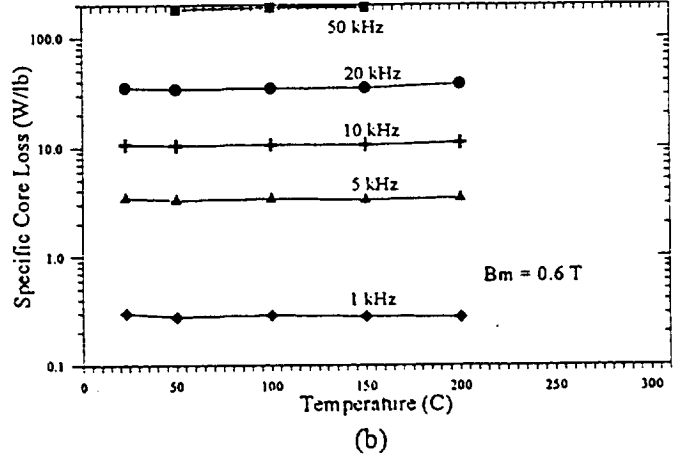
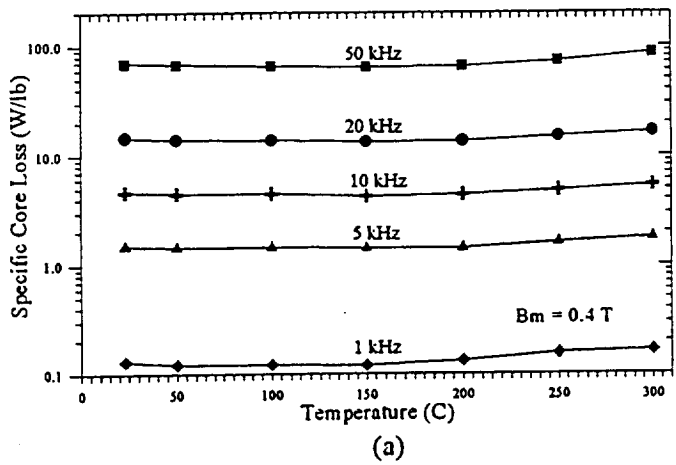


FIGURE 2. SUPERMALLOY SPECIFIC CORE LOSS FOR SINE WAVE VOLTAGE EXCITATION VERSUS TEMPERATURE WITH FREQUENCY AS PARAMETER FOR 0.001 INCH THICK TAPE TOROID (IF20). (a) $B_M = 0.4T$, (b) $B_M = 0.6T$

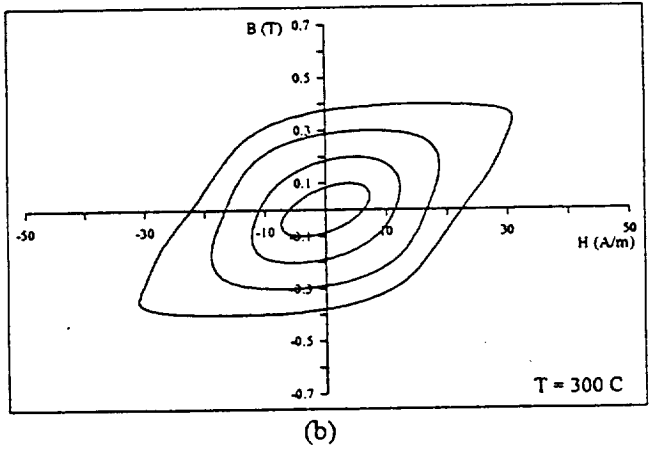
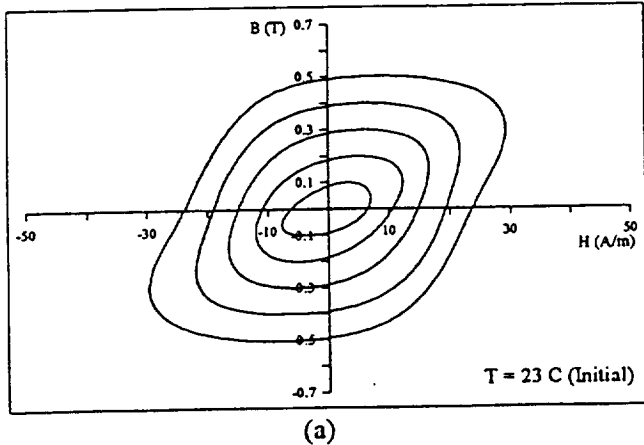


FIGURE 3. SUPERMALLOY B-H LOOPS FOR $f = 50$ kHz AND SINE WAVE VOLTAGE EXCITATION FOR 0.001 INCH THICK TAPE TOROID. (a) T = 23 C (INITIAL), (b) T = 300 C

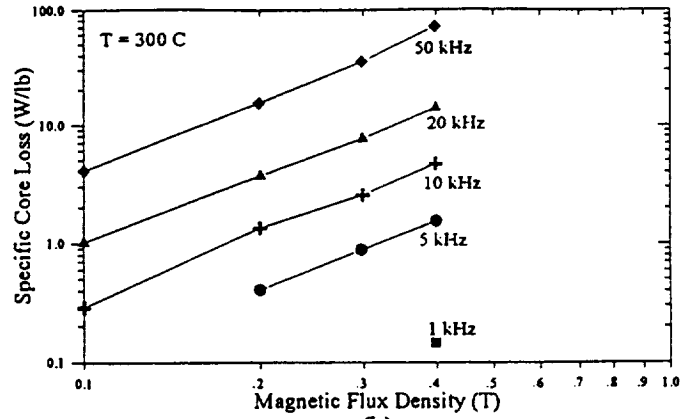
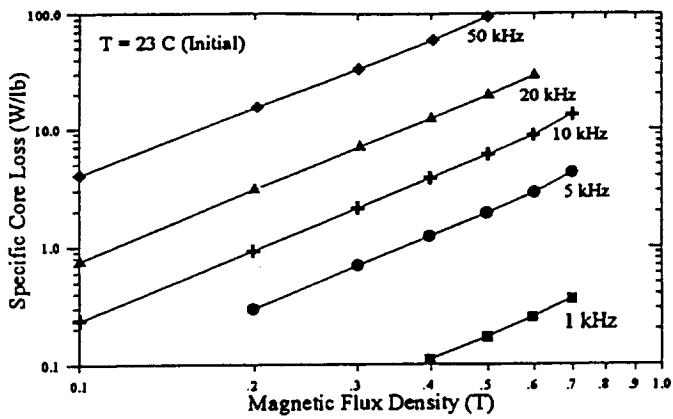


FIGURE 4. SUPERMALLOY SPECIFIC CORE LOSS FOR SQUARE WAVE VOLTAGE EXCITATION VERSUS MAXIMUM FLUX DENSITY WITH FREQUENCY AS PARAMETER FOR 0.001 INCH THICK TAPE TOROID (IF20). (a) $T = 23\text{ C (Initial)}$, (b) $T = 300\text{ C}$

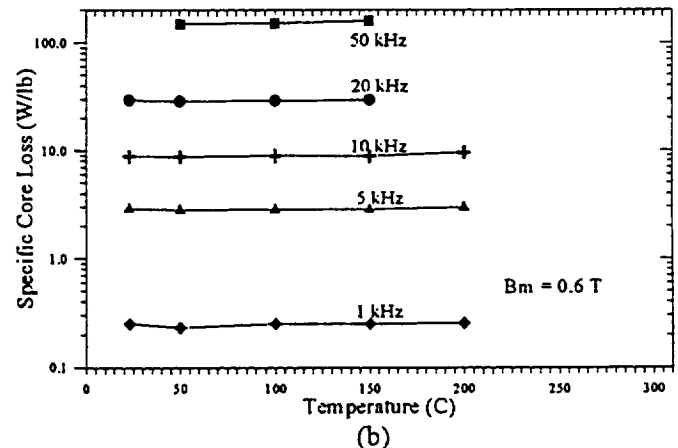
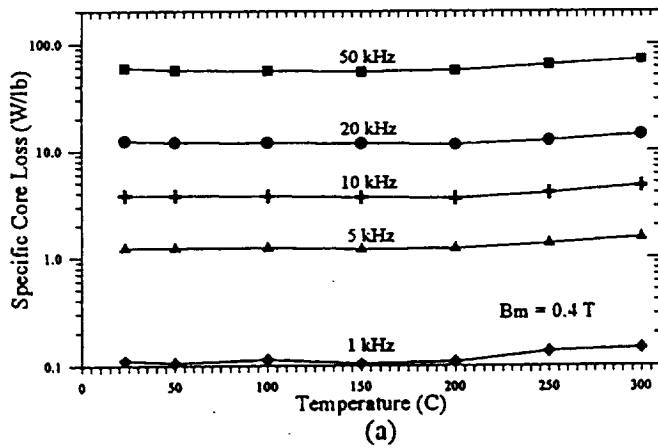


FIGURE 5. SUPERMALLOY SPECIFIC CORE LOSS FOR SQUARE WAVE VOLTAGE EXCITATION VERSUS TEMPERATURE WITH FREQUENCY AS PARAMETER FOR 0.001 INCH THICK TAPE TOROID (IF20). (a) $B_m = 0.4\text{ T}$, (b) $B_m = 0.6\text{ T}$

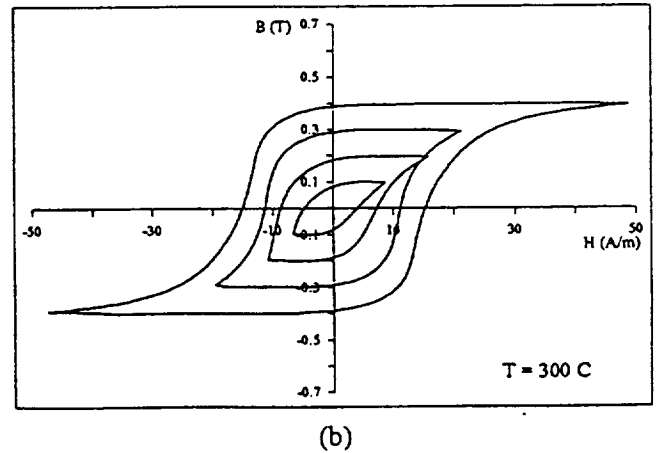
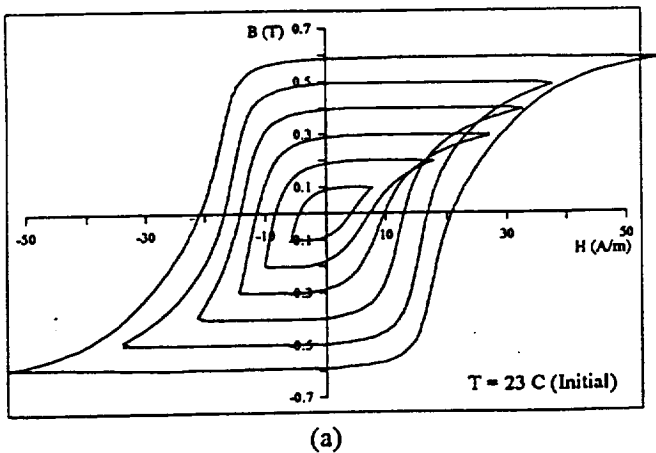


FIGURE 6. SUPERMALLOY B-H LOOPS FOR $f = 50\text{ kHz}$ AND SQUARE WAVE VOLTAGE EXCITATION FOR 0.001 INCH THICK TAPE TOROID. (a) $T = 23\text{ C (Initial)}$, (b) $T = 300\text{ C}$

TABLE 1. COMPARISON OF SPECIFIC CORE LOSS (SCL) OF SUPERMALLOY FOR SINE AND SQUARE WAVE VOLTAGE EXCITATION FOR $B_M = 0.4$ T

TEMP (C)	f (kHz)	SCL (W/lb)		(SCL) _{SINE} / (SCL) _{SQ}
		SINE	SQUARE	
23	50	69.3	59.2	1.17
	20	14.6	12.3	1.19
	10	4.6	3.8	1.22
	5	1.5	1.2	1.22
	1	0.13	0.11	1.17
150	50	64.3	54.4	1.18
	20	13.4	11.7	1.15
	10	4.2	3.7	1.16
	5	1.4	1.2	1.20
	1	0.12	0.10	1.15
300	50	86.0	71.3	1.21
	20	16.5	14.1	1.17
	10	5.4	4.7	1.15
	5	1.8	1.5	1.15
	1	0.16	0.15	1.11

where

$$K = \frac{(W_e)_{SINE}}{(W_e)_{SQ}}, \quad r = \frac{(W_h)_{SQ}}{(W_e)_{SQ}}, \quad H = \frac{(W_h)_{SINE}}{(W_h)_{SQ}}$$

and $(W_e)_{SINE}$ and $(W_e)_{SQ}$ represent the sine and square wave eddy current loss, respectively, and $(W_h)_{SINE}$ and $(W_h)_{SQ}$ represent the sine and square wave hysteresis loss, respectively.

If the eddy current loss is equivalently represented by a voltage drop V_{RMS} across a resistor R in parallel with the exciting winding, then K would be given by

$$K = \frac{(W_e)_{SINE}}{(W_e)_{SQ}} = \frac{(V_{RMS}^2)_{SINE} / R}{(V_{RMS}^2)_{SQ} / R} = (\pi^2 / 8) = 1.234 \quad (2)$$

where Faraday's Law and the condition of the same B_M , f , number of turns, and core cross-sectional area for both types of excitation gives

$$(V_{RMS})_{SINE} = (\pi / 2 \sqrt{2}) (V_{RMS})_{SQ}$$

Shenk and Young derived this same value of K given in Equation (2) by a more elaborate analysis based on the calculus of variations.

Examination of Equation (1) indicates that R is not a constant because R should be dependent on f as follows: Classical theory assumes that the hysteresis loss is independent of exciting waveform and so with this assumption $H = 1$. By Equation (2), K is a constant, making R dependent only on $r = (W_h)_{SQ} / (W_e)_{SQ}$. For a given B_M and T , it would be expected according to classical eddy current theory that as f increases, $(W_e)_{SQ}$ should increase relative to $(W_h)_{SQ}$ so that R should approach $K = \pi^2/8$. Likewise, as f decreases, $(W_e)_{SQ}$ should decrease relative to $(W_h)_{SQ}$ and R should approach 1. Thus, according to classical core loss theory, our experimental values of R should not be expected to be a constant, but rather should increase as f increases from 1 to 50 kHz. However, as seen in Table 1, and in general for the total SCL data set, the experimental values of R for a given B_M and T do not consistently increase with increasing f . The exact cause for the discrepancy between the experimental R -values and the predictions of classical theory

has not been fully determined at this time. Most likely, additional tests would be required to determine the repeatability of the experimental results given in this paper.

As previously indicated, the experimental R -range was 1.07 to 1.34. An analysis of the SCL data shows that 28% of the R values are equal to or greater than the upper limit of $R = 1.234$, and this percentage drops to 18% if all SCL data for $B_M = 0.1$ T is excluded, and to 7% if all SCL data for $B_M \leq 0.3$ T is excluded. These results are consistent with the previous observation above that the R -values for low B_M tended to be larger than those for high B_M .

TRANSFORMER APPLICATION

As previously indicated, the test data show that $(SCL)_{SINE}$ is always greater than $(SCL)_{SQ}$ for a given f and T when $(B_M)_{SINE} = (B_M)_{SQ}$. In order to put this result in the proper perspective from a transformer design viewpoint, requires that the transformer's power and voltage ratings be included in the comparison of the core loss of a sine and square wave driven transformer. For a constant load R_L , the ratio of the transformer's output power P for sine and square wave voltage excitation is

$$\frac{P_{SINE}}{P_{SQ}} = \frac{(V_{RMS}^2)_{SINE} / R_L}{(V_{RMS}^2)_{SQ} / R_L} = \frac{(\pi^2)}{8} \frac{(B_M^2)_{SINE}}{(B_M^2)_{SQ}} \quad (3)$$

The last equality in Equation (3) is obtained using Faraday's Law along with the conditions that the core size and geometry, frequency of operation, and number of turns are the same for both transformers. Imposing these conditions is equivalent to saying that the sine and square wave driven transformers are physically identical. Removal of any one of these conditions would require a much more in-depth analysis, which is beyond the scope of this paper.

When the condition of $(B_M)_{SINE} = (B_M)_{SQ}$ is applied to Equation (3), then it is seen that the sine wave voltage driven transformer has a power level of $(\pi^2/8) = 1.234$ times that of the square wave driven transformer, or equivalently, the output RMS voltage for sine excitation is 1.11 times that of the output RMS voltage for square excitation. Clearly, from a transformer design viewpoint, any attempt to compare the core loss of the two identical

transformers with different output power and voltage ratings presents numerous difficulties. A more realistic approach for core loss comparison is to have both transformers deliver the same output power and RMS voltage. By Equation (3) when $P_{\text{SINE}} = P_{\text{SQ}}$ and $(V_{\text{RMS}})_{\text{SINE}} = (V_{\text{RMS}})_{\text{SQ}}$, then the resulting condition imposed on the relationship between the sine and square wave maximum flux densities is

$$(B_M)_{\text{SINE}} = \frac{(2\sqrt{2})}{\pi} (B_M)_{\text{SQ}} = 0.9003 (B_M)_{\text{SQ}} \quad (4)$$

When the condition given in Equation (4) is applied to the SCL test data, it is found that $R = (\text{SCL})_{\text{SINE}} / (\text{SCL})_{\text{SQ}}$ varies from 0.82 to 1.07. An analysis of the R-values shows that 76% of them satisfy the condition of $R < 1$, 4% are for $R = 1$, and the remaining 20% are for $R > 1$. If all SCL data for $B_M \leq 0.3$ T are excluded, then more than 97% of the R-values are less than 1. Thus, even though all the R-values do not meet the condition of $R < 1$, there is a strong indication that the core loss is less for the sine than for the square wave voltage driven transformer when the transformers have the same output power and voltage ratings and are physically identical. When all R-values for $B_M \leq 0.3$ T are eliminated from consideration, then it can be said with almost 100% certainty that the core loss for the two physically identical transformers is less for sine than for square wave voltage excitation for the conditions of $P_{\text{SINE}} = P_{\text{SQ}}$ and $(V_{\text{RMS}})_{\text{SINE}} = (V_{\text{RMS}})_{\text{SQ}}$.

SUMMARY AND CONCLUSIONS

An experimental investigation was conducted on a Ni-Fe soft magnetic alloy, known in the trade as Supermalloy, to determine the combined effects of temperature (23-300 C), frequency (1-50 kHz), maximum flux density (0.1 - 0.7 T), and voltage excitation waveform (sine and square) on the core loss and the size and shape of the dynamic B-H loops. Over the range of parameters investigated, the experimental results show that when the maximum flux densities are the same for sine and square wave voltage excitation at a given frequency and temperature, then the specific core loss (SCL) is greater for sine than for square wave voltage excitation.

The classical theory of core loss separation into a hysteresis and eddy current component was used to determine the theoretical upper and lower bounds on the ratio, R, of sine to square wave SCL. All of the experimental R-values satisfy the lower bound but only 72% satisfy the upper bound. However, when all SCL data for $B_M \leq 0.3$ T is excluded from the experimental data set, then 93% of the R-values satisfy the theoretical upper bound of R.

A comparison of the core loss of two physically identical transformers with equal power and voltage ratings and with one driven by sine and the other by square wave voltage, shows that when SCL data for $B_M \leq 0.3$ T is excluded, then the transformer driven by sine wave voltage has the lowest core loss. It should be noted that in this comparison the maximum flux densities for sine and square wave excitation are not equal, but are related to the condition given in Equation 4.

In conclusion then, it must be emphasized that in making sine and square wave core loss comparisons all the conditions imposed in making the comparisons must be clearly stated; otherwise, the comparisons are essentially meaningless. Also, other soft magnetic materials, both crystalline and amorphous, should be experimentally investigated to determine whether the R-range for these materials follow a pattern similar to that for Supermalloy. Finally, it is possible that long term exposure at elevated temperatures could adversely affect the SCL characteristics of Supermalloy. Thus, aging tests should be

conducted at the intended operating temperature to determine if sustained operation in a high temperature environment leads to degradation of this material's electrical and magnetic characteristics.

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13. ABSTRACT (Maximum 200 words) The availability of experimental data which characterize the performance of soft magnetic materials for the combined conditions of temperature and frequency over a wide flux density range for different types of excitation is almost nonexistent. An experimental investigation of an 80-20 Ni-Fe alloy (Supermalloy) was conducted over the temperature (T) range of 23 to 300 C, frequency (f) range of 1 to 50 kHz, and maximum flux densities (B_M) from 0.1 T up to 0.7 T for both sine and square wave voltage excitation. The investigation focused on the effects of B_M , f, T, and excitation waveform on the specific core loss (SCL) and dynamic B-H loops. The results show that the ratio (R) of sine to square wave excitation specific core loss was always greater than unity for a given f and T and identical values of B_M . The values of R ranged from 1.07 to 1.34. The classical theory of core loss separation into a hysteresis and eddy current loss component was used to theoretically determine the lower and upper bounds on R, against which the experimental R-values were compared. The experimental R-values were also used to make a comparison of the core loss of a sine and square wave voltage driven transformer.				
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