GAPPED MAGNETIC CORE STRUCTURES

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ABSTRACT

Most laminated magnetic core structures have magnetic airgaps. Airgaps in magnetic structures can be used to change and control the hysteresis loop of magnetic structures. In stacks made of overlapping laminations, the main goal is to minimize the effective airgap. In butted lamination stacks, sometimes purposely gapped, the goal is to shear the hysteresis loop. This paper reviews the mathematics for calculating the effective stack permeability and remanence of these structures and how to optimize stacks for specified temperature stability of inductance, highest a.c. inductance with superposed d.c. fields, and lowest remanence or for highest permeability.

INTRODUCTION

Laminated magnetic core structures made of EE, EI or F laminations have magnetic airgaps. (Fig. 1) These airgaps influence the shape of the hysteresis loop, the permeability and the remanence of the core structure. The effect of the airgaps can be controlled by methods of stacking, for instance, overlapping the laminations 1 x 1, 2 x 2, etc. or by butt gapping the stacks of E's and I's. The optimum airgap for achieving desired hysteresis loops can be calculated by mathematical algorithms. This is especially desirable whenever the magnetic inductor or transformer carries dc and ac currents and a high ac permeability is desired.

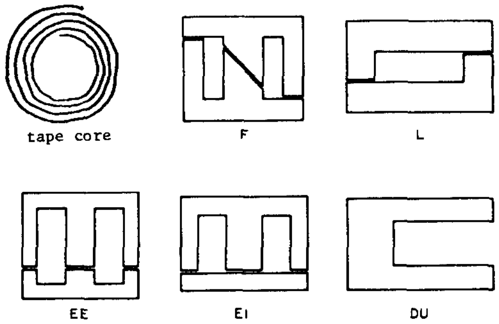


Fig. 1 Commonly Used Magnetic Core Shapes

Inductors and transformers, (Fig. 2), consist always of a wound coil with n turns in an area A_W (in^2) which is surrounded by a magnetic structure of a cross section A_C (in^2). The magnetic structure has a mean path length lm, cm and might also have a small airgap la. Such a magnetic structure can transform the following power measured in volt amperes at a frequency f.

$$VA = 4.55\ s\ A_w\ A_c\ B\ f \times 10^{-8} \text{ in which}$$

$s = A/in^2$, $A_W = in^2$, $A_C = in^2$ B = Gauss, f = frequency

The dimensions are given in inches, because many catalogs list A_W A_C values in inches.

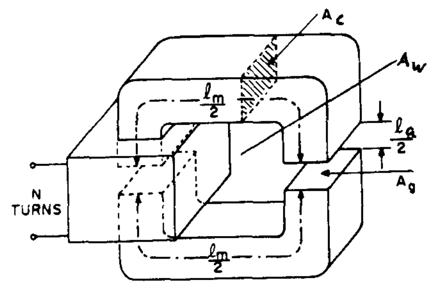


Fig. 2 Transformer Core

The magnetic core structure has an inductance L measured in Henry, when the effective permeability is μe,

$$L = \frac{.4\pi\, n^2\, A_C}{10^8\ lm}\ \mu e \qquad \mu e = \frac{B}{H}\ \frac{\text{Gauss}}{\text{Oersted}}$$

Here Ac is given in cm^2, and lm in cm.

The effective permeability μe not only is dependent on the material, but also depends strongly on the effective airgap. In Fig. 3A is shown the dc hysteresis loop. The initial permeability is measured on the demagnetized core at very low flux density. With increasing flux density, the permeability increases until it reaches a maximum μm. Up to this

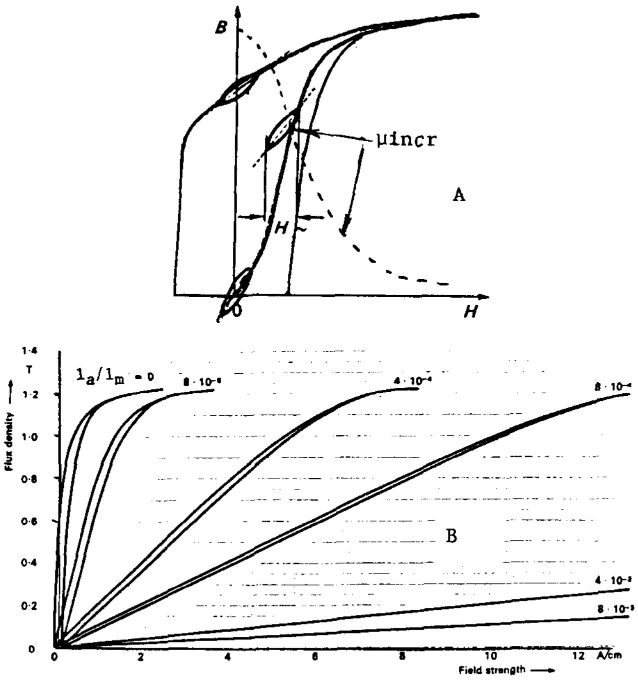


Fig. 3 A) d.c. hysteresis loop and incremental a.c. permeability

B) Sheared hysteresis loops of gapped cores

flux level, domain wall motion is the main cause for the change of magnetization. Above μmax, domain wall motion decreases and orientation of spins from the easy direction of orientation into the applied field direction occurs and the permeability μ decreases. It is also shown how the incremental permeability for small ac fields decreases with increasing dc fields. The general rule is, dc fields should not magnetize the stack above ½ Bmax, if good incremental permeability is to be maintained. In Fig. 3B, it is shown how airgaps change the hysteresis loop by shearing or pivoting it at the H_c points, the remanence decreases.

Reluctance and Permeability of Stacks

A) Butted Gaps

The intrinsic permeability of a material can be measured on rings which have no airgaps. The effective permeability of tape cores, EE, EI lamination stacks can be calculated by the summation over the reluctances of the flux paths. $R_{tot} = \Sigma\, lm/Ac\mu$

Example: Butt gapped EI laminations

$$R_{tot} = \frac{lm}{A\mu e} = \underbrace{\frac{lm}{A_c \cdot \mu m}}_{\text{core}} + \underbrace{\frac{la}{A_c \cdot 1}}_{\text{airgap}}$$

A_c = area of the core and airgap
μm = material permeability
μe = effective permeability

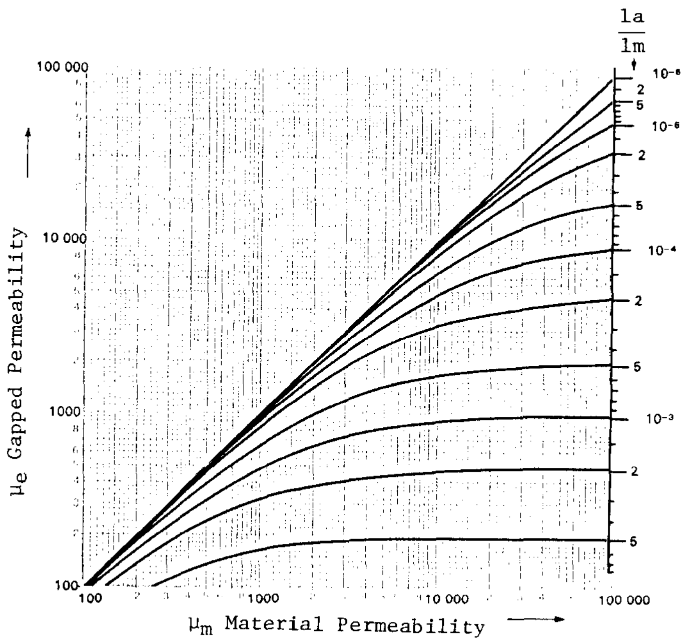


Fig. 4 Effect of airgap upon the gapped core permeability for various ratios of airgap l_a to mean path length l_m.

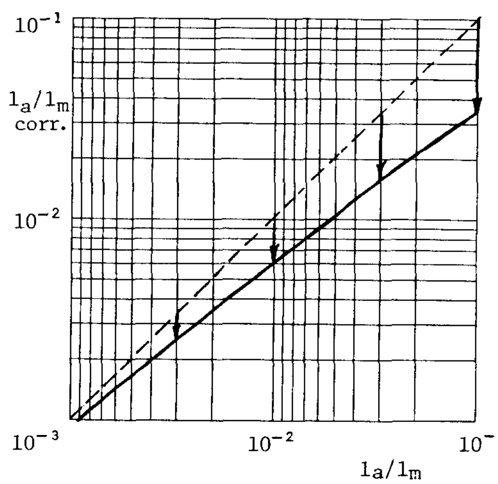
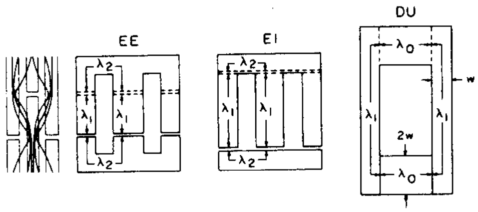


Fig. 5 Corrected effective airgap ratio l_a/l_m for core structure with large airgaps.

This equation can be rewritten as

$$\mu e = \frac{\mu m}{1 + \frac{la}{lm} \cdot \mu m},$$

μe over μm with $\frac{la}{lm}$ as parameters is presented in Fig. 4. When the airgaps are larger, the flux will spread in the airgap area over a larger area, so that the effective reluctance of the airgap is smaller. Fig. 5 gives an empirically derived graph to correct the $\frac{la}{lm}$ ratio for EE and EI laminations. The effective magnetic airgap for larger airgaps is smaller than the actual airgap.



$$\left.\begin{matrix}EE\\EI\end{matrix}\right\}\quad \mu_s = \frac{\mu_m\,\ell_m}{\ell_m + 2a\left(\coth\frac{\lambda_1}{a} + \tanh\frac{\lambda_2}{a}\right)}$$

$$DU\}\quad \mu_s = \frac{\mu\,\ell_m}{\ell_m - w + a\,\dfrac{2 - \tanh\frac{\lambda_1}{a}\tanh\frac{w}{a} - \tanh^2\frac{w}{a}}{\tanh\frac{\lambda_1}{a} + \tanh\frac{w}{a} - 2\tanh\frac{\lambda_1}{a}\tanh^2\frac{w}{a}}}$$

Fig. 6 Stack permeability μ_s for 1 x 1 overlapped EI, EE, DU, DE laminations.

t = thickness
l_a = airgap between lamination layer
a = $\sqrt{l_a\, t\, \mu_m}$ effective shearing length
$\lambda 1$ = overlap length
$\lambda 2$ = shunt length
μ_m = permeability

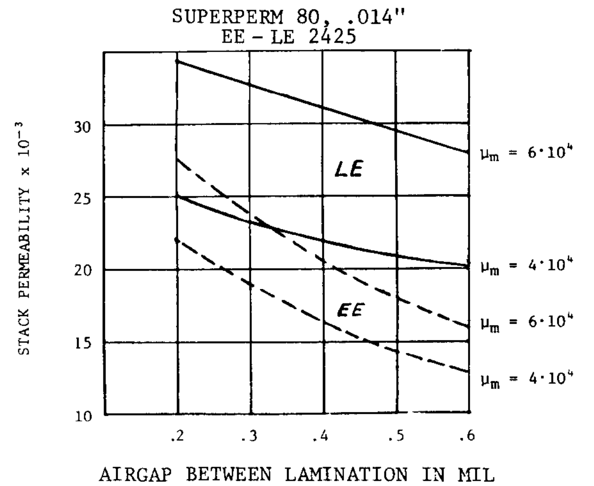


Fig. 7 Stack permeability of 2425 EE and LE laminations. Material permeability 40,000 to 60,000

B) Overlapping Gaps

The effective permeability of overlappingly stacked laminations or tape cores up to ½ Bmax can be accurately calculated following an analysis by Brenner and Pfeifer[1]. In overlapping lamination stacks the flux will circumvent the butt gap, having high reluctance, and pass from one long overlapping leg into the adjacent legs. The short E or the I is only a shunt. Fig. 6 shows the overlapping and shunt lengths for EE, EI, DU laminations. $\lambda 1$ is the overlapping length of the long laminations. $\lambda 2$ is the shunt length of the short laminations, $a = \sqrt{l_a\, t\, \mu_m}$ can be considered as effective shearing or airgap length, l_a is the airgap between the laminations, t the thickness of the laminations and μ_m the intrinsic material permeability. It is obvious from the equations that thinner and flat laminations have smaller effective airgaps and therefore, a higher permeability. Further consider that tanh varies from 0 to 1 and coth becomes large only for small values. The effective permeability μ_g can therefore be increased by minimizing "a" (make the airgap between the laminations small: flat laminations, thin insulation) and maximizing $\lambda 1$. This conclusion lead for instance to the development of long overlapping E laminations[2], on which we will report later.

In Fig. 7 is shown how the permeability of 2425 EE and LE lamination stacks can be improved by minimizing the airgap between the lamination layers. It is important for instance, to stack such laminations with the burr in one direction and not to alternate the burr direction. Long E laminations have higher stack permeability.

Multilayer Core Structures

The Pfeifer Brenner theory can be used to calculate and explain also the effective shearing and permeability of multilayer core structures. Multilayer tape wound core structures are for instance showing a sheared hysteresis loop and a slightly lower permeability than single layer wound cores as seen in Fig. 8. The permeability can be calculated by

$$\mu_e = \frac{\mu_m}{1 + \dfrac{n^2 \cdot t \cdot l_1}{l_m^2}\,\mu_m}$$

in which n is the number of layers, l_1 the airgap between these layers, t the material thickness and l_m the mean path length.

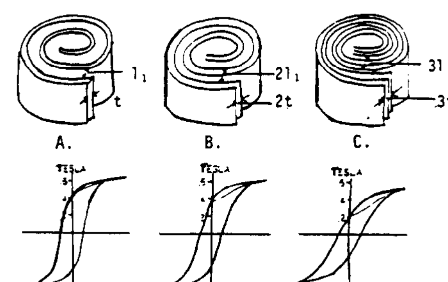


Fig. 8 DC hysteresis loops of Supermalloy tape cores: a. single layer b. two layers c. three layers

t = thickness of tape
l_1 = air gap between tapes (coating thickness)

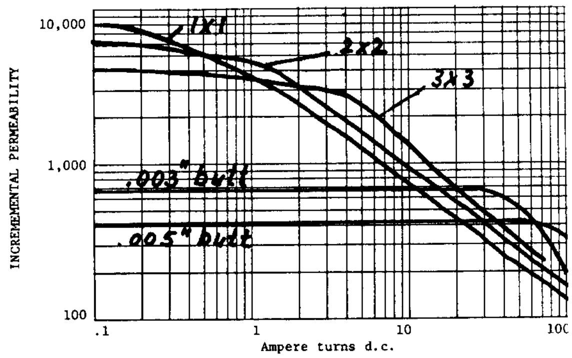


Fig. 9 Incremental a.c. permeability for .014" EE2425, 50% Ni-Fe over superposed d.c. field, stacked 1 X 1, 2 X 2, 3 X 3 and butt gapped.

For laminations, the implication is the same. By stacking 2 x 2, 3 x 3 or 4 x 4 EE laminations, the effective airgap can be increased and the loop more effectively sheared. This is important for electronic transformers carrying dc and ac currents, Fig. 9.

Airgaps for Superimposed dc and ac Currents

Various design methods have been proposed. Those of Hanna (1927)[3] and Ohri, Wilson, Owen (1976)[4] are the better known. Hanna curves are presented in Fig. 10 for .014" thick grain oriented Si-steel laminations and in Fig. 11 for .014" thick 50% NiFe-steel laminations annealed for high incremental permeability. The data were derived from the following two Hanna equations:

$$\frac{LI^2}{V} = \frac{B^2 \left(\frac{1}{\mu} + \frac{a}{l}\right)^2 \cdot 10^{-8}}{.4\pi \left(\frac{1}{\mu\Delta} + \frac{a}{l}\right)}$$

$$\frac{NI}{l} = \frac{B}{.4\pi}\left(\frac{1}{\mu} + \frac{a}{l}\right)$$

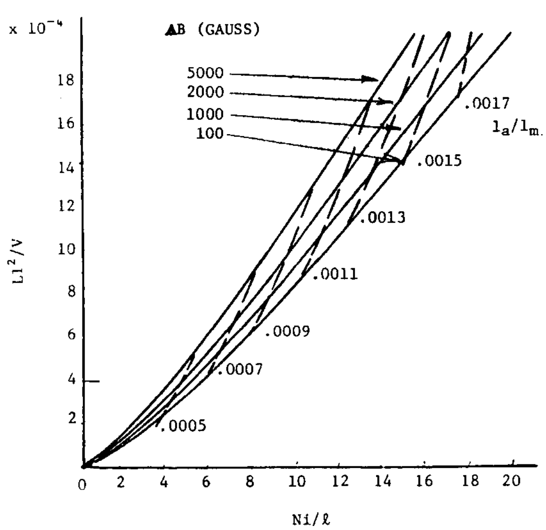


Fig. 10 Hanna design curves for .014" G.O. SiFe 60Hz
I = d.c. current, L = a.c. inductance (H)
V = core volume (cm^3), l_a/l_m = airgap ratio

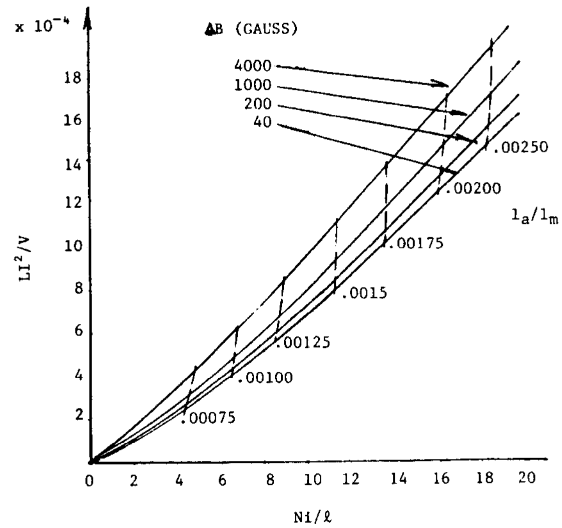


Fig. 11 Hanna design curves for .014" Superperm 49
I = d.c. current (A), L = a.c. inductance (H)
V = core volume (cm^3), l_a/l_m = airgap ratio

Ohri et. al.[4] give algorithms and flow charts for similar calculations to be done on a computer for selected lamination shapes and maximum $B_Q H_Q \leq 2/3\, B_s$ at H_Q, where H_Q is the dc field. Hanna curves consider only small ac signals, Ohri et. al. consider large ac and dc signals.

Airgaps to Stabilize the Permeability Over Temperature.

The intrinsic permeability of most magnetic materials varies with the temperature. To stabilize the variation of permeability, airgaps can be used. In Mo-Permalloy powder cores for instance, the permeability is much more stable than in solid ring cores because the insulation of the powder particles provides effective airgaps. The variation of permeability for a gapped structure from room temperature, RT, to another temperature, TC, is

$$\frac{\Delta\mu e\,(RT - TC)}{\mu e RT} \times 100\ (\%),\ \text{substituting}$$

$$\mu e = \frac{\mu_m}{1 + \frac{l_a}{l_m}\mu m} \quad \text{leads to}$$

$$\frac{\Delta\mu}{\mu}\ (\%) = \frac{\mu t\left(1 + \frac{l_a}{l_m}\mu\, RT\right)}{\mu R\left(1 + \frac{l_a}{l_m}\mu t\right)}$$

In Fig. 12 is plotted the percent variation of gapped laminations with l_a/l_m 5×10^{-4} to 10^{-2}, when the material permeability changes by 40%. For material with an intrinsic permeability, $\mu i \sim 30{,}000$, the change of such permeability can be lowered to less than 1% with an airgap of $l_a/l_m < 10^{-3}$.

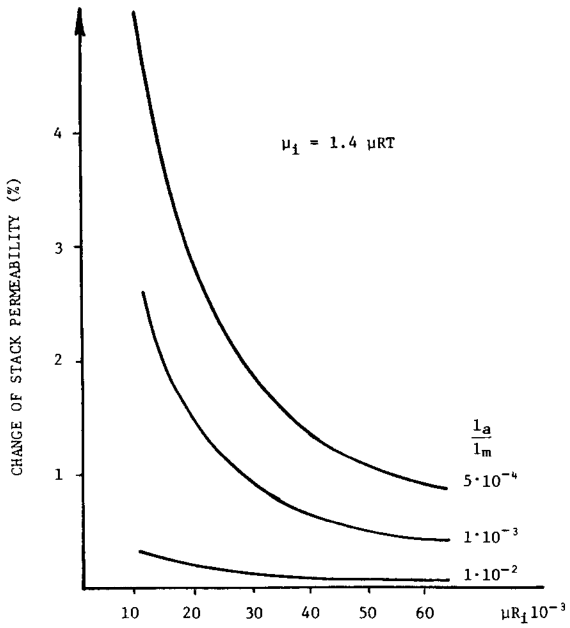


Fig. 12 Variation of permeability as fraction of material permeability μ_i/μ_R = 40%

In Fig. 13, the percent change of permeability is shown for typical 80% NiFe laminations, one made of Super "Q" material, heat treated for lowest core loss, the other made of Supertherm 80 heat treated for highest temperature stability.

Gapping for Low Remanence or High Unidirectional Magnetization.

Quite often it is desirable to lower the remanence of a magnetic circuit. Airgaps are an excellent tool to do this. In a magnetic circuit, the sum of the internal field and the magnetic path length vectors have to be zero, when all external fields are removed,

$$\oint Hds = 0 \therefore H_m \cdot l_m + B_R \cdot l_a = 0$$

$$l_a = \frac{H_m \, l_m}{B_R}$$

H_m is the demagnetizing field acting on the material. From a practical viewpoint, it is sufficient to use the coercive field of the material, H_c and the desired remanence B_R in Gauss to calculate the airgap l_a required. For unipolar pulsed cut cores or EI lamination stacks, the proper gap can be calculated, Example: grain oriented SiFe material, $H_c \sim .3$ Oe, $B_R < 1,000$ Gauss, mean path length l_m = 20 cm, l_a = .01 cm or 4 mil.

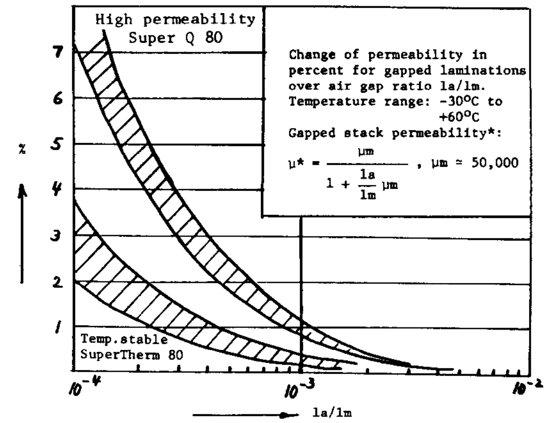


Fig. 13 Variation of the permeability 80% NiFe for gapped core structures.

Special Lamination Shapes

Optimizing for High Initial ac Permeability

The Pfeifer-Brenner theory clearly showed that the effective permeability of an EE stack be improved if the overlapping lengths λl would be increased. EI lamination stacks have, for instance, a higher effective permeability than EE stacks. Further improvement is possible, especially for small laminations if the I's are removed and the legs of the E's are lengthened. This not only yields a better effective permeability, but eliminates the difficulty to handle the small I's. There is only one lamination per layer. The larger airgaps between the ends of the E's are meaningless as long as the stack operates below $\frac{1}{2}B_S$. This lead to the development of long E laminations. The improvement in permeability for the most common small shapes is shown in table Fig. 14. DE-laminations, like DU-laminations have a double width base and these form an even larger overlapping area.

Airgap between lamination layers smaller than .0004" for .014" and .006" material thickness						
	SUPERMU 60					
SIZE	EE		LE		DE	
	006	014	006	014	006	014
30-31	9300	4800	26400	17600	35000	23800
32-33	16300	9800	28800	20000	40300	29800
28-29	20800	12600	29900	20000	39800	29000
22	18000	9900	29000	21600	—	—
24-25	29400	20000	36600	31000	50200	43200

Fig. 14 Stack permeability of EE, EL, DE laminations.

CONCLUSION

The effect of airgaps in magnetic lamination stacks can be minimized by providing large overlapping areas when high initial permeability is desirable. On the other hand, airgaps can effectively be used to improve temperature stability, ac permeability with superposed dc currents, unidirectional pulse permeability, and to lower the remanence. The algorithms presented are useful for the design of optimum stack configurations.

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