EFFECT OF INTERFACE RESISTANCE BETWEEN MAGNET LAMINATIONS

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Measurements by G. Cottingham show the interlamination resistance between glued laminations to be 1.2 $\mu\Omega$ in one block and 0.45 $\mu\Omega$ in another. The lamination cross-section has an area of 0.312 m^2. The second block thus has a surface resistance of $\rho_s = (0.45)(.312) = 0.142\ \mu\Omega\text{-m}^2$.

A proper analysis of eddy currents would be a two-dimensional solution to the diffusion equation with anisotropic resistivity. A simple treatment of the surface current density in glued blocks in the case of steady-state, constant $\dot{B}$ is possible. Figure 1 shows a block of n laminations of thickness t and width w; the height (perpendicular to the paper) is h. Consider a thin layer on the surface of thickness αt, where α is much less than one. The changing magnetic field $\dot{B}$ is in the direction of h and causes a current in αt which is assumed to cross through the lamination thickness in a path of thickness αw, i.e., the current flows in the same fraction of w as it does of t. The fraction of this current which returns inside a single lamination instead of passing through the interface resistance to the next lamination is determined by the relative resistance of the two paths and by the respective loop emfs. The complete set of 2n-1 loop equations (which reduces to n+1 because of symmetry) is solved numerically and the case of two laminations is solved analytically.

The equivalent circuit for two laminations has three loops, as shown in Figure 2. Here, $r_1 = \rho t/\alpha wh$, $r_2 = \rho t/\alpha wh$ and $r_3 = \rho_s/\alpha wh$. The three loop equations are:

1) $$2I_1(r_1+r_2)-I_2r_1 = \dot{B}tw(1-\alpha)^2$$

2) $$-I_1r_1+2(r_1+r_3)I_2-r_1I_3 = \dot{B}tw\alpha^2$$

3) $$-r_1I_2+2(r_1+r_2)I_3 = \dot{B}tw(1-\alpha)^2$$

From 1) and 3), $I_1 = I_3$; the same statement could be made immediately by recourse to symmetry. The solution is, for $\alpha \ll 1$,

$$I_2/I_1 = \rho w^2/(\rho w^2+\rho_s t) = 1/(1+\beta)$$

where $\beta = \rho_s t/(\rho w^2)$. For $\rho_s = 0.142\ \mu\Omega\text{-m}^2$, $\rho = 0.14\ \mu\Omega\text{-m}$, t = 1.5mm and w = 0.133 m (the return leg thickness), $\beta = .086$, i.e., 92.1% of the current crosses the resistive barrier. The pole face is wider: 10 inch. For this value of w, $\beta = .024$ or 97.7% crosses.

For the n - lamination case, after letting α approach zero, a typical lamination equation is

$$-r_1I_{j-1} + 2(r_1+r_2)I_j - r_1I_{j+1} = \epsilon$$

and a typical interface equation is

$$-r_1I_{j-1} + 2(r_1+r_3)I_j - r_1I_{j+1} = 0$$

Here, in effect r_1, r_2 and r_3 are as given above with $\alpha h = 1$ and $\epsilon = \dot{B}tw$; I is in amp/meter. By symmetry, $I_m = I_{n-m+1}$ so there are n+1 equations of which the first is $2(r_1+r_2)I_1 - r_1 I_2 = \epsilon$ and the last is either

$$-2r_1 I_{(n-1)/2} + 2(r_1+r_2)I_{(n+1)/2} = \epsilon \quad \text{(n odd) or}$$

$$-2r_1 I_{n/2} + 2(r_1+r_3)I_{n/2+1} = 0 \quad \text{(n even)}$$

This set of tridiagonal equations is efficiently solved using the Thomas algorithm.

The calculations show that in the backleg, with w = 5 $^1/_4$ inch, and t = 1.5 mm (59 mil thick laminations), the surface resistance must be about $2\text{x}10^{-5}$ Ωm^2, or a resistance between laminations of 64 $\mu\Omega$ in order to reduce the interface current to 1/10 the intra-lamination current. In the pole laminations, with w = 10 inch, and if t is 30 mil, the surface resistance must be about $1\text{x}10^{-4}$ Ωm^2, or an inter-lamination resistance of 0.45 mΩ, 1000 times the measured value. The computer printout in this latter case is given by Figure 3. In Fig 3, the odd-numbered columns are the lamination loop current density and the even-numbered columns are the interface loop current density. The final number, column 6, row 4 is the interface current density between the 12th and the 13th of the 24 laminations.

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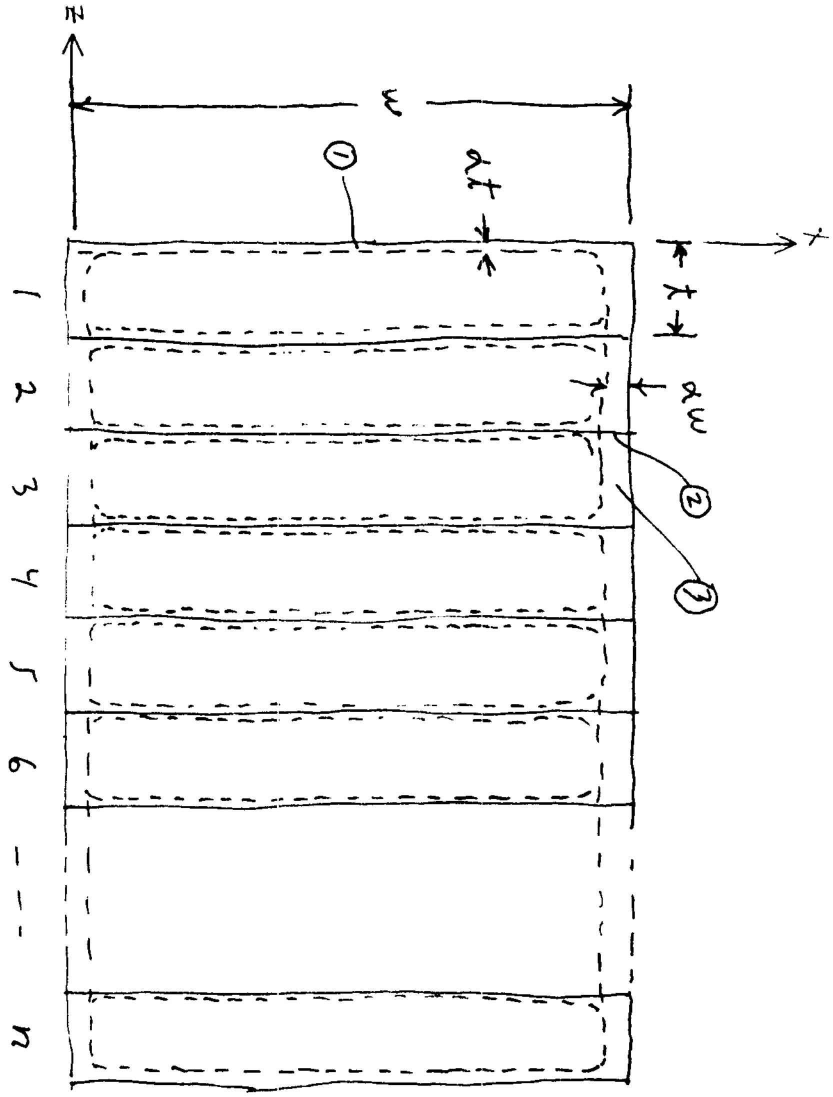

Fig. 1

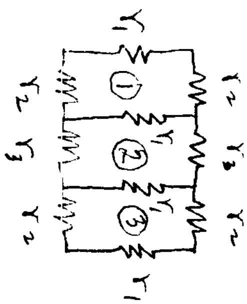

Fig. 2

10" pole

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GIVE N,RHO,RHOS,W,T,BDOT
24,1 4E-7,1.E-5,.254,7.6E-4,5.
 1.53E+01   9.89E+00   2.12E+01   1.18E+01   2.23E+01   1.22E+01
 2.25E+01   1.22E+01   2.26E+01   1.23E+01   2.26E+01   1.23E+01
 2.26E+01   1.23E+01   2.26E+01   1.23E+01   2.26E+01   1.23E+01
 2.26E+01   1.23E+01   2.26E+01   1.23E+01   2.26E+01   1.23E+01
G$WE1HERH0,RHOS,W,T,BDOT
 1.09E+01   1.19E+00   1.15E+01   1.22E+00   1.15E+01   1.23E+00
 1.15E+01   1.23E+00   1.15E+01   1.23E+00   1.15E+01   1.23E+00
 1.15E+01   1.23E+00   1.15E+01   1.23E+00   1.15E+01   1.23E+00
 1.15E+01   1.23E+00   1.15E+01   1.23E+00   1.15E+01   1.23E+00
GIVE N,RHO,RHOS,W,T,BDOT
24,,1.E-4/
 1.09E+01   1.19E+00   1.15E+01   1.22E+00   1.15E+01   1.23E+00
 1.15E+01   1.23E+00   1.15E+01   1.23E+00   1.15E+01   1.23E+00
 1.15E+01   1.23E+00   1.15E+01   1.23E+00   1.15E+01   1.23E+00
 1.15E+01   1.23E+00   1.15E+01   1.23E+00   1.15E+01   1.23E+00
GIVE N,RHO,RHOS,W,T,BDOT
0/
FORTRAN STOP
$
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Figure 3