IS 7616 (1974): Guide for calculation of the effective parameters of magnetic piece parts [LITD 5: Semiconductor and Other Electronic Components and Devices]

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GUIDE FOR CALCULATION OF THE EFFECTIVE PARAMETERS OF MAGNETIC PIECE PARTS

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Addendum

(*Page* 6, *clause* **4.1.2**) — Add the following note after the existing clause:

'NOTE — When the winding is uniformly distributed over a toroid, it may be expected that at all points inside the toroid the flux lines will be parallel to its surfaces. No leakage flux will, therefore, leave or enter the toroid. This justifies the use of a theoretically more correct, derivation of the effective parameters as given above, which does not make use of the assumption of **3.2** (b), that the flux is uniformly distributed over the cross section.'

(LTDC 13)

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GUIDE FOR CALCULATION OF THE EFFECTIVE PARAMETERS OF MAGNETIC PIECE PARTS

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Indian Standard

GUIDE FOR CALCULATION OF THE EFFECTIVE PARAMETERS OF MAGNETIC PIECE PARTS

0. FOREWORD

0.1 This Indian Standard was adopted by the Indian Standards Institution on 28 December 1974, after the draft finalized by the Magnetic Components and Ferrite Materials Sectional Committee had been approved by the Electrotechnical Division Council.

0.2 This standard has been prepared to lay down uniform rules for the calculation of the effective parameters of closed circuits of ferromagnetic material intended to increase the permeability of that circuit.

0.3 While preparing this standard, assistance has been derived from IEC Pub 205 (1966) 'Calculation of the effective paramcters of magnetic piece parts', and IEC Pub 205A (1968) 'Supplement to Publication 205 (1966)' issued by the International Electrotechnical Commission.

0.4 For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the result of a test, shall be rounded off in accordance with IS : 2-1960*. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

1. SCOPE

1.1 This standard lays down uniform rules for the calculation of the effective parameters of closed circuits of ferromagnetic material intended to increase the permeability of that circuit.

2. LETTER SYMBOLS

2.1 In this standard, the following letter symbols have been used in the formulae for the various types of cores :

A = Cross-sectional area at a given part of the core (mm^2)
A_e = Effective cross-sectional area (mm^2)
B = Momentary value of flux density (T)
B_e = Momentary value of effective flux density (T)
$\hat{B}_e$ = Peak value of effective induction (T)

*Rules for rounding off numerical values (*revised*).

C_1	= Core constant (mm^{-1})
C_2	= Core constant (mm^{-3})
$\tan \delta_h$	= Tangent of the loss angle due to hysteresis loss
f	= Frequency (Hz)
H	= Momentary value of field strength (A/m)
$\hat{H}$	= Peak value of field strength (A/m)
H_e	= Momentary value of effective field strength (A/m)
$\hat{H}_e$	= Peak value of effective field strength (A/m)
η_B	= Hysteresis material constant (T^{-1})
i	= Momentary value of current (A)
$\hat{i}$	= Peak value of current (A)
l	= Length of a part of the core with constant cross-sectional area (mm)
l_e	= Effective magnetic length of the core (mm)
L	= Self-inductance (H)
μ_0	= Absolute permeability of vacuum, $4\pi \times 10^{-7}$ H/m
μ_a	= Relative amplitude permeability [*see* IS : 1885 (Part XII)-1966*]
μ_e	= Effective permeability [*see* IS : 1885 (Part XII)-1966*]
μ_i	= Relative initial permeability [*see* IS : 1885 (Part XII)-1966*]
μ_r	= Relative permeability, general
N	= Number of turns
v	= Rayleigh hysteresis coefficient (m/A)
ω	= Angular frequency $= 2\pi f$ (rad/s)
P_h	= Hysteresis loss (W)
U_{av}	= Average value per half period of voltage (V)
$\hat{u}$	= Peak value of voltage (V)
V	= Volume (mm^3)
V_e	= Effective volume (mm^3)
Φ	= Momentary value of magnetic flux (Wb)
$\hat{\Phi}$	= Peak value of magnetic flux (Wb)

3. SOME NOTES ON THE USE OF EFFECTIVE PARAMETERS

3.1 When calculating the magnetic properties of cores on the basis of those of the material, use may be made of so-called effective parameters. For this method of calculation, the core is substituted by an ideal toroid such that a coil wound on that toroid would give exactly the same electrical performance as a coil with the same number of turns placed on the original core.

The magnetic properties and dimensional parameters of that substitute toroid are called the *effective parameters*. These are indicated by the suffix 'e' added to the symbols for these properties.

These effective parameters are :

a) the magnetic field strength H_e,

---

*Electrotechnical vocabulary: Part XII Ferromagnetic oxide materials.

b) the induction B_e,
c) the effective permeability μ_e,
d) the magnetic path length l_e,
e) the cross-sectional area A_e, and
f) the core volume V_e.

3.2 It is possible to calculate the effective parameters from the core dimensions and material properties when the following two assumptions are made:

a) In every cross section of the core the flux is the same (so there is no flux leakage), and
b) The flux is uniformly distributed over the cross section.

3.3 When using the effective parameters to calculate the hysteresis losses, the Rayleigh expression given below shall be valid:

$$\frac{B}{\mu_0} = (\mu_1 + v\hat{H})H \pm \frac{v}{2}(\hat{H}^2 - H^2)$$

3.4 When the effective parameters are used the general magnetic circuit equations for a core of arbitrary geometry become simpler, as follows:

$$\oint H \, \mathrm{d}l = Ni \qquad \text{becomes } H_e \, l_e = Ni$$

$$\phi = \int_A B \, \mathrm{d}A \qquad \text{becomes } \phi = B_e \, A_e$$

$$P_h = f \int_V \mathrm{d}V \oint H \, \mathrm{d}B \qquad \text{becomes } P_h = f \, V_e \oint H \, \mathrm{d}B$$

3.5 With the aid of $L = N\frac{\hat{\phi}}{\hat{i}}$ and $\frac{\tan \delta_h}{\mu_e} = \eta_B \, \hat{B}_e$, the following expressions may be derived, which may be used to calculate the effective parameters. For practical reasons, the dimensional parameters are normally expressed in millimetres, so that the appropriate power of 10 appears in the electromagnetic equations:

$$C_1 = \Sigma \frac{l}{A} \text{ (\textit{see} Note)} \qquad C_2 = \Sigma \frac{l}{A^2}$$

$$l_e = \frac{C_1^2}{C_2} \qquad A_e = \frac{C_1}{C_2} \qquad V_e = l_e \, A_e = \frac{C_1^3}{C_2^2}$$

$$\hat{H}_e = \frac{N\hat{i}}{l_e} 10^3 \qquad \hat{B}_e = \frac{u_{av} \, 10^6}{4 f A_e N} \qquad \mu_e = \frac{C_1}{\Sigma \frac{l}{\mu_r A}}$$

$$\hat{B}_e = \frac{\hat{u} \, 10^6}{\omega \, A_e \, N} \text{ (For sinusoidal voltage only)}$$

For cores and parts of cores with cross-sectional area which changes continuously along the magnetic path length, the summation of the above equations may be replaced by an integration.

With these effective parameters, the self inductance and the hysteresis losses may be calculated according to:

$$L = \frac{\mu_0 \mu_e N^2 A_e}{l_e} 10^{-3} \qquad P_h = \frac{\eta_B \hat{u}^3}{2\omega^2} \sqrt{\frac{\mu_0 \mu_e^3}{L^3 V_e}} 10^9$$

The equations also hold true for a core with small air gap. This air gap is taken into account by the calculation of μ_e.

NOTE — Sometimes the permeance factor $c = \frac{\mu_0}{C_1} 10^{-3}$ (in henries) is used mainly to calculate the effective permeability from the inductance factor.

4. CALCULATION OF EFFECTIVE PARAMETERS

4.0 The formulae for the calculation of the effective parameters of various types of cores are given in the following clauses.

4.1 Uniform Toroid

4.1.1 The shape of the uniform toroid is shown in Fig. 1.

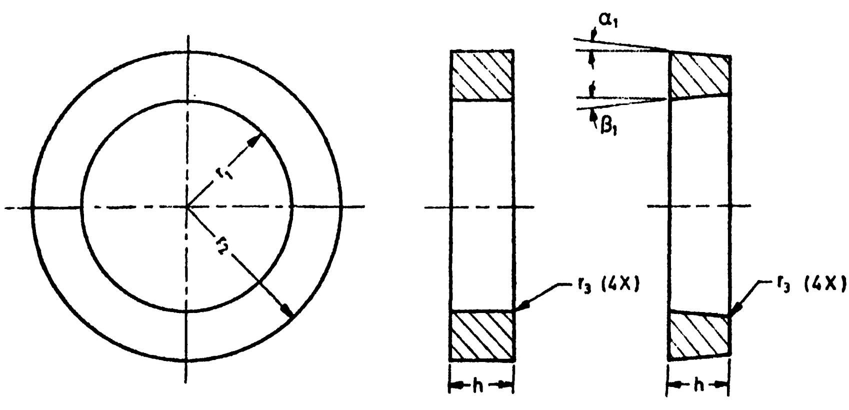

FIG. 1 UNIFORM TOROID

4.1.2 The effective parameters are calculated as follows:

a) $C_1 = \dfrac{2\pi}{h_e \log_e \dfrac{r_2}{r_1}}$ mm^{-1}

b) $C_2 = \dfrac{2\pi\left(\dfrac{1}{r_1} - \dfrac{1}{r_2}\right)}{h_e^2 \log_e^3 \dfrac{r_2}{r_1}}$ mm^{-3}

where

1) For toroids of rectangular cross section with sharp corners:

$$h_e = h$$

2) For toroids of rectangular cross section with an appreciable average rounding radius r_3:

$$h_e = h\,(1 - k_1) \qquad k_1 = \frac{0.858\,4\,r_3^2}{h(r_2 - r_1)}$$

3) For toroids of trapezoidal cross section with sharp corners:

$$h_e = h\,(1 - k_2) \qquad k_2 = \frac{h\,(\tan\alpha + \tan\beta)}{2(r_2 - r_1)}$$

4) For toroids of trapezoidal cross section with an appreciable average rounding radius r_3:

$$h_e = h(1 - k_1 - k_2)$$

4.2 Pair of U-Cores of Rectangular Section

4.2.1 This type of core is shown in Fig. 2.

4.2.2 The effective parameters are calculated as follows:

a) Length of flux path associated with area A_2:

$$l_2 = l'_2 + l''_2$$

b) Mean length of flux paths at corners:

1) $l_4 = l'_4 + l''_4 = \frac{\pi}{4}(p + h)$ mm, and

2) $l_5 = l'_5 + l''_5 = \frac{\pi}{4}(s + h)$ mm.

c) Mean areas associated with l_4 and l_5:

1) $A_4 = \dfrac{A_1 + A_2}{2}$ mm^2, and

2) $A_5 = \dfrac{A_2 + A_3}{2}$ mm^2.

d) $C_1 = \sum_1^5 \dfrac{l_1}{A_1}$ mm^{-1}, and

e) $C_2 = \sum_1^5 \dfrac{l_1}{A_1^2}$ mm^{-3}.

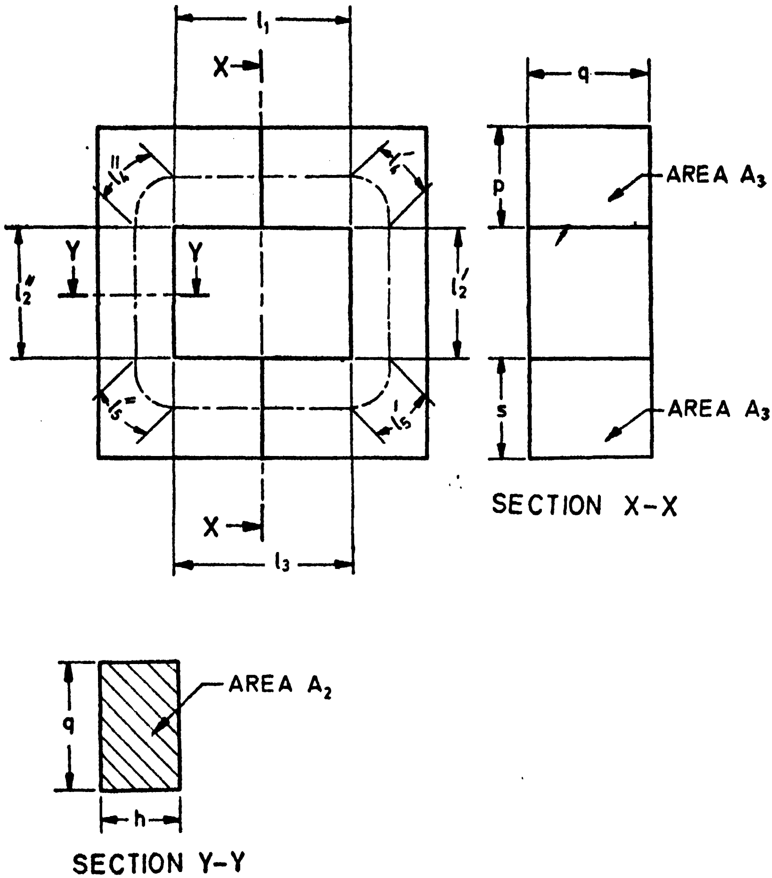

FIG. 2 PAIR OF U-CORES OF RECTANGULAR SECTION

4.3 Pair of U-Cores of Rounded Section

4.3.1 This type of core is shown in Fig. 3.

4.3.2 The effective parameters are calculated as follows:

a) Length of flux path associated with area A_2:

$$l_2 = l'_2 + l''_2$$

b) Mean length of flux path at corners:

1) $l_4 = l'_4 + l''_4 = \frac{\pi}{4}(p+h)$ mm, and

2) $l_5 = l'_5 + l''_5 = \frac{\pi}{4}(s+h)$ mm.

c) Mean area associated with l_4 and l_5:

1) $A_4 = \dfrac{A_1 + A_2}{2}$ mm², and

2) $A_5 = \dfrac{A_2 + A_3}{2}$ mm².

d) $C_1 = \sum_{1}^{5} \dfrac{l_i}{A_i}$ mm^{-1}, and

e) $C_2 = \sum_{1}^{5} \dfrac{l_i}{A_i^2}$ mm^{-3}.

NOTE — In calculating A_2 ignore any ridges introduced for the purpose of facilitating manufacture.

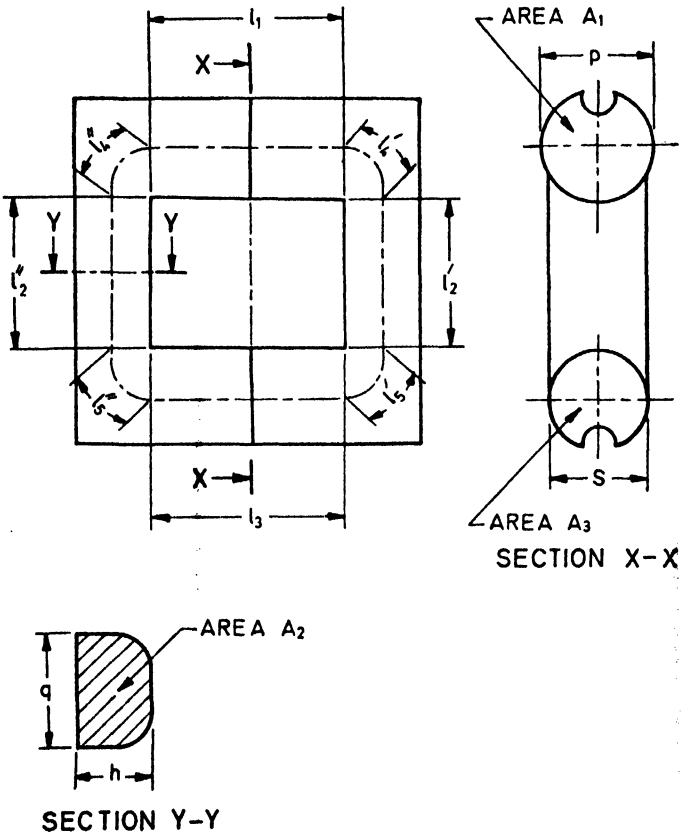

FIG. 3 PAIR OF U-CORES OF ROUNDED SECTION

4.4 Pair of E-Cores of Rectangular Section

4.4.1 This type of core is shown in Fig. 4.

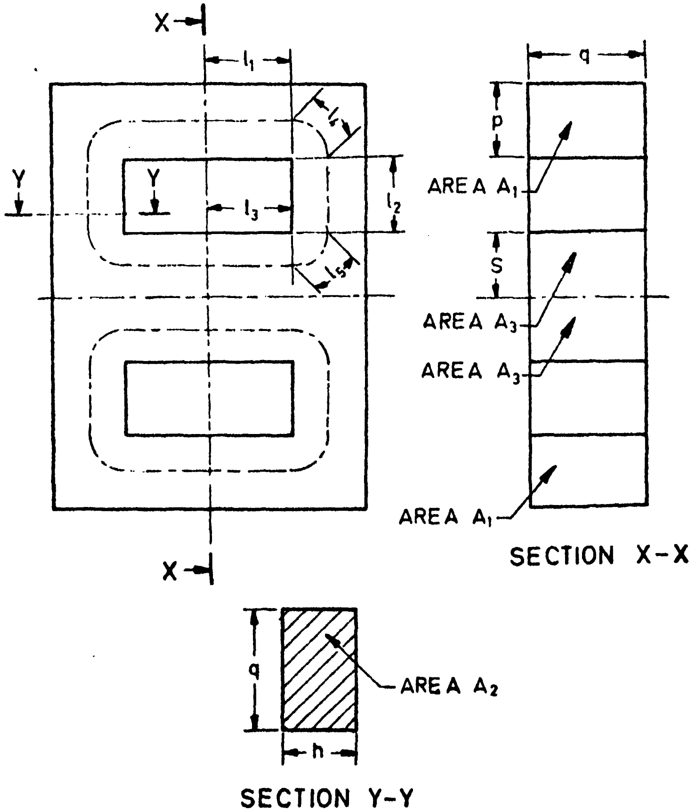

FIG. 4 PAIR OF E-CORES OF RECTANGULAR SECTION

4.4.2 The effective parameters are calculated as follows:

a) Area of half the centre limb: A_3.

b) Mean length of flux path at corners:

1) $l_4 = \frac{\pi}{8}(p+h)$ mm, and

2) $l_5 = \frac{\pi}{8}(s+h)$ mm.

c) Mean areas associated with l_4 and l_5:

1) $A_4 = \frac{A_1 + A_2}{2}$ mm², and

2) $A_5 = \frac{A_2 + A_3}{2}$ mm^2.

d) $C_1 = \sum_{1}^{5} \frac{l_i}{A_i}$ mm^{-1}, and

c) $C_2 = \sum_{1}^{5} \frac{l_i}{2A_i^2}$ mm^{-3}.

4.5 Pair of E-Cores of Rounded Section

4.5.1 This type of core is shown in Fig. 5.

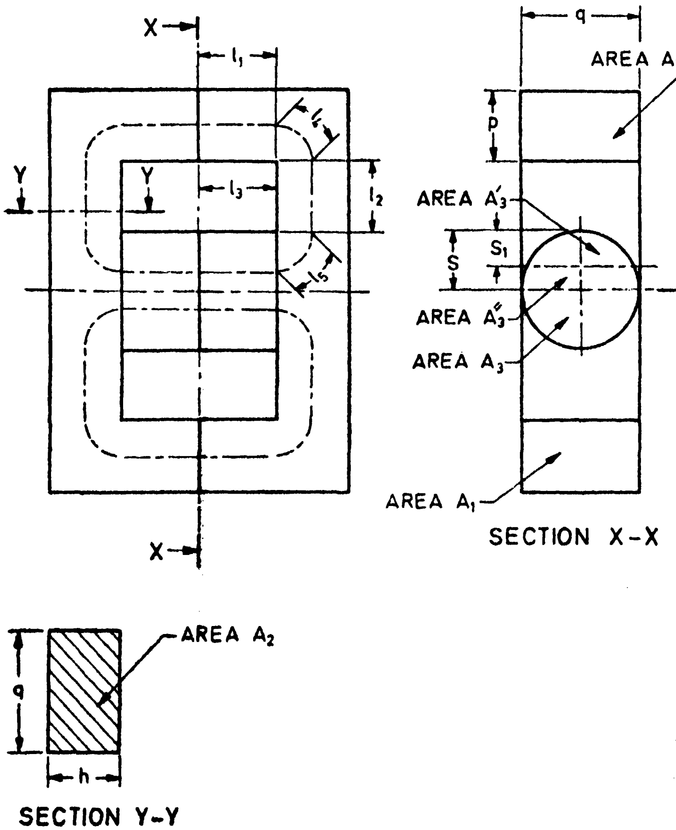

FIG. 5 PAIR OF E-CORES OF ROUNDED SECTION

4.5.2 The effective parameters are calculated as follows:

a) Area of half the centre limb:

$$A_3 = A'_3 + A''_3$$

The condition to obtain $A'_3 = A''_3$ is:

$$s_1 = 0{\cdot}595\ 9\ s$$

b) Mean length of flux path at corners:

1) $l_4 = \frac{\pi}{8}(p+h)$ mm, and

2) $l_5 = \frac{\pi}{8}(2s_1+h)$ mm.

c) Mean areas associated with l_4 and l_5:

1) $A_4 = \frac{A_1+A_2}{2}$ mm², and

2) $A_5 = \frac{A_2+A_3}{2}$ mm².

d) $C_1 = \sum_{1}^{5} \frac{l_1}{A_1}$ mm⁻¹, and

e) $C_2 = \sum_{1}^{5} \frac{l_1}{2A_1^2}$ mm⁻³.

4.6 Complete Pot-Core

4.6.1 This type of core is shown in Fig. 6.

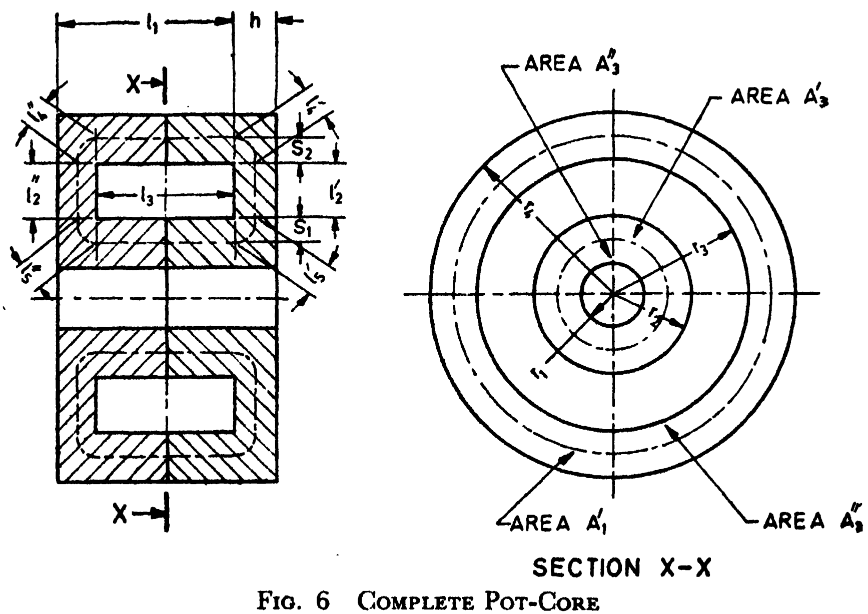

Fig. 6 Complete Pot-Core

4.6.2 The effective parameters are calculated as follows:

a) Area of outer ring:

$$A_1 = A'_1 + A''_1$$

The condition to obtain $A'_1 = A''_1$ is:

$$s_2 = -r_3 + \sqrt{\frac{r_3^2 + r_4^2}{2}}$$

b) Area of centre limb:

$$A_3 = A'_3 + A''_3$$

The condition to obtain $A'_3 = A''_3$ is:

$$s_1 = r_2 - \sqrt{\frac{r_1^2 + r_2^2}{2}}$$

c) Area of ring:

$$A_1 = \pi \ (r_4 - r_3) \ (r_4 + r_3) \text{mm}^2$$

For two plates:

1) $\dfrac{l_2}{A_2} = \dfrac{1}{\pi h} \log_e \dfrac{r_3}{r_2} = \dfrac{0{\cdot}733\,0}{h} \log_{10} \dfrac{r_3}{r_2}$ mm^{-1}, and

2) $\dfrac{l_2}{A_2^2} = \dfrac{1}{2\ \pi^2\ h^2} \times \dfrac{r_3 - r_2}{r_3 r_2}$ mm^{-3}.

d) Area of centre limb:

$$A_3 = \pi \ (r_2 - r_1) \ (r_2 + r_1) \text{ mm}^2.$$

e) Mean length of flux paths at corners:

1) $l_4 = l'_4 + l''_4 = \dfrac{\pi}{4} \ (2s_2 + h)$ mm, and

2) $l_5 = l'_5 + l''_5 = \dfrac{\pi}{4} \ (2s_1 + h)$ mm.

f) Areas associated with l_4 and l_5:

1) $A_4 = \dfrac{\pi}{2} \ (r_4^2 - r_3^2 + 2\ r_3 h)$ mm^2, and

2) $A_5 = \dfrac{\pi}{2} \ (r_2^2 - r_1^2 + 2\ r_2 h)$ mm^2.

g) $C_1 = \sum_1^5 \dfrac{l_1}{A_1}$ mm^{-1}, and

h) $C_2 = \sum_1^5 \dfrac{l_1}{A_1^2}$ mm^{-3}.

NOTE — This calculation ignores the effect of slots which may be taken into account by the following corrections:

From A_1 subtract $n\ g\ (r_4 - r_3)$

Multiply $\dfrac{l_2}{A_2}$ by $\dfrac{1}{1 - \dfrac{n\ g}{2\pi\ r_3}}$

Multiply $\frac{l_2}{A_2^2}$ by $\frac{1}{\left(1-\frac{n\,g}{2\pi\,r_3}\right)}$

Multiply A_4 by $1-\frac{n\,g}{\pi\,(r_3+r_4)}$

where

n = number of slots, and
g = slot width.

4.7 Complete Cross-Core (X-Core)

4.7.1 This type of core is shown in Fig. 7.

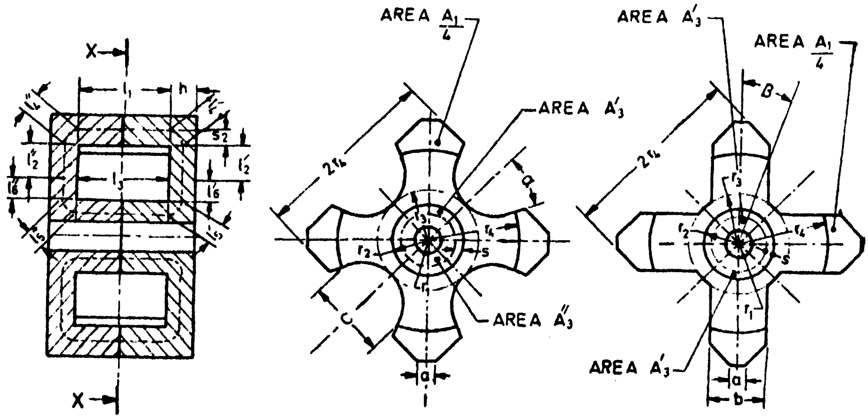

FIG. 7 COMPLETE CROSS-CORE (X-CORE)

4.7.2 The effective parameters are calculated as follows:

a) Area of centre limb:

$A_3 = A'_3 + A''_3$ mm²

The condition to obtain $A'_3 = A''_3$ is

$$s = r_2 - \sqrt{\frac{r_1^2 + r_2^2}{2}} \text{ mm}$$

b) Total area of the leg:

1) For cores with rounded legs

$$A_1 = 4\left(r_4^2 - \frac{\pi}{4}\cdot r_4^2 - \frac{1}{4}a^2 - \frac{c\,.\,r_4^2}{\sqrt{4r_4^2 - c^2}} + \frac{\alpha\cdot\pi}{180}\cdot r_4^2\right) \text{ mm}^2$$

where $\alpha = \text{arc sin}\,\frac{c}{2r_4}$

2) For cores with straight legs:

$$A_1 = 4 \left\{ b r_4 \cdot \sqrt{2} - \pi r_4^2 \cdot \frac{\beta}{180} - \frac{b}{4}\sqrt{(4r_4^2 - b^2)} - \frac{1}{4}(a^2+b^2) \right\} \text{ mm}^2$$

where $\beta = \text{arc}\cdot\sin \dfrac{b}{2r_4}$

c) Core factors associated with l_2

1) For cores with rounded legs:

$$\frac{l_2}{A_2} = \frac{66}{h(45-\alpha)} \log_{10} \frac{2r_4}{r_3+r_4} \text{ mm}^{-1}$$

$$\frac{l_2}{A_2^2} = \frac{1}{\left(\pi h \dfrac{45-\alpha}{45}\right)^2} \left[\frac{2}{r_3+r_4} - \frac{1}{r_4} \right] \text{ mm}^{-3}$$

2) For cores with straight legs:

$l_2 = l'_2 + l''_2 = 2\ (r_4 - r_3)$ mm

$A_2 = 4 \cdot b \cdot h$ mm^2

d) Area of centre limb:

$A_3 = \pi\ (r_2^2 - r_1^2)$ mm^2

e) Mean length of flux path at corners:

$$l_4 = l'_4 + l''_4 = \frac{\pi}{4} \left[h + \frac{4}{5} \left\{ r_4 (\sqrt{2} - 1) - \tfrac{1}{2} a \right\} \right] \text{mm}$$

$$l_5 = l'_5 + l''_5 = \frac{\pi}{2} \left[\frac{h}{2} + r_2 - \sqrt{\frac{r_1^2 + r_2^2}{2}} \right] \text{mm}$$

f) Sum of areas associated with l_4:

1) For cores with rounded legs:

$$A_4 = 4 \left(\frac{A_1}{8} + \pi \cdot h \cdot r_4 \frac{45-\alpha}{180} \right) \text{mm}^2$$

where $\alpha = \text{arc}\cdot\sin \dfrac{c}{2r_4}$

2) For cores with straight legs:

$$A_4 = 4 \left(\frac{A_1}{8} + \pi \cdot h \cdot r_4 \frac{\beta}{180} \right) \text{mm}^2$$

where $\beta = \text{arc}\cdot\sin \dfrac{b}{2r_4}$

g) Sum of areas associated with l_5:

$$A_5 = \frac{\pi}{2} (r_2^2 - r_1^2) + \pi\, h\, r_2 \cdot \text{mm}^2$$

h) Length of flux path in ring joining the central limb:

$l_6 = l'_6 + l''_6 = 2\ (r_3 - r_2)$ mm

j) Core factors associated with l_6:

1) $\dfrac{l_6}{A_6} = \dfrac{0{\cdot}733}{h} \log_{10} \dfrac{r_3}{r_2}$ mm^{-1}, and

2) $\dfrac{l_6}{A_6^2} = \dfrac{1}{2\,\pi^2 h^2}\left(\dfrac{1}{r_2} - \dfrac{1}{r_3}\right)$ mm^{-3}.

k) $C_1 = \sum\limits_{1}^{6} \dfrac{l_1}{A_1}$ mm^{-1}, and

m) $C_2 = \sum\limits_{1}^{6} \dfrac{l_1}{A_1}$ mm^{-3}.

4.8 Complete Square-Core (RM Core)

4.8.1 This type of core is shown in Fig. 8.

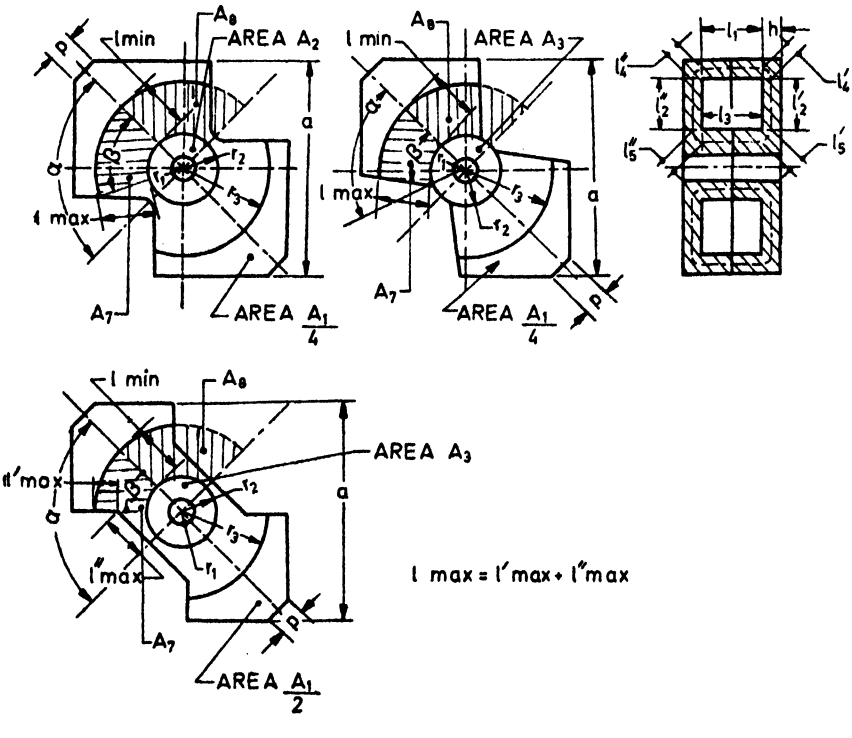

FIG. 8 COMPLETE SQUARE-CORE (RM CORE)

4.8.2 The effective parameters are calculated as follows:

a) Total area of the leg:

$$A_1 = \tfrac{1}{2}\, a^2 \left\{1 + tg\ (\beta - 45)\right\} - \pi \cdot r_3^{\,2} \cdot \frac{4\beta}{360} - \tfrac{1}{2}\, p^2 \text{ mm}^2$$

b) Core factors associated with l_2:

$$\frac{l_2}{A_2} = \frac{l_n \dfrac{r_3}{r_2} \times f}{C \times \pi \times h}$$

$$\frac{l_2}{A_2^{\,2}} = \frac{\left(\dfrac{1}{r_2} - \dfrac{1}{r_3}\right) \times f}{2\ (C \times \pi \times h)^2}$$

where

$$l_2 = l'_2 + l''_2$$

$$f = \frac{l_{\min} + l_{\max}}{2 \times l_{\min}}$$

$$C = \frac{A_7}{A_8}$$

NOTE — Surfaces A_7 and A_8 may be determined either by calculations or by measurement, for example, using a planimeter on a ten-time enlarged drawing of the core.

c) Area of centre limb:

$$A_3 = \pi\ (r_2^{\,2} - r_1^{\,2}) \text{ mm}^2$$

d) Mean length of flux path at corners and mean areas associated with these:

$$l_4 = l'_4 + l''_4 = \frac{\pi}{4}(h + \tfrac{1}{2}\, a - r_3)$$

$$A_4 = \tfrac{1}{2}\left(A_1 + 2\ \pi\ r_3 \cdot h \times \frac{4\beta}{360}\right)$$

$$l_5 = l'_5 + l''_5 = \frac{\pi}{4}\left(2r_2 + h - \sqrt{2r_1^{\,2} + 2r_2^{\,2}}\right)$$

$$A_5 = \frac{\pi}{2}\ (r_2^{\,2} - r_1^{\,2}) + \pi \cdot r_2 \cdot h \cdot \frac{\alpha}{90}$$

e) $C_1 = \displaystyle\sum_{1}^{5} \frac{l_1}{A_1} \text{mm}^{-1}$, and

f) $C_2 = \displaystyle\sum_{1}^{5} \frac{l_1}{A_1^{\,2}} \text{mm}^{-3}$.

NOTE — This calculation ignores the effect of spring recesses and stud recesses. These may have a considerable influence, specially for smaller cores.

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