CHAPTER 10

CALCULATION OF INDUCTANCE

based on original chapter in the previous edition by L. G. Dobbie, M.E.

Revised by G. Builder, B.Sc., Ph.D., F. Inst. P. and E. Watkinson, A.S.T.C., A.M.I.E. (Aust.), S.M.I.R.E. (Aust.).

SECTION 1 : SINGLE LAYER COILS OR SOLENOIDS

(i) Current-sheet inductance (ii) Solenoid wound with spaced round wires (iii) Approximate formulae (iv) Design of single layer solenoids (v) Magnitude of the difference between L_s and L_0 (vi) Curves for determination of the " current sheet " inductance (vii) Effect of concentric, non-magnetic screen.

(i) Current-sheet inductance

For the ideal case of a very long solenoid wound with extremely thin tape having turns separated by infinitely thin insulation we have the well-known formula for the low frequency inductance which is called the " current-sheet inductance " L_s :

$L_s = 4\pi N^2 A'/l$ electromagnetic units (1)

where N is the total number of turns, A' is the cross-sectional area in cm.^{2} and l is the length in cm. This result for L_s may be expressed also as

$L_s = 0.100\,28 a^2 N^2/l$ microhenrys (2)

when l is measured in inches, and a is the radius of coil, also in inches.

For solenoids of moderate length—more precisely, for those for which a/l is not small compared with unity—there is an end-correction, and we find that

$L_s = (0.100\,28 a^2 N^2/l)K$, (3)

where K is a function of a/l, which approaches unity as a/l tends to zero. Values of K, computed by Nagaoka (Bulletin, Bureau of Standards, 8, p. 224, 1912), are shown by the curves in Fig. 10.1.

The concept of current sheet inductance is introduced because such (theoretical) inductances can be calculated with high precision, and the formulae used in practical cases can be derived from these results by making approximate allowances for the deviations from the ideal case. In many cases these deviations are less than 1%.

(ii) Solenoid wound with spaced, round wires

The low frequency inductance, L_o, of an actual solenoid wound with round wire is obtained from the equivalent cylindrical current-sheet inductance L_s by introducing two correction terms, thus :

$$L_o = L_s - 0.0319aN(A + B) \text{ microhenrys,} \quad (4)$$

where a is the radius of the coil, in inches, measured to the centre of the wire, A is a constant taking into account the difference in self-inductance of a turn of wire from that of a turn of the current sheet, and B depends on the difference in mutual inductance of the turns of the coil from that of the turns of the current sheet. The quantity A is a function of the ratio of wire diameter to pitch, and B depends only on the total number of turns, N. Values of A and B are shown by means of curves in Fig. 10.2.

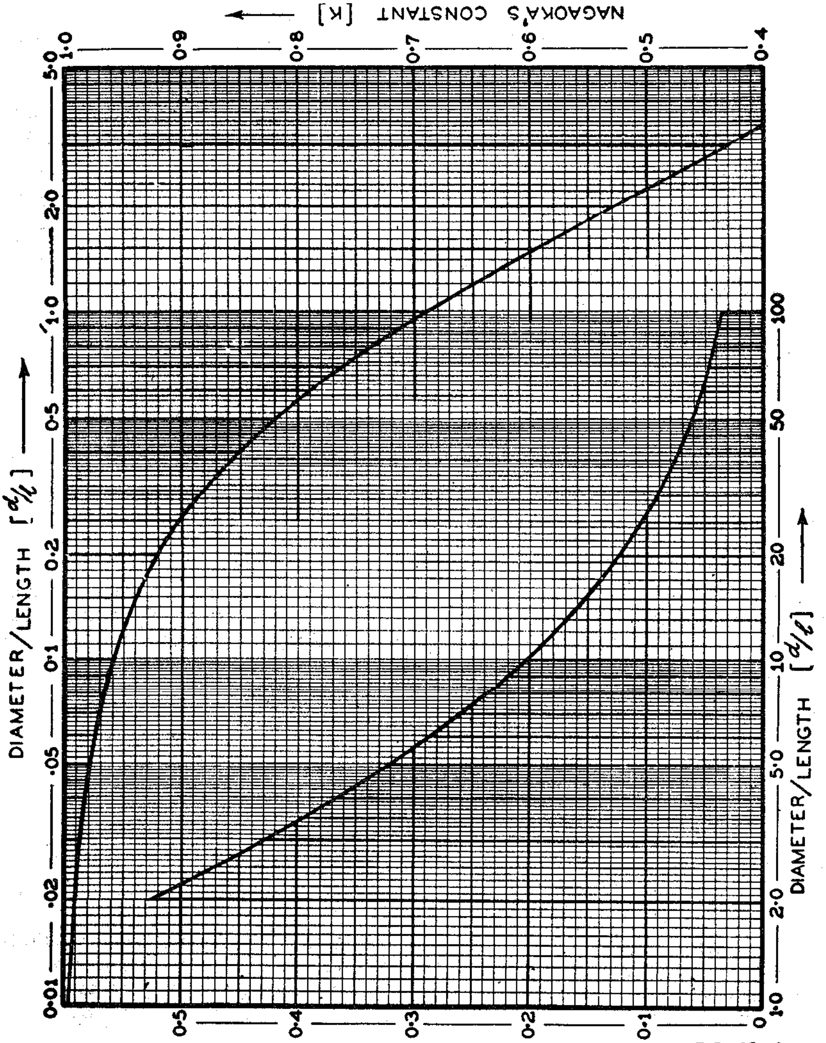


FIG. 10.1

Fig. 10.1. Nagaoka's Constant (K) for a wide range of d/l.

This formula for L_o, together with the values of A and B, have been taken from the above quoted Bulletin of the Bureau of Standards. The value thus obtained for L_o is given as correct to one part in a thousand.

The equation given above for L_o can be expressed in the alternative forms :

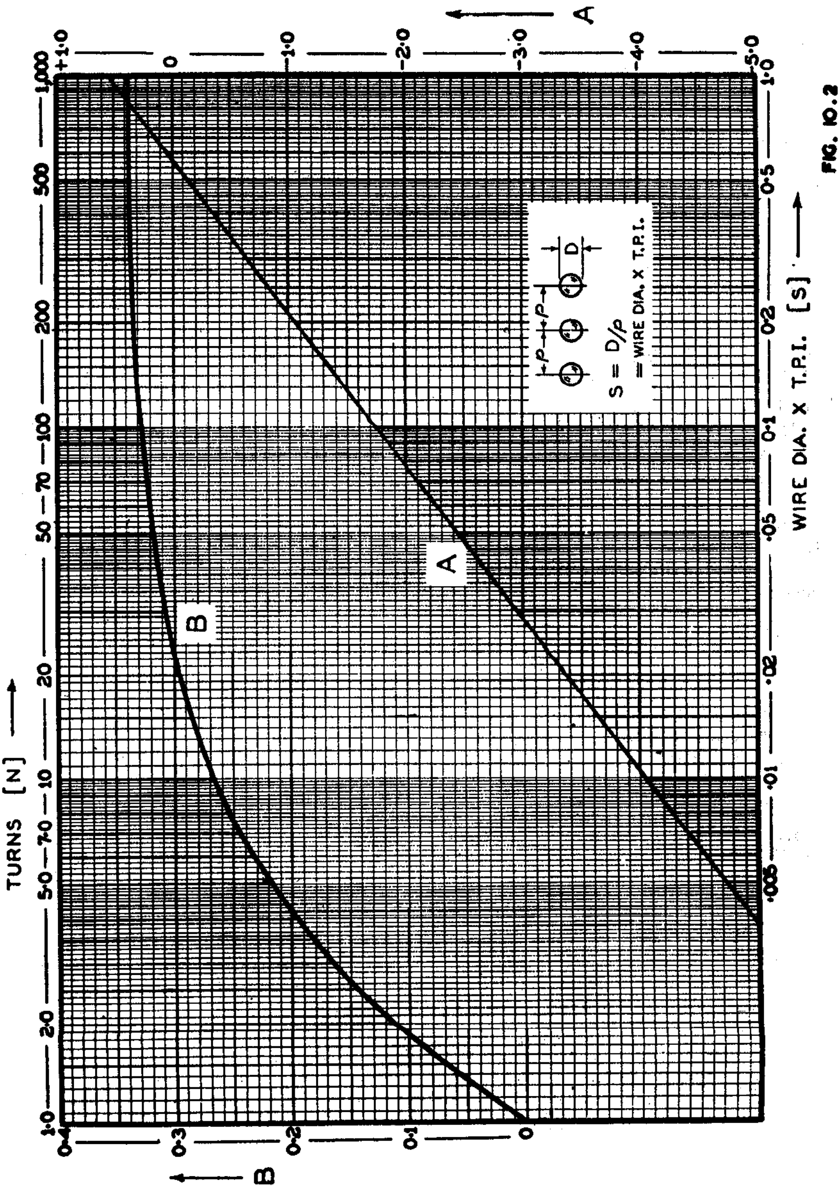


Fig. 10.2. *Constants A and B as used in the formula for the correction of " current sheet " formulae for application to round wire with spaced turns (eqn. 4).*

$$L_o = L_s\left[1 - \frac{l(A+B)}{\pi aNK}\right] = L_s\left[1 - \frac{P}{\pi aK}(A+B)\right] \quad (5)$$

where P, the pitch of the winding in inches, is equal to l/N.

As an example of the use of these formulae and curves, let us consider the following case : a coil of 400 turns of round wire of bare diameter $D = 0.05$ inch, is wound with a pitch of 10 turns per inch, on a form of such a diameter that the mean radius to the centre of the wire is 10 inches. Then,

$a = 10, l = NP = 40, N = 400, P = 0.1, D/P = 0.5.$

The value of K corresponding to $2a/l = 0.5$ is 0.8181 from Fig. 10.1. Therefore,

$L_s = 0.100\,28\,(400)^2 \times (100/40) \times 0.8181$
$= 32\,815$ microhenrys.

From Fig. 10.2 with $D/P = 0.5$, $N = 400$,

$A = -0.136$
$B = \quad 0.335$

Therefore $A + B = \quad 0.199.$

The correction is, therefore, $0.0319 \times 10 \times 400\,(0.199)$
$= 25.4$ microhenrys.

The total inductance $L_o = 32\,815 - 25 = 32\,790$ microhenrys, and the error which would be introduced by calculating as a current sheet inductance is less than 0.08%.

(iii) Approximate formulae

In many instances it is not necessary to calculate L_o to the accuracy given by the expression above. There are available a number of approximate formulae suitable for slide-rule computation. For example :

$$A \approx 2.3 \log_{10} 1.7\,S \quad (6)$$

where $S = D/P$, i.e. the ratio of wire diameter to pitch, with an accuracy of 1% for all values of S.

$$B \approx 0.336\,[1 - (2.5/N + 3.8/N^2)] \quad (7)$$

accurate to 1% when N exceeds four turns.

(a) **Wheeler's Formula**

$$L_s = \frac{a^2N^2}{9a + 10\,l} \quad (8)$$

This expression is accurate to 1% for all values of $2a/l$ less than 3. Wheeler's formula gives a result about 4% low when $2a/l = 5$.

(b) Approximate expression based on a value of K given by **Esnault-Pelterie**

$$L_s \approx 0.1008\,\frac{a^2N^2}{l + 0.92a} \quad (9)$$

This expression is accurate to 0.1% for all values of $2a/l$ between 0.2 and 1.5.

(c) For solenoids whose length is small compared with the diameter

$$L_s = \frac{a^2N^2}{[9 - (a/5l)]\,a + 10l} \quad (10)$$

which is accurate to 2% for all values of $2a/l$ up to 20. The error approaches + 2% when $d/l = 2.0$ to 3.5 and at $d/l = 20$. The error approaches − 2% in the range $d/l = 10$ to 12.

Let us apply Wheeler's and Esnault-Pelterie's formulae to the solenoid already considered, namely :

$a = 10$ in., $l = 40$ in., $N = 400$.

Wheeler's formula gives $L_s = \dfrac{10^2 \times 400^2}{90 + 400} = 32\,650$ microhenrys.

Esnault-Pelterie's formula yields

$$L_s = 0.1008\,\frac{10^2 \times 400^2}{40 + 9.2} = 32\,790 \text{ microhenrys.}$$

These results agree, within the stated limits, with the value 32 815 obtained previously.

(iv) Design of single layer solenoids

The difference between L_s and L_o is usually less than 1%. Design formulae are based on L_s, as this is easier to compute, and then the correction is estimated.

Two of the many possible formulae are given in the Bureau of Standards Circular 74 (Ref. 2).

(A) Where it is required to design a coil which shall have a certain inductance with a given length of wire, the dimensions of the winding and the kind of wire being unrestricted within broad limits. This design problem includes a consideration of the question as to what shape of coil will give the required inductance with the minimum resistance.

We have the relations :

$L_s = 0.100\,28 a^2N^2K/l$ from (3),

$l = NP$, $\lambda = 2\pi aN$,

where λ is the length of wire. Eliminating N gives :

$$L_s = 0.004\,50 \frac{\lambda^{3/2}}{\sqrt{P}}\left(K\sqrt{\frac{2a}{l}}\right) \text{ microhenrys} \tag{11}$$

This gives the inductance in terms of the length of wire, the pitch P, and the shape $2a/l$, as K is a function of $2a/l$.

From the graph of the quantity $K\sqrt{2a/l}$ against $2a/l$, its maximum value is found to occur at $2a/l = 2.46$. **Thus, for a given length of wire, wound with a given pitch, that coil has the greatest inductance, which has a shape $d/l = 2.46$ approximately** ; or to obtain a coil of a required inductance, with a minimum resistance, this relation should be realized. Further, the inductance diminishes rapidly for coils longer than this optimum value, but decreases only slowly for shorter coils.

The optimum value of d/l can also be obtained roughly from the approximate expression for K :

$K = 1/(1 + 0.45\, d/l)$.

Therefore $(d/l)_{opt} = (1/0.45) = 2.2$ approximately (12)

(B) Given the diameter of the coil, the pitch and inductance, to determine the length of the coil.

A suitable form of the equation is obtained by substituting for N its value l/P in the formula :

$L_s = 0.100\,28\, a^2N^2\, K/l$ from (2) ;

we find :

$$L_s = 0.200\,56\,(a^3/P^2)(Kl/2a) \tag{13}$$

$$\approx 0.200\,(a^3/P^2)f \tag{14}$$

where $f = K(l/2a)$. The quantity f, clearly a function of $2a/l$, is shown by the curve in Fig. 10.3.

For example, supposing we require a coil of 200 microhenrys to be wound on a former of 1 inch diameter, let us determine the length of the coil for a pitch of 0.02 inch.

From the equation,

$$f = \frac{200 \times (0.02)^2}{0.200 \times (0.5)^3} = 3.2.$$

Then, from Fig. 10.3, the value of $2a/l$ corresponding to $f = 3.2$ is 0.28. Hence the length of the coil is

$l = 2a/0.28 = 1/0.28 = 3.6$ inches.

The number of turns required would be :

$N = l/P = 3.6/0.02 = 180$ turns.

The length of wire needed would be :

$\lambda = 2\pi aN = \pi 180 = 565.5$ inches.

When the calculated length is too long, the turns per inch should be increased. Let us consider the effect of using 100 T.P.I. in the above example :

$$f = \frac{200 \times (0.01)^2}{0.200 \times (0.5)^3} = 0.8.$$

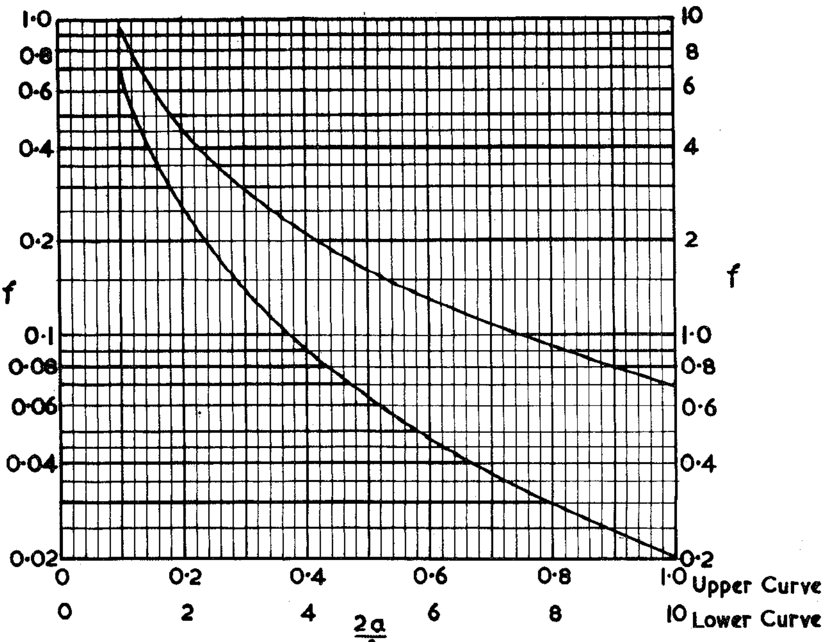


FIG. 10.3

Fig. 10.3. *Variation of f with (2 a/l). Curves derived from U.S. Dept. of Commerce Circular C74 "Radio instruments and measurements".*

From Fig. 10.3, we see that the value of $2a/l$ is 0.9, and hence
$l = 1/0.9 = 1.1$ inches.

Formula for determining the coil length when the coil diameter and winding pitch are known for coils such that $d < 3l$.

As an alternative to the use of Fig. 10.3, we derive a simple result for solenoids such that $2a/l < 3$. Here we have

$$K \approx 1/[1 + 0.45\,(2a/l)] \tag{15}$$

$$\text{Hence, } f = K \cdot \frac{l}{2a} = \frac{l}{2a} \cdot \frac{1}{1 + 0.45\,(2a/l)} \tag{16}$$

$$\text{Therefore, } 0.9(2a/l) = -1 + \sqrt{1 + 1.8/f} \tag{17}$$

Thus, in the first case above, where $f = 3.2$,

$0.9(2a/l) = -1 + \sqrt{1 + 1.8/3.2} = 0.25$,
and $2a/l = 0.25/0.9 = 0.28$;

for the second case, where $f = 0.8$,

$0.9(2a/l) = \sqrt{1 + (1.8/0.8)} - 1 = 0.803$,
and $2a/l = 0.803/0.9 = 0.89$.

These values agree well with those above.

The limitation $2a/l < 3$ is equivalent to $f \nless 0.14$.

Eqn. (14) for L_s is suitable too when the former diameter and coil length have been decided. For example, suppose we require a coil of inductance 500 microhenrys on a former of diameter 2 inches, and having a coil length of 2 inches.

Then, from equation (14)

$$L_s = 0.200(a^3/P^2)\,.f, \tag{18}$$

we have

$$P = \sqrt{(0.200a^3\,.f)/L_s} \tag{19}$$

Here $a = 1$, $L_s = 500$, $f = Kl/2a = 0.688$.

Therefore,

$P = \sqrt{0.200 \times 0.688/500} = 0.0167$ inch,

equivalent to 60 T.P.I.

Simple procedure for computing the length and total turns when the coil diameter and pitch of winding are known for coils such that $d < 3l$.

Substituting in equation (17),

$0.9(2a/l) = -1 + \sqrt{1 + 1.8/f}$,

where $f = 5L_sP^2/a^3 = 5L_s/n^2a^3$, n being T.P.I.

Putting $F = 1.8/f$ and $y = 0.9(2a/l)$,

we obtain

$$y = -1 + \sqrt{1 + F}, \quad (20)$$

where $F = 0.36n^2a^3/L_s$,

and $l = 1.8a/y$.

As an example, let us consider a coil of 2 inches diameter, wound with 33 T.P.I. of required inductance 380 microhenrys.

(a) $F = 0.36n^2a^3/L_s = 0.36 \times 33^2 \times 1^3/380 = 1.031$

(b) $y = -1 + \sqrt{1 + F} = -1 + \sqrt{2.031} = 0.426$

(c) $l = 1.8a/y = 1.8/0.426 = 4.23$ inches

(d) $N = nl = 33 \times 4.23 = 139\frac{1}{2}$ turns.

Another method applicable to the same type of problem is due to Hayman.

From Wheeler's formula (equation 8):

$$L_s \approx \frac{a^2N^2}{9a + 10l},$$

the length l is eliminated by the substitution $l = N/n$, n being the turns per inch; and then the resulting expression is solved for N, yielding:

$$N = \frac{5L_s}{na^2}\left[1 + \sqrt{1 + \frac{0.36a^3n^2}{L_s}}\right] \quad (21)$$

For convenience in computation, the quantity $x = 5/na^2$ is introduced, so that finally

$$N = xL_s[1 + \sqrt{1 + (9/ax^2L_s)}] \quad (22)$$

As an example, we take the same problem as above, namely, $a = 2$ inches, $n = 33$, $L_s = 380$ microhenrys. The procedure is as follows:

(a) $x = 5/na^2 = 5/(33 \times 1) = 0.151$,

(b) $x^2 = 0.0227$,

(c) $9/ax^2L_s = 9/(1 \times 0.0227 \times 380) = 1.042$,

(d) $N = 380 \times 0.151 \times (\sqrt{2.042} + 1) = 139$ turns,

(e) $l = N/n = 139/33 = 4.2$ inches.

(C) Given the diameter and length of coil, value of capacitance and frequency of resonance, to determine the number of turns.

See Chapter 38 Sect. 9(v)B.

(v) Magnitude of the difference between L_s and L_o

In Sect. 1(iv) it was stated that in many practical cases the difference between L_s and L_o is less than 1 per cent. Here, we examine briefly the necessary conditions for this difference to be small.

A formula given in Sect. 1(ii) for L_o, namely:

$L_o = L_s[1 - P(A + B)/\pi aK]$ from equation (5)

is in a useful form; clearly the ratio of $P(A + B)/\pi aK$ to unity determines the order of the difference between L_s and L_o. From the curves of Fig. 10.2, $A = +0.5$ for $P/D = 0.95$ and decreases steadily to -0.7 for $P/D = 0.25$, while $B = 0.114$ at $N = 2$ and 0.336 at $N = 1000$, and remains approximately constant for higher values of N. Hence, for coils having P/D between 0.95 and 0.25—as most have—the value of $(A + B)$ is less than 0.83; i.e.

$P(A + B)/\pi aK < (P/a) \times (0.26/K)$.

Thus, when $(2a/l) = d/l < \frac{1}{2}$, $K > 0.82$, so that $P(A + B)/\pi aK < 0.32\, P/a$.

The correction is less than 1% when $P/a < 0.03$.

Similarly, for $2a/l < 1$, $K > 0.69$, and the correction is less than 1% when $P/a < 0.026$. Corresponding results for $2a/l < 5$ and $2a/l < 10$ are $P/a < 0.012$ and $P/a < 0.0078$.

In the table opposite are given some examples of the minimum turns per inch, n, for a number of coil diameters required to make the difference between L_s and L_0 less than 1% :

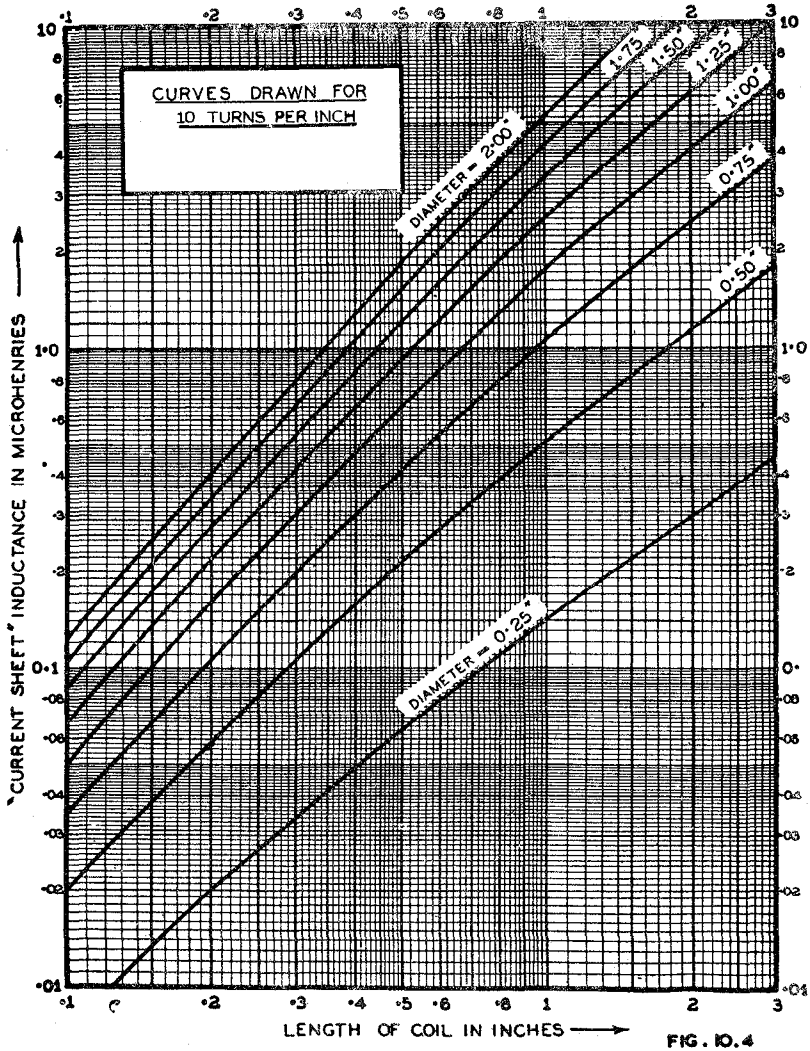


Fig. 10.4. *Curves for the determination of Current Sheet Inductance (L_s) for small solenoids, plotted against length of coil (l). For other pitches refer to Fig.* 10.5.

$\left(\frac{\text{Coil diameter}}{\text{length}}\right)$ not exceeding	Minimum turns per inch, n for $d = 5$ inches	$d = 2$ inches	$d = 1$ inch	$d = \frac{1}{2}$ inch
0.5	13	33	66	132
1	16	40	80	160
5	32	80	160	320
10	52	130	260	520

In many practical cases the ratio of pitch to wire diameter lies between 0.8 and 0.95 in which range $A = 0.4 + 0.1$; and N, the number of turns, exceeds 10, so that $B = 0.3 \pm 0.035$. In such cases $A + B = 0.7 \pm 0.135$. Hence, from eqn. (4) :

$$L_o = L_s - 0.0319aN(A + B),$$

we have, under such conditions,

$$L_o \approx L_s - 0.0223aN, \qquad (23)$$

with an error not exceeding 20% of $0.0223aN$; and thus in many cases not exceeding 0.2% of L_o.

(vi) Curves for determination of the "current sheet" inductance

(A) Method of using the curves

Figure 10.4 applies to a winding pitch of 10 turns per inch only; for any other pitch the inductance scale must be multiplied by a factor, which is easily determined from Fig. 10.5. The diameter of a coil is considered to be twice the distance from coil axis to centre of the wire.

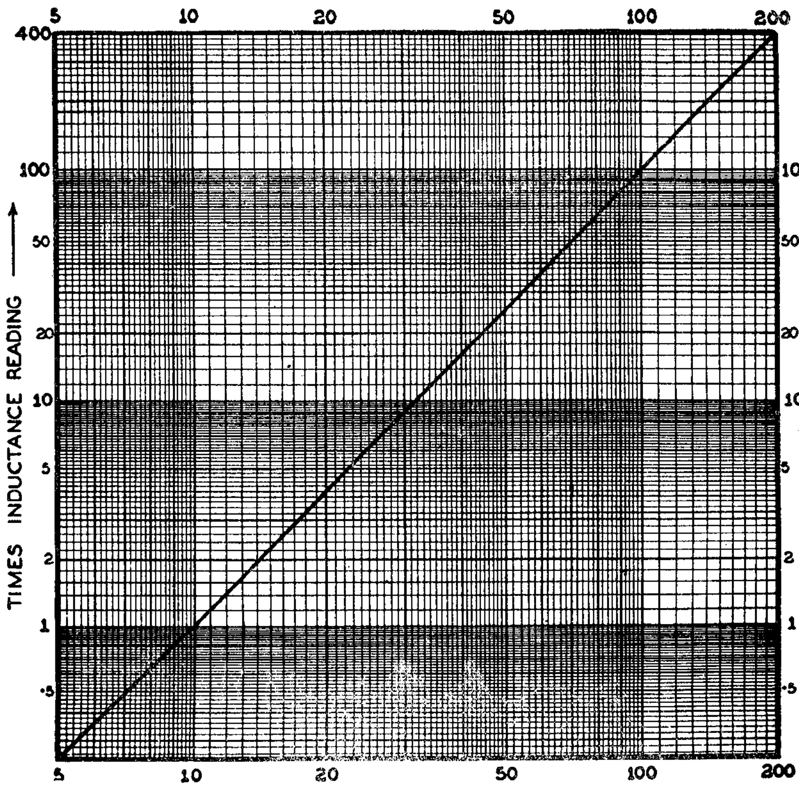


Fig. 10.5. *Winding pitch correction for Fig.* 10.4.

(B) To design a coil having required " current sheet " inductance

Determine a suitable diameter and length, and from Fig. 10.4 read off the " current sheet " inductance for a pitch of 10 T.P.I. The required inductance may then be obtained by varying the number of turns per inch. The correct number of turns may be found by calculating the ratio of the required inductance to that read from Fig. 10.4 and referring it to Fig. 10.5 which will give the required turns per inch.

Alternatively if the wire is to be wound with a certain pitch, a conversion factor for that pitch may first be obtained from Fig. 10.5, and the required inductance divided by that factor. The resultant figure of inductance is then applied to Fig. 10.4 and suitable values of diameter and length determined.

(C) To find the " current sheet " inductance of a coil of known dimensions

Knowing the diameter and length, determine from Fig. 10.4 the inductance for a pitch of 10 T.P.I. Then from Fig. 10.5 determine the factor for the particular pitch used, and multiply the previously determined value of inductance by this factor.

(vii) Effect of concentric, non-magnetic screen

A shield surrounding a coil acts as a short-circuited turn coupled to the coil and reflects an impedance into the coil. The value of this reflected impedance is given by the expression $M^2\omega^2/Z_t$, where M is the mutual inductance between the coil and the shield, and Z_t is the impedance of the shield. In practice, the resistance of the screen may be neglected, so that the effective impedance of the coil Z_c', is

$$Z_c' = r_o + j\omega L_o + M^2\omega^2/j\omega L_t \quad (24)$$

where r_o and L_o are the resistance and the inductance of the coil in the absence of the shield, and L_t is the inductance of the shield. The expression for Z_c' may be put in the forms :

$$Z_c' = r_o + j\omega(L_o - M^2/L_t), \quad (25a)$$
$$= r_o + j\omega(1 - M^2/L_oL_t), \quad (25b)$$
$$= r_o + j\omega L_o' \quad (25c)$$
$$= r_o + j\omega L_o(1 - k^2) : \quad (25d)$$

where L_o' is the effective inductance of the enclosed coil, and k is the coefficient of coupling between the coil and the can. The presence of the shield thus lowers the effective inductance, and we have

$$L_o' = L_o(1 - k^2), \quad (26a)$$

or $$(L_o - L_o')/L_o = k^2 \quad (26b)$$

It has not proved possible to obtain a simple, accurate formula for the apparent decreases in inductance of a shielded coil, but various estimates have been made by Hayman, Kaden, Davidson and Simmonds, Bogle and others (see bibliography). Here we review briefly some of the published work.

(A) H. Kaden (Electrishe Nachrichten Tecknik, July, 1933, p. 277)

Kaden first showed that the shape of the shield is not important. Then, in his theoretical treatment, he replaced the actual solenoid in the concentric cylindrical shield by a magnetic dipole placed at the centre of a spherical screen ; the dipole having the same magnetic moment as the solenoid and the spherical screen a radius equal to the geometrical mean of the three dimensions of the cylinder. In this way he obtained an expression for the relative decrease in inductance of the solenoid.

$$\frac{L_o - L_o'}{L_o} = \frac{2}{3}\frac{V_c}{V_t}\frac{\alpha}{K}, \quad (27)$$

where V_c is the volume of the coil, V_t is the volume of the shield, K is Nagaoka's constant, and α is a constant which depends upon the permeability and the shield and the dimensions. When the shielding is effective and the shield is non-magnetic, α is approximately 1 and then :

$$\frac{L_o - L_o'}{L_o} \approx \frac{2}{3}\frac{V_c}{V_t}\frac{1}{K} \quad (28)$$

(B) C. F. Davidson and J. C. Simmonds (Ref. 41)

Following Kaden, these authors also considered the case of a spherical screen. Here the solenoid was taken to consist of a small number of closely spaced circular turns placed at the centre of the sphere. The change in inductance was found to be

$$L_o - L_o' = 0.1\,aN^2(a/b)^3 . f(a/b), \tag{29}$$

where a is the coil radius, N is the number of turns, b is the shield radius and $f(a/b)$ is a function of (a/b). This function f is approximately 0.5 for values of $(a/b) \ngtr 0.5$, and it increases to 0.73 at $(a/b) = 0.9$. Thus, for values of $(a/b) < 0.5$, we have :

$$L_o - L_o' \approx (0.05\,aN^2)(a/b)^3, \tag{30}$$

in agreement with Kaden's result. The authors point out that their formula holds only for very short solenoids; they indicate how the change in inductance of long solenoids in spherical screens may be calculated, but it is clear that no simple formula can be thus obtained.

(C) R.C.A. Application Note No. 48 (June, 1935)

In this Application Note (Ref. 48) curves are given for k^2 in the case of a concentric cylindrical shield whose length exceeds the coil length by at least the radius of the coil. These curves (Fig. 10.6) show k^2 as a function of the ratio coil length to coil diameter $(l/2a)$ for various values of the ratio coil radius to shield radius ranging from 0.2 to 0.9. It is stated that these values of k^2 have been calculated and also verified experimentally. The shields are not closed at the ends, but see (D) below.

It is stated that these curves may also be used for cans of square cross-section by taking A as 0.6 of one side of the can.

(D) A. G. Bogle (Ref. 45)

Bogle obtains an approximate theoretical formula for the effective change in inductance, valid in a restricted range, and then, from measurements of L_o', he derives an empirical expression which is of the same form as the theoretical formula, but which gives good results over a wide range.

For a coil inside a concentric cylindrical shield, Bogle's expression is :

$$\frac{L_o - L_o'}{L_o} = \frac{1}{1 + 1.55g/l}\left(\frac{a}{b}\right)^2 \tag{31}$$

where b is the shield radius, and $g = b - a$, the distance between the coil and the shield. It is assumed that the shield length l_t is not less than $l + 2g$. An accuracy of 2% over a wide practical range is claimed for this simple result.

An investigation of this expression shows that it is useful in almost all practical cases, the only restriction being the non-stringent one that the length of the coil must not be very much less than the distance between the coil and the shield, i.e. $g/l \ngtr 1$.

For very long coils this formula shows that

$$(L_o - L_o')/L_o = a^2/b^2$$

in agreement with theoretical expectations. It is in accord, too, with the R.C.A. curves for k^2 in that the proportional change in inductance depends upon the two ratios a/b and l/a, as can be seen by writing the formula in the form :

$$\frac{L_o - L_o'}{L_o} = \frac{1}{1 + 1.55\frac{a}{l}\left(\frac{b}{a} - 1\right)}\left(\frac{a}{b}\right)^2.$$

Bogle showed also that when $l_t > l + 2g$ the effect on L_o' of closing the ends of the shield is negligible. He investigated the effect of eccentricity of the coil, of ellipticity of the screening tube, and of small axial displacements in a closed screen ; and found that in practice these would not need to be taken into account.

Sowerby has published data charts (Ref. 44) calculated from Bogle's formula.

(E) W. G. Hayman (Ref. 51)

Hayman gives an empirical formula for coils in concentric cylindrical cans :

$$(L_o - L_o')/L_o = (a/b)^3, \tag{32}$$

provided $l_t \gg l$. For coils of length $l > \frac{1}{2}l_t$ there is an end-correction factor, and he gives :

$$(L_o - L_o')/L_o = (1 - l/2l_t)^2 (a/b)^3 \qquad (33)$$

It is true that there is fair agreement between Hayman's calculated and measured values of L_o' for a number of coils ; but, nevertheless, the useful range of eqn. (32) must be somewhat restricted.

(F) Where the coil diameter and length are equal, the curves of Fig. 11.13 can be used for a shield can with ends.

It is recommended that either the R.C.A. curves for k^2, reproduced in Fig. 10.6, or Bogle's formula be used. Comparison of the results obtained from these curves and from the formula will be found to be in good agreement except for very

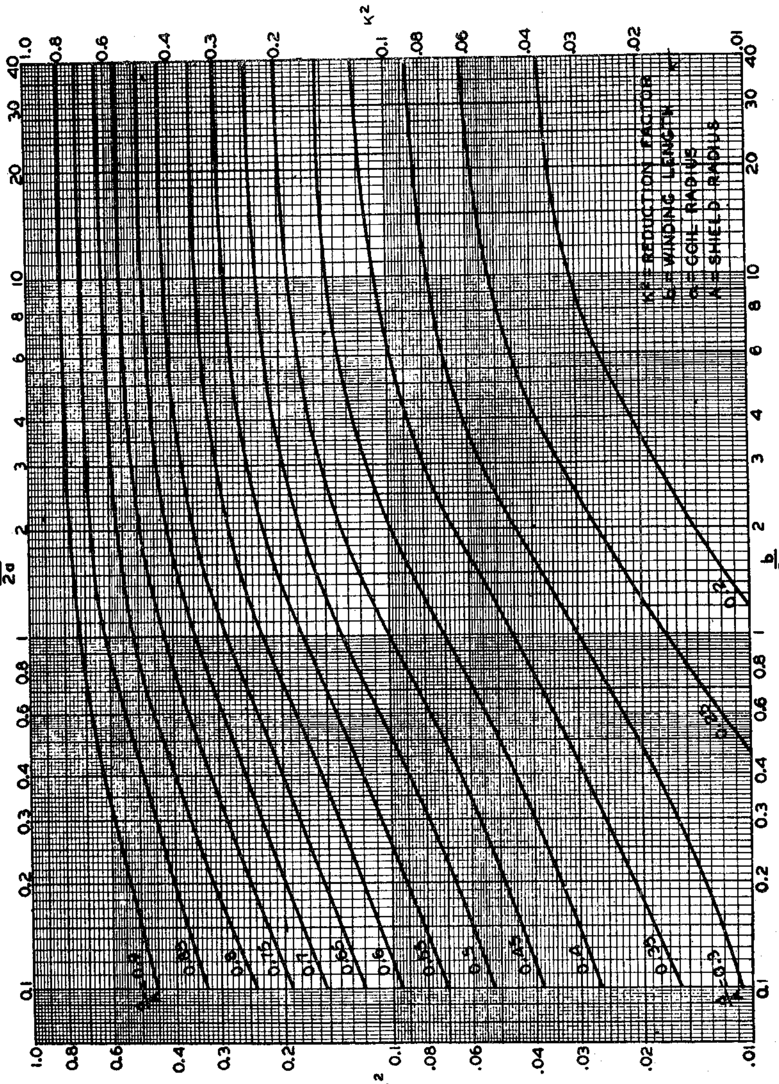


FIG. 10.6

Fig. 10.6. *Curves for determination of decrease in inductance produced by a coil shield (reprinted by kind permission of Radio Corporation of America).*

small values of l/g where Bogle's formula should not be used. In the tables below comparisons are made in a number of typical cases :

Table 1 : Comparison between estimates of the percentage reduction in inductance caused by a cylindrical screen for various coil shapes when the ratio of coil diameter to screen diameter = 0.7.

l/d	$(L_o - L_o')/L_o$ R.C.A.	$(L_o - L_o')/L_o$ Bogle	g/l
20	49%	48.2%	0.0107
10	48%	47.3%	0.0215
5	46%	46.0%	0.0430
1	35%	36.8%	0.215
0.2	20%	18.3%	1.075
0.1	15%	11.3%	2.15

where l = coil length, d = coil diameter, g = distance between coil and shield.

Table 2 : Comparison between estimates of the percentage reduction in inductance caused by a cylindrical screen for various ratios of coil diameter to screen diameter.

	$(L_o - L_o')/L_o$					
	$l/d = 10$		$l/d = 1$		$l/d = 0.2$	
a/b	R.C.A.	Bogle	R.C.A.	Bogle	R.C.A.	Bogle
0.9	80%	80.6%	72%	74.5%	54%	56.5%
0.7	48%	47.3%	35%	36.8%	20%	18.3%
0.5	23%	23.2%	13.6%	14.0%	6.7%	5.7%
0.3	7.8%	7.6%	3.0%	3.2%	1.4%	0.9%

where a = coil radius, b = shield radius.

SECTION 2 : MULTILAYER SOLENOIDS

(i) Formulae for current sheet inductance (ii) Correction for insulation thickness (iii) Approximate formulae (iv) Design of multilayer coils (v) Effect of a concentric screen.

(i) Formulae for current sheet inductance

(A) Long coils of a few layers

The Bureau of Standards Circular No. 74 gives a simple formula for the current sheet inductance, correct to 0.5% for long solenoids of a few layers ; it is

$$L_s = L_s' - \frac{0.0319N^2ac}{l}(0.693 + B_s), \tag{1}$$

where N = total number of turns,
c = radial depth of winding,
l = length of winding
B_s = a tabulated function of l/c
a = radius of coil to centre of winding,
and $L_s' = (0.100\,28a^2N^2/l)K$.

This result may be expressed in the form :

$$L_s = L_s'\left[1 - \frac{c(0.693 + B_s)}{\pi aK}\right] \tag{2}$$

The quantity $B_s = 0$ for $l/c = 1$; it rises to 0.279 for $l/c = 10$, and then increases very slowly, being 0.322 at $l/c = 30$.

(B) Short coils of rectangular cross-section

The solution of the problem for short coils is based on that for the ideal case of a circular coil of rectangular cross section. Such a coil would be closely realized by a winding of wire of rectangular cross section, arranged in several layers, with negligible insulating space between adjacent wires.

When the dimensions l and c are small in comparison with a (see Fig. 10.7) the inductance is given closely by **Stephan's formula,** which, for $l > c$, takes the form :

$$L_s = 0.031\,93aN^2\left[2.303\left(1 + \frac{l^2}{32a^2} + \frac{c^2}{96a^2}\right)\log_{10}\frac{8a}{g'} - y_1 + \frac{l^2y_2}{16a^2}\right] \quad (3)$$

while for $l < c$, that is for pan-cake coils, the formula becomes :

$$L_s = 0.031\,93aN^2\left[2.303\left(1 + \frac{l^2}{32a^2} + \frac{c^2}{96a^2}\right)\log_{10}\frac{8a}{g'} - y_1 + \frac{c^2y_3}{16a^2}\right] \quad (4)$$

where $g' = \sqrt{c^2 + l^2}$ and y_1, y_2 and y_3 are functions of c/l which are tabulated in the Bureau of Standards Circular No. 74 (p. 285).

The formulae of this section have been put in the form of a family of curves by Maynard (Ref. 38).

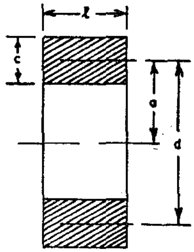


FIG. 10.7

(ii) Correction for insulation thickness

Unless the percentage of the cross section occupied by the insulation is large the formulae given in Sect. 2(i) apply very well to an actual coil. When the spacing P is appreciably greater than the diameter of the wire D a correction term should be added to L_s to give L_o. Thus :

$$L_o = L_s + 0.073\,35aN\,[\log_{10}(P/D) + 0.0675] \quad (5)$$

(iii) Approximate formulae

(A) Long coils of a few layers

For long coils of a few layers $l/c > 10$ and $B \approx 0.3$, so that we obtain from equation (1) ;

$$L_s \approx \frac{0.1003a^2N^2K}{l}\left[1 - \frac{c}{\pi aK}\right] \quad (6)$$

$$\approx \frac{a^2N^2}{9a + 10l}\left[1 - \frac{c}{10\pi al}(9a + 10l)\right]; \quad (7)$$

$$\text{or} \quad L_s \approx \frac{a^2N^2}{9a + 10l} - \frac{caN^2}{10\pi l} \quad (8)$$

(B) Short coils

For short coils such that both l and c are much less than a, it follows from Stephan's formula that :

$$L_s = 0.073\,35aN^2\left[\log_{10}\frac{8a}{\sqrt{l^2 + c^2}} - 0.4343y_1\right] \quad (9)$$

$$= \frac{aN^2}{13.5}\log_{10}\frac{3.6a}{\sqrt{l^2 + c^2}} \text{ when } \frac{l}{c} \text{ or } \frac{c}{l} \text{ lies between 0.35 and 1} \quad (10)$$

$$= \frac{aN^2}{13.5}\log_{10}\frac{4.02a}{\sqrt{l^2 + c^2}} \text{ when } \frac{l}{c} \text{ or } \frac{c}{l} \text{ lies between 0.15 and 0.35} \quad (11)$$

$$= \frac{aN^2}{13.5}\log_{10}\frac{4.55a}{\sqrt{l^2 + c^2}} \text{ when } \frac{l}{c} \text{ or } \frac{c}{l} \text{ lies between 0 and 0.15} \quad (12)$$

These results are accurate to 5% as l and c approach a, and are increasingly accurate as l and c decrease compared with a. When l/a and c/a are both **very** small, it is sufficient to use the approximation :

$$L_s \approx \frac{aN^2}{13.5}\log_{10}\frac{4}{\sqrt{l^2 + c^2}}$$

for all values of the ratio l/c.

(C) Bunet's formula

Bunet (Ref. 24) gives the following approximate formula applicable to coils whose diameters are less than three times their length :

$$L_s = \frac{a^2N^2}{9a + 10l + 8.4c + 3.2cl/a} \tag{13}$$

The range of usefulness of this formula can be best judged from its accuracy for various coil dimensions given below :

	Accuracy	
For $c/a = 1/20$	1% for $(2a/l)$ up to 3	4% for $(2a/l) = 5$
For $c/a = 1/5$	1% for $(2a/l)$ up to 5	2% for $(2a/l) = 10$
For $c/a = 1/2$	1% for $(2a/l)$ up to 2	3% for $(2a/l) = 5$
For $c/a = 1$	1% for $(2a/l)$ up to 1.5	5% for $(2a/l) = 5$

It is easy to verify that for long coils of a few layers Bunet's formula is approximately :

$$L_s \approx \frac{a^2N^2}{9a + 10l} - \frac{a^2N^2(3.2cl/a)}{(9a + 10l)^2} \tag{14}$$

$$\approx \frac{a^2N^2}{9a + 10l} - \frac{CaN^2}{10\pi l} \tag{15}$$

in accord with the result given previously for this type of coil.

(D) Wheeler's formula for short coils

Wheeler gives a formula for short coils having l and c less than a (Ref. 22). This result, which he states was obtained theoretically, is :

$$L_s = \frac{aN^2}{13.5}\log_{10}\frac{4.9a}{l + c} \tag{16}$$

The accuracy is given as 3% when $(l + c) = a$, and is stated to improve as $(l + c)/a$ decreases towards zero.

This formula is slightly different in form from those given in (B) of this section. Nevertheless, the numerical agreement is quite good, as can be seen from the following considerations :

For the case $l = c$,

$$\frac{3.6a}{\sqrt{l^2 + c^2}} = \frac{3.6a}{0.707(l + c)} = \frac{5.1a}{l + c};$$

when $l = 3c$ or $c = 3l$,

$$\frac{4.02a}{\sqrt{l^2 + c^2}} = \frac{4.02a}{0.792\,(l + c)} = \frac{5.1a}{l + c};$$

when $l = 10c$ or $c = 10l$,

$$\frac{4.55a}{\sqrt{l^2 + c^2}} = \frac{4.55a}{0.91\,(l + c)} = \frac{5.0a}{l + c}:$$

Thus when $\log 4.9/(l + c)$ is compared with the logarithms of these quantities the percentage difference is found to be small.

Another formula due to Wheeler (Ref. 22) which covers the shape of many universal windings, is

$$L_s = \frac{0.8a^2N^2}{6a + 9l + 10c}$$

accurate to within about 1% when the three terms in the denominator are about equal.

(iv) Design of multilayer coils

(A) Short coils

The Bureau of Standards Circular No. 74 gives two of the possible approaches to the design of short multilayer coils.

(1) The two forms of Stephan's equation given in eqns. (9) to (12) may be expressed as :

$$L_s = \frac{\lambda^{5/3}}{p^{2/3}}G, \tag{17}$$

where λ is the wire length, P is the distance between centres of adjacent wires and G is a function of the shape of cross section (l/c) and of the shape ratio of the coil (c/a). The quantity G is represented by means of curves. This equation is used, in cases where the ratios l/c and c/a have been decided, to determine the necessary wire-length for a given pitch, or vice versa. The mean radius of the winding is then obtained from

$$a = \sqrt[3]{\frac{\lambda}{2\pi}\frac{c}{l}\frac{P^2}{(c/a)^2}}; \quad (18)$$

and the total number of turns is given by $N = \lambda/2\pi a$ or lc/P^2.

It can be shown that, for a given resistance and coil shape, the square cross section $(l/c = 1)$ gives a greater inductance than any other form ; and, further, for a square cross section, the inductance for a given length of wire is a maximum for $c/a = 0.662$.

(2) Stephan's formulae may also be expressed in the form :

$$L_s = 0.031\,93 aN^2g, \quad (19)$$

where g is a known function of l/c and c/a.

This form is useful when a, c and l have been decided to give N, and thence P. We have

$$P = \frac{lc}{N}$$

and $\lambda = 2\pi aN$.

(B) Universal coils

The usual problem is the calculation of the inductance of a given number of turns before winding the coil, with only former size and wire size known. It is stated in Ref. 20 that the inductance of universal coils is about 10% greater than that of normal multilayer windings of the same external dimensions.

A suitable procedure is to determine the gear ratio from the formula,

$$\text{gear ratio} = \tfrac{1}{2}n(P + 1)/P \quad (20)$$

as described in Chapter 11, Sect. 3(iv). The radial depth of winding, c, can then be obtained from the formula

$$c = Nqw'/(P + 1) \quad (21)$$

where N = number of turns in coil,
q = number of crossovers per winding cycle
[Refer Table 1 in Chapter 11, Section 3(iv)]
w' = diameter of wire plus insulation,
and P = an integer defined in Chapter 11, Section 3(iv).

Since the length of the winding, l, is equal to the sum of the cam throw and the wire diameter, the dimensions of the coil are then known and the inductance can be calculated from the methods previously described.

Example : A coil of 500 turns of 38 A.W.G. enamelled wire (0.0044 inch) is to be wound on a 0.5 inch diameter former with a 0.1 inch cam. From Chapter 11 Sect. 3(iv), $P = 43$ and $q = 2$. Therefore

$c = 500 \times 2 \times 0.0044/44$ inch $= 0.1$ inch
$l = 0.1$ inch $+ 0.0044$ inch $= 0.1044$ inch
and $a = 0.25$ inch $+ c/2 = 0.3$ inch.

(v) Effect of a concentric screen

No formulae have apparently been given for the change in inductance produced by a concentric shield. It is clear that the percentage change in inductance of a multi-layer coil will be less than that of a single layer coil of equal outside dimensions ; and that the greater the winding depth c the less will be the effect of the shield. For solenoids of a few layers the percentage change in inductance will be very closely the same as for a single layer solenoid of corresponding dimensions.

SECTION 3 : TOROIDAL COILS

(i) Toroidal coil of circular section with single layer winding (ii) Toroidal coil of rectangular section with single layer winding (iii) Toroidal coil of rectangular section with multilayer winding.

(i) Toroidal coil of circular section with single layer winding

The current sheet inductance of a single layer coil wound on a torus, that is a ring of circular cross-section, is given by

$$L_s = 0.031\,93N^2\,[R - \sqrt{R^2 - a^2}] \text{ microhenrys,} \qquad (1)$$

where R is the distance in inches from the axis to the centre of cross-section of the winding, a is the radius of the turns of the winding and N is the total number of turns.

(ii) Toroidal coil of rectangular section with single layer winding

For this type of coil the current sheet inductance is readily shown to be :

$$L_s = 0.011\,70N^2h \log_{10}\frac{r_2}{r_1} \text{ microhenrys,} \qquad (2)$$

where r_1 is the inner radius of the winding, r_2 is the outer radius of the winding and h is the axial depth of the winding.

The difference between L_s and L_0 for single layer toroidal coils is usually small. Where high precision is required the value of L_0 may be obtained from L_s by using the corrections shown in Bulletin, Bureau of Standards, 8 (1912) p. 125.

(iii) Toroidal coil of rectangular section with multilayer winding

Dwight (Ref. 11) has obtained an expression for the current sheet inductance of this type of coil. His expression contains only simple terms, but it is too long to reproduce here. In an example quoted by the author the calculated and measured values of an inductance agreed within 1%.

Richter (E.E. Supplement. Dec. 1945, p. 999) stated that in practice fair results are obtained by use of the empirical formula :

$$L = 0.0117N^2h' \log_{10}(r_2'/r_1') \qquad (3)$$

where h', r_2' and r_1' are determined as follows :

Let t_1 be the thickness of winding on the inside face,
t_2 be the thickness of winding on the outside face,
t_3 be the thickness of winding on the inside edge of the top and bottom faces, and
t_4 be the thickness of winding on the outside edge of the top and bottom faces,

then

$$r_2' = r_2 + t_2/3\,;\; r_1' = r_1 - t_1/3\,;\; h' = h + (t_3 + t_4)/3\,;$$

h, r_1 and r_2 having the same meanings as in Section 3(ii).

SECTION 4 : FLAT SPIRALS

(i) Accurate formulae (ii) Approximate formulae.

(i) Accurate formulae

The current sheet inductance of flat spirals can be obtained from Stephan's formula for short multilayer coils [see Sect. 2(i)].

(a) Wire of rectangular cross section

For spirals wound with metal ribbon or with thicker rectangular wire the procedure is as follows :

Use Stephan's formula with these conventions :

for l put the width of the wire ;
for c put NP, where P is the distance between the centre of cross section of a turn and the corresponding point of the next turn ;

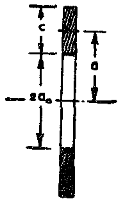
for a put $a_o + (N - l)P/2$, where $2a_o$ is the distance (Fig. 10.8) across the centre of the innermost end of the spiral.

The correction for cross section is given in the Bureau of Standards Circular No. 74 in the form :

$$L_0 = L_s - 0.0319aN(A_1 + B_1),$$

where A_1 and B_1 are tabulated functions. The accuracy obtained for L_0 is 1%.

FIG. 10.8



(b) Round wire

For spirals wound with round wire the same conventions are adopted to obtain a and c, but a simplified form of Stephan's equation, obtained by setting $l = 0$, is used. It is

$$L_s = 0.3193aN^2\left[2.303 \log_{10} \frac{8a}{c} - \tfrac{1}{2} + \frac{c^2}{96a^2}\left(2.303 \log_{10} \frac{8a}{c} + \frac{43}{12}\right)\right].$$

The inductance L_o of a spiral is given more closely by :

$$L_o = L_s - 0.0319aN(A + B),$$

where A and B are shown in Fig. 10.2.

(ii) Approximate formulae

For **round wires** it follows immediately that

$$L_s \approx 0.031\,93 \times 2.303aN^2\left[\log \frac{8a}{c} - \frac{0.5}{2.303}\right]$$

$$\approx \frac{aN^2}{13.5} \log \frac{4.9a}{c}.$$

Wheeler has given an approximate formula for spirals where $c > 0.2a$. It is :

$$L_s = \frac{a^2N^2}{8a + 11c}.$$

The first of these formulae is the more accurate as the ratio c/a decreases, while the second is the more accurate the closer c/a approaches unity. The agreement between them is quite fair :

For $c/a = 0.2$, we have from the first result,

$$L_s \approx (aN^2/13.5) \log 24.5 = 0.103aN^2,$$

while from Wheeler's formula

$$L_s \approx aN^2/(8 + 2.2) = 0.098aN^2.$$

For $c/a = 0.5$, we obtain, respectively,

$$L_s \approx (aN^2/13.5) \log 9.4 = 0.97aN^2/13.5 \text{ and}$$

$$L_s \approx aN^2/(8 + 5.5) = aN^2/13.5.$$

SECTION 5 : MUTUAL INDUCTANCE*

(i) Accurate methods (ii) Approximate methods.

(i) Accurate methods

Accurate methods for the calculation of mutual inductance between coils of many different shapes and relative dispositions are given in the Bureau of Standards Circular No. 74, and in the Bureau of Standards Scientific Paper No. 169. The book by Grover (Ref. 15) covers the subject comprehensively in Chapters 12, 15 and 20. The possible accuracy of these methods is always better than one part in one thousand.

The mutual inductance of coaxial single-layer coils, with tables to facilitate the calculation, is covered in Ref. 15 Chapter 15 (see also Ref. 5).

*By the Editor.

There are few simple formulae which can be used for the more common practical cases, such as are possible with self inductance. The following exact method may be used for two windings on the same former with a space between them, both windings being similar in pitch and wire diameter (Fig. 10.9).

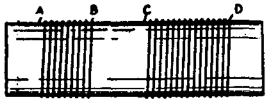


FIG. 10.9

Assume that the space between the windings is wound as a continuation of the windings on the two ends, to form a continuous inductor from A to D with tappings at points B and C. Then the required mutual inductance, M, between the two original windings is given by

$$M = \tfrac{1}{2}(L_{AD} + L_{BC} - L_{AC} - L_{BD}) \quad (1)$$

where L_{AD} is the inductance between points A and D, and similarly for other terms. These inductances may be calculated from the formulae given in earlier sections of this chapter.

References to accurate methods : Refs. 2, 3, 5, 13, 14, 15, 18.

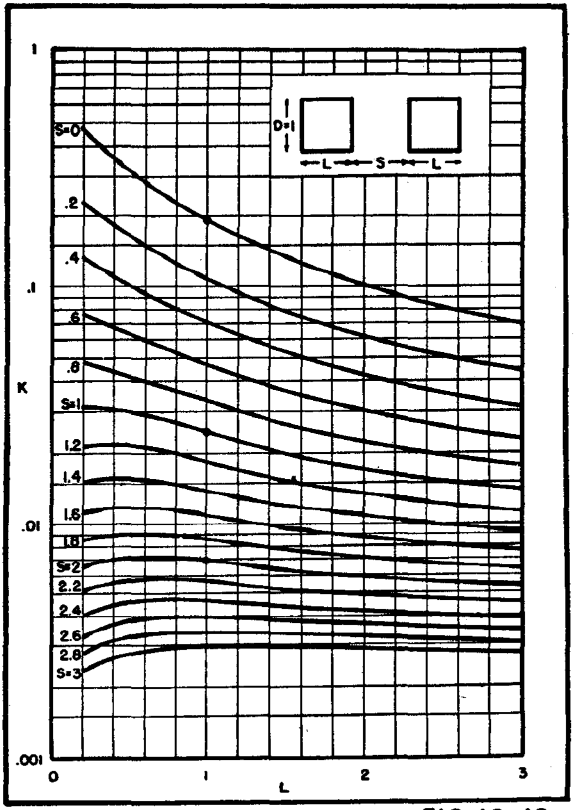


FIG. 10. 10

Fig. 10.10. *Chart giving coefficient of coupling for a specified spacing between two coaxial solenoids having identical dimensions. The quantities S and L are measured in terms of coil diameters. (Ref.* 56.)

(ii) Approximate methods

The coefficient of coupling for a specified spacing between two coaxial solenoids having identical dimensions, but not necessarily identical numbers of turns, is given by Fig. 10.10 (Ref. 56). The accuracy should be better than 5%.

SECTION 6 : LIST OF SYMBOLS

Note : Inductances are given in microhenrys and dimensions in inches.

L_s = current sheet inductance
L_o = low frequency inductance
L_o' = effective inductance of a shielded coil
N = total turns in coil
n = turns per unit length
l = coil length
P = pitch of winding $= 1/n$
a = coil radius (from axis to middle of winding)
$d = 2a$ = coil diameter
A' = cross sectional area of coil
D = (bare) wire diameter
$S = D/P$
λ = total length of wire
K = Nagaoka's constant—see Fig. 10.1
A, B = correction terms—see Fig. 10.2
$f = Kl/2a$—see Fig. 10.3
$F = 1.8/f$
$y = 1.8/l$
b = radius of concentric cylindrical screen
l_t = length of concentric cylindrical screen
$g = b - a$, i.e. coil to screen spacing
k = coefficient of coupling between coil and concentric can
c = radial depth of winding
$g' = \sqrt{l^2 + c^2}$
B_s = correction term, function of l/c
y_1, y_2, y_3 = functions of l/c in Stephan's formula
q = number of crossovers per winding cycle
R = mean radius of a toroidal coil of circular cross section
r_1 = inner radius of a toroidal coil of rectangular cross section
w' = diameter of wire plus insulation
r_2 = outer radius of a toroidal coil of rectangular cross section
h = axial depth of a toroidal coil of rectangular cross section
M = mutual inductance

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