RADIOTRON DESIGNER'S HANDBOOK (THIRD EDITION)
F LANGFORD SMITH SYDNEY, AUSTRALIA
1940

CHAPTER 16 (continued)

Part 3—Design of Low Loss Inductances

Division of coils for high frequency tuned circuits into three classes—papers dealing with the practical and theoretical design—Pollack's summary—Barden and Grimes' summary—Harris and Siemen's summary—Butterworth's conclusions—Austin's summary—dielectric losses—eddy currents—skin effect—current in coil concentrates at the minimum diameter—multistrand (litz) wires—solid round wires — insulating materials — screens — iron core materials — Bibliography.

Coils for high frequency tuned circuits may be divided into three main classes:—

(1) Coils for frequencies higher than 3 Mc/s., which are usually air cored solenoids employing solid round wire, with spaced turns above 10 Mc/s.

(2) Multilayer air cored coils of single or multistrand (Litz) type, usually arranged in two to four pies, unless the progressive method of winding is used. These are suitable for frequencies less than 3 Mc/s.

(3) Single and multilayer coils adapted specially for the use of high permeability iron core materials, also suitable for frequencies less than 3 Mc/s.

The subject as a whole is too large to be treated in detail here, and instead a summary with a representative bibliography is provided.

For short wave coils, the work by Pollack, Harris and Siemens, and Barden and Grimes is very complete from the practical design viewpoint. The papers by Butterworth, Palermo and Grover, and Terman are basically theoretical. Austin has provided an excellent summary and practical interpretation of Butterworth's four papers.

Pollack summarises the procedure for the optimum design of coils for frequencies from 4 to 25 Mc/s. as follows :—

1. Coil diameter and length of winding: Make as large as is consistent with the shield being used. The shield diameter should be twice the coil diameter, and the ends of the coil should not come within one diameter of the ends of the shield.

2. A bakelite coil form with a shallow groove for the wire, and enamelled wire may be used with little loss in Q. The groove should not be any deeper than is necessary to give the requisite rigidity. The use of special coil form constructions and special materials* does not appear to be justified.

---

*Except for the reduction of frequency drift due to temperature changes.—Ed.

3. Number of turns: Calculate from

$$N = \sqrt{L\ (102S + 45)/D}$$

where S = ratio of length to diameter of coil,
D = diameter of coil in centimetres,
and L = inductance in microhenries.

(See Chapter 16, Part 2, for alternative formulae using inch units for turns calculation).

4. Wire size: Calculate from

$$d_o = b/\sqrt{2}\ N,$$

$$= \text{optimum diameter in cms.}$$

where b = winding length in cms.
That is, the optimum wire diameter is $1/\sqrt{2}$ times the winding pitch, measured from centre to centre of adjacent turns.

Barden and Grimes recommend for coils working near 15 Mc/s. that No. 14 or No. 16 g., B & S., enamelled wire on a form not less than one inch diameter at a winding pitch equal to twice the wire diameter is desirable. The screen diameter should be not less than twice the coil diameter. A comparison of coils of equal inductance on 0.5" and 1" forms in screens double the coil diameter indicates that the value of Q is twice as great for the larger diameter coil. No. 24 g. B.&S. wire was used for the small diameter coil.

Harris and Siemens quote the following conclusions:—

(1) Q increases with coil diameter.

(2) Q increases with coil length, rapidly when the ratio of length to diameter is small, and very slowly when the length is equal to or greater than the diameter.

(3) Optimum ratio of wire diameter to pitch is approximately 0.6 for any coil shape. Variation of Q with wire diameter is small in the vicinity of the optimum ratio; hence, selection of the nearest standard gauge is satisfactory for practical purposes.

Butterworth's paper deals with the copper loss resistance only, and insulation losses must be taken into account separately. Insulation losses are minimised by winding coils on low loss forms, using a form or shape factor which provides the smallest possible self capacity with the highest power factor. Thus air is the best separating medium for the individual turns, and the form should provide only the very minimum mechanical support. Multilayer windings in one pie have high self capacity due to proximity of the high and low potential ends of the winding. The same inductance obtained by several pies close together in series greatly reduces the self capacity and associated insulation losses. Heavy coatings of poor quality wax of high dielectric constant may introduce considerable losses.

The shape of a coil necessary for minimum copper loss (from Butterworth's paper) is stated by **Austin** as follows:—

(1) **Single layer solenoids:** Winding length equal to one-third of the diameter.

(2) **Single layer discs (pancake):** Winding depth equal to one-quarter of the external diameter.

(3) **Multilayer coils:** There is a wide range of choice, any of which is nearly equally efficient. The limits are fixed roughly by the rule that five times winding depth plus three times winding length should be equal to the external diameter.

1537

Dielectric losses present in the self capacity of the coil are reduced by altering the shape to separate the high potential end from all low potential parts of the circuit. These losses become relatively more important the higher the frequency. Thus, the shape of a solenoid for minimum total losses may need to be increased beyond one-third of the diameter to half or two-thirds.

The high frequency alternating field of a coil produces eddy currents in the metal of the wire, which are superimposed upon the desired flow of current. The first effect is for the current to concentrate at the outside surface of the conductor, leaving the interior relatively idle. This phenomenon is designated **"skin effect,"** and is the only effect in straight wires clear of neighbouring conductors. In a coil, where there are numbers of adjacent turns carrying current, each has a further influence upon its neighbour.

In turns near the centre of a solenoid **the current concentrates on the surface of each turn where it is in contact with the form, i.e., at the minimum diameter.** In turns at either end of a solenoid the maximum current density occurs still near the minimum diameter of the conductor, but is displaced away from the centre of the coil.

Thus most of the conductor is going to waste. **Multistrand or litz (litzendraht) wires** have been developed to meet this difficulty. A number of strands (5, 7, 9, 15 being common) is woven together, each being of small cross section and completely insulated by enamel and silk covering from its neighbours. Due to the weaving of the strands, each wire carries a nearly similar share of the total current, which is now forced to flow through a larger effective cross section of copper. The former tendency towards concentration at one side of a solid conductor is greatly overcome, and the copper losses are correspondingly reduced.

Litz wire is most effective at frequencies between one-third and three megacycles per second. Outside of this range comparable results are usually possible **with round wire of solid section**, because at low frequencies "skin effect" steadily disappears while at high frequencies it is large even in the fine strands forming the litz wire, and is augmented by the use of strands having increased diameter.

The insulating materials covering the wire and composing the form on which a coil is wound should be treated to reduce moisture content as far as possible. Baking for a period of about one hour at a little higher temperature than the boiling point of water, followed by impregnation with moisture resisting wax or varnish, is an important procedure that should not be neglected if permanence of high quality performance be desired. Multilayer coils are particularly susceptible to atmospheric humidity unless carefully impregnated. The presence of moisture within the insulating material allows ionisation of soluble impurities, and perhaps of the material itself. Electrolytic conduction between turns and strands is then possible, with consequent increase in insulation losses.

Screens placed around coils of all types at radio frequencies should be of non-magnetic good conducting material to introduce the least losses. In other words, the Q of the screen considered as a single turn coil should be as high as possible. In addition, the coupling to the coil inside it should be low to minimise the screen losses reflected into the tuned circuit. For this reason the screen diameter should if possible be at least double the outside diameter of the coil. A ratio smaller than 1.6 to 1 causes a large increase of losses due to the presence of the screen.

The design of coils for use with **iron core materials** depends mainly upon the type of core material and the shape of the magnetic circuit proposed. Nearly closed core systems are sometimes used with high permeability low loss material. More commonly, however, the core is in the form of a small cylindrical plug which may be moved by screw action along the axis of the coil and fills the space within the inside diameter of the form. The main function of the core in the latter case may be only to provide a means of tuning the circuit rather than of improving its Q. When improvement in Q is possible with a suitable material, the maximum benefit is obtained by insuring that the largest possible percentage of the total magnetic flux links with the core over as much of its path as possible; the ultimate limit in this direction is of course the closed core. The compromise between cost and quality of performance usually results in a coil of three or four pies of small winding depth, or a progressive winding between one and two diameters long, traversed by a cylindrical plug of magnetic material. The wall thickness of the form should be as small as is consistent with mechanical strength; between 0.010" and 0.020" is usual for 0.25" to 0.375" diameter forms.

For further detailed information it is suggested that reference should be made to the papers listed in the latter part of the following bibliography.

Bibliography

D. Pollack, "The Design of Inductances for Frequencies between 4 and 25 Megacycles," R.C.A. Review, Vol. II, No. 2, p. 184, October, 1937, and Electrical Engineering, September, 1937.

W. A. Harris and R. H. Siemens, "Superheterodyne Oscillator Design Considerations," R.C.A. Radiotron Division Publication No. ST-41, November, 1935.

W. S. Barden and D. Grimes, "Coil Design for Short Wave Receivers," Electronics, p. 174, June, 1934.

F. H. Scheer, "Notes on Intermediate-Frequency Transformer Design," Proc. I.R.E., Vol. 23, No. 12, p. 1483, December, 1935.

A. L. M. Sowerby, "The Modern Screened Coil," Wireless World, September 23, 30, and October 7, 14, 1931.

S. Butterworth, "The Effective Resistance of Inductance Coils at Radio Frequency," Wireless Engineer, Vol. III, Nos. 31, 32, 34, 35, pp. 203, 309, 417, 483, April, May, July, August, 1926.

B. B. Austin, "The Effective Resistance of Inductance Coils at Radio Frequency" (abstract of paper by S. Butterworth, 1926), Wireless Engineer, Vol. XI, No. 124, p. 12, January, 1934.

E. B. Moullin, "Radio Frequency Measurements," p. 341, 1931 ed., Charles Griffin and Co., Ltd., London.

A. J. Palermo and F. W. Grover, "A Study of the High-Frequency Resistance of Single Layer Coils," Proc. I.R.E., Vol. 18, No. 12, p. 2041 December, 1930, and supplementary note Vol. 19, No. 7, p. 1278, July, 1931.

Bureau of Standards Circular No. 74, p. 304, 1924.

F. E. Terman, "Some Possibilities for Low Loss Coils," Proc. I.R.E., Vol. 23, No. 9, p. 1069, September, 1935.

G. Reber, "Optimum Design of Toroidal Inductances," Proc. I.R.E., Vol. 23, No. 9, p. 1056, September, 1935.

D. R. Parsons, "Winding Short Wave Coils," Wireless World, Vol. XLIV, No. 22, p. 507, June 1, 1939 (erratum, p. 555, June 15, 1939).

W. J. Polydoroff, "Ferro Inductors and Permeability Tuning," Proc. I.R.E., Vol. 21, No. 5, p. 690, May, 1933.

A. Schneider, "Iron-Content Cores for High-Frequency Coils," Wireless Engineer, Vol. X, No. 115, p. 183, April, 1933.

G. W. O. Howe, editorials, Wireless Engineer, Vol. X, Nos. 112, 117, 120, pp. 1, 293, 467, January, June, September, 1933.

ticular pitch used, and multiply the previously determined value of inductance by this factor.

1(b). Solenoids Inside Concentric Cylindrical Screens.

The formulae given in the preceding section for the "current sheet" inductance L and actual low frequency inductance L_o should be multiplied by a factor K_s depending upon the relative dimensions of the coil and the screen. Calling L_s the value of low frequency inductance in the presence of the screen,

$$L_s = K_s L_o = (1 - k^2)\ L_o,$$

where k = coupling factor between the coil and the screen.

Curves have been published (R.C.A. Radiotron Division Application Note No. 48, June 12th, 1935, reprinted in Radio Engineering, p. 11, July, 1935) for k^2 in terms of the ratio of coil to shield radius and of coil length to diameter. It is stated that the values of k have been calculated and verified experimentally. The screen has no ends, and should exceed the length of the coil by at least the radius of the coil.

The following approximate formula for K_s has been derived from these curves:

$$K_s = 1 - \frac{1.55}{1 + 0.45\ (d/l)} \cdot (d/d_s)^3,$$

where $\dfrac{1}{1 + 0.45\ (d/l)} = K$, Nagaoka's constant,

and d_s = diameter of screen.

The accuracy of the values of K_s is 2% from d/l = 0.5 to d/l = 5.0, at any value of d/d_s up to 0.6. The accuracy is 5% from d/l = 0.2, to d/l = 5.0, at all values of d/d_s up to 0.7.

2. Multilayer Circular Coils of Rectangular Cross Section.

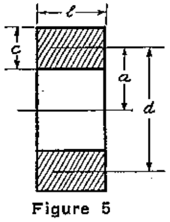

Figure 5

The Bureau of Standards Circular No. 74 provides formulae and tables capable of one part in one thousand accuracy for a very wide range of coil shapes.

This data has been put in the form of families of curves by J. E. Maynard ("Multilayer Coil Inductance Chart," Electronics, p. 33, January, 1939).

Bunet (Revue Generale de l'Electricite,, Tome XLIII, No. 4, p. 99, Jan. 22nd, 1938) gives the following approximate formula, which has been converted to inch and microhenry units:

$$L = 0.0251\ .\ (d^2N^2/l)\ .\ \frac{1}{1 + 0.45\ (d/l) + 0.64\ (c/d) + 0.84\ (c/l)}$$

$$\text{or } L = \frac{a^2N^2}{9a + 10\,l + 8.4c + 3.2\ (cl/a)} \text{ microhenries}$$

where a, d, l and c have the significance indicated in Fig. 5. When the winding depth c is very small, Bunet's formula reduces to Wheeler's formula for solenoids. The accuracy is

1% for c/a zero to 1/20 and 2a/l zero to 3.0; −4% at 2a/l = 5.0
1% for c/a = 1/5 and 2a/l zero to 5.0; −1.9% at 2a/l = 10.0.
1% for c/a = 1/2 and 2a/l zero to 2.0; +2.8% at 2a/l = 5.0
1% for c/a = 1 and 2a/l zero to 1.5; +4.7% at 2a/l = 5.0

As in the case of "current sheet" formulae for solenoids, a correction is required when the percentage of the cross section of the winding occupied by insulating space is large. The correction is

$$L_o = L\left(1 + \frac{l}{\pi aNK}\ (2.3 \log_{10} \frac{P}{D} + 0.155)\right)$$

$$\text{where } K = \frac{1}{1 + 0.9\ (a/l) + 0.32\ (c/a) + 0.84\ (c/l)}$$

p = winding pitch, centre to centre of wires, and
D = wire diameter.

In most practical cases this correction is less than 1%.

The effect upon the inductance of a multilayer coil of a concentric cylindrical shield will be less than that for a solenoid of equal outside dimensions. At very small winding depths the correction will be almost exactly the same as for solenoids.

Wheeler gives a formula for multilayer coils of very small winding space (Proc. I.R.E., Vol. 17, p. 582, March, 1929).

I FIND THIS
IS EASY AND →
ACCURATE FOR
LOOP ANTENNAS

$$L = \frac{a\ N^2}{13.5} \log_{10}\left(\frac{4.9a}{l + c}\right) \text{ microhenries,}$$

accurate to 3% when (l + c) is not larger than a, and all dimensions in inches. The accuracy is claimed to be good as (l + c) decreases indefinitely. Bunet's formula becomes inaccurate when l is much less than a. Thus each formula has its own special range of application, and the two ranges overlap when the winding length l is about equal to the mean radius a.

3. Single Layer Spiral.

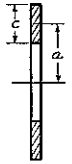

Fig. 6

An accurate method of calculating the inductance of flat spirals is given in the Bureau of Standards Circular No. 74.

Wheeler gives an approximate formula (Proc. I.R.E., Vol. 16, p. 1398, October, 1938),

$$L = \frac{a^2\ N^2}{8a + 11c} \text{ microhenries,}$$

accurate to 5% when c is larger than 0.2 a. The significance of a and c is indicated in Fig. 6.

4. Mutual Inductance.

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. The case of two coaxial single layer