the Cornell-Dubilier Capacitor

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INDUCTANCE DATA FOR EXPERIMENTERS

Inductance is one of the three basic properties of conventional electronic circuits. Without it we would be hard put, at frequencies lower than microwaves, to tune our transmitters, receivers, and test instruments and to transfer electrical energy at one level to higher levels, all conveniently and effectively in the manner that we now do.

The experimenter and beginning technician soon acquire an appreciation of the functioning of radio coils. As they construct more equipment of their own, they quickly require as much practical information as possible regarding inductance. The existence of several types of "slide rules" and alignment charts for the quick determination of coil dimensions and inductance has not removed the need to know the basis upon which these devices are constructed. When the facts are understood, the technician is not inconvenienced when the "calculator" is lost, mislaid, or otherwise not available.

The purpose of this article is to present basic inductance data in its simplest form for the benefit of the student who is encountering these facts for the first time and for the other readers who may care to refresh their knowledge.

We believe that the coils selected for presentation are the particular types that the experimenter will be apt to construct. There are, of course, many more which are not practical to build in the small shop and which can be purchased more economically.

Single-Layer Solenoids

The most universally-used radio coil is the single-layer air-core solenoid. In this type, a single layer of wire is wound on a cylindrical form. Often, in order to reduce losses at high frequencies, the form is eliminated entirely and the cylindrical coil made self-supporting **(air-wound).** But whether air-wound or form-supported, the coil still is classified as a solenoid.

The inductance of a single-layer solenoid may be determined by means of the formula:

$$(1) \quad L = \frac{0.2\ d^2\ N^2}{3d + 9\ell}$$

Where L is the inductance in microhenries,
d the diameter of the coil (inches),
ℓ the length of the coil (inches), and
N the number of turns

Figure 1 shows the dimensions of this type of coil. The length of the coil is the length of the actual winding, not of the entire supporting form. The diameter, likewise, is the diameter of the winding (measured from the radius of the wire). However, this will be the same as the form diameter (with negligible error) unless the wire is very thick.

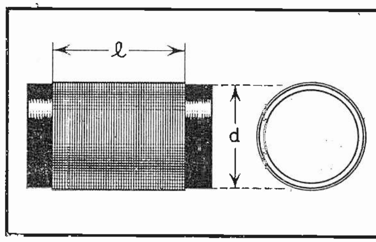


Fig. 1. Dimensions of single-layer solenoid.

Illustrative Example: A coil consists of 37 turns of No. 22 enamelled wire on a 2½-inch-diameter form. The length of the winding is found by measurement to be 1 inch. What is the inductance in microhenries?

$$L = \frac{0.2\ (2.5)^2\ 37^2}{3(2.5) + 9(1)} = \frac{0.2(6.25)1369}{7.5 + 9} = \frac{1711.25}{16.5} = 103.7 \text{ uh.}$$

From the formula and the example; note that for a given coil length and diameter, the inductance varies directly as the square of the number of turns. Also note that for a given number of turns and coil diameter, the inductance varies inversely as the length.

Formula (1) may be solved for the number of turns when the diameter and length of the coil have been chosen:

$$(2) \quad N = \sqrt{\frac{3d + 9\ell}{0.2d^2} L}$$

Where N is the required number of turns,
d the coil diameter (inches),
ℓ the coil length (inches), and
L the required inductance (microhenries)

Illustrative Example: How many turns will be required for a 50-microhenry coil having a diameter of 1 inch and a length of 1 inch?

$$N = \sqrt{\frac{3(1) + 9(1)}{0.2(1)^2} 50} = \sqrt{\frac{3 + 9(50)}{0.2}} = \sqrt{\frac{600}{0.2}} = \sqrt{3000} = 55 \text{ turns}$$

A coil is *closewound* when its turns are laid tightly side by side and are separated only by the insulation of the wire. It is *space-wound* when each turn is separated from the other by a discrete distance. In a given coil length, closewinding gives the maximum number of turns for a given size of wire. Closewinding also results in the highest **distributed capacitance** (capacitance due to capacitor effect between adjacent turns) because of the close spacing of turns. Since efficient r. f. coils must have low distributed capacitance, space-winding is preferred to closewinding.

A desirable configuration for a single-layer solenoid is obtained by making the coil length and diameter equal. This "block" shape should be effected whenever possible.

Multilayer Solenoid

The single-layer, air-core solenoid becomes ungainly in size and often impossible to achieve with a good length/diameter ratio, when large inductance values (many turns) are required. More compact construction is secured by winding the turns in several layers, one layer upon the other. This is the arrangement of the layer-wound coil or multilayer solenoid (See Figure 2). Such coils often are wound on bobbins, spools, and similar supporting forms which can hold the various layers in place.

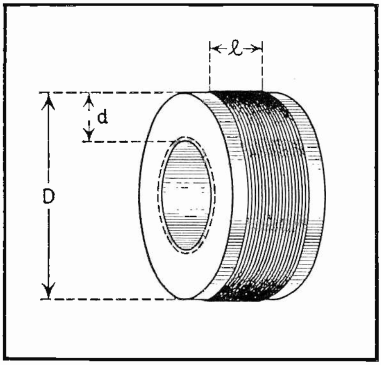


Fig. 2. Dimensions of multilayer solenoid.

The inductance of a multilayer solenoid may be determined by means of the formula:

$$(3) \quad L = \frac{0.2\ d^2\ N^2}{3d + 9\ell + 10D}$$

Where L is the inductance in microhenries,
d the diameter of the coil (inches),
ℓ the length of the coil (inches), and
D the radial depth of the coil (inches).

As in the case of the single-layer solenoid, the coil diameter is measured across the coil from the turn radii. However, when the form is wound full, this diameter will be the same as the diameter of the form itself as shown by the dimension D in Figure 2. Dimension d is the actual depth of the winding ("thickness" of the coil) and is measured from the radius of the outside turn to the radius of the inside turn (the latter is shown by the dotted ring around the hole of the form in Figure 2).

Illustrative Example: A 1½-inch-diameter bobbin is wound full with 150 turns of wire. The coil length is ½ inch. The bobbin wall around the ⅛-inch-diameter central hole is $\frac{1}{16}''$ thick. The winding depth therefore is 0.625 inch (⅝"). What is the inductance?

$$L = \frac{0.2(1.5)^2\ 150^2}{3(1.5) + 9(0.5) + 10(0.625)} =$$

$$\frac{0.45(22{,}500)}{4.5 + 4.5 + 6.25} = \frac{10{,}125}{15.25} = 664 \text{ uh.}$$

When each layer of a multilayer solenoid is closewound, the result is a neat-appearing coil resembling a spool of thread. But the internal capacitance of such a winding is very high. In addition to the usual capacitance between adjacent turns in each layer, there also is capacitance between layers. This adds up to a troublesome total which reduces efficiency. The criss-cross winding methods (lattice-winding, universal winding, and duo-lateral honeycombing) were developed to reduce this capacitance by separating as nearly as possible all turns between which large capacitances ordinarily would exist. Special machines are needed to do this kind of winding, but substantial capacitance reduction can be achieved by the experimenter by deliberately avoiding neat winding. By allowing the turns to fall where they may, the familiar "jumble-wound" coil is produced.

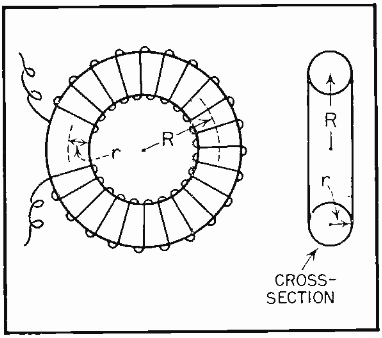


Fig. 3. Dimensions of toroid of round cross section.

Toroidal Coils

The enclosed field of the toroidal (doughnut) coil recommends this type of winding for a number of exacting radio-frequency applications. While the **single-layer** torus is not as common as it was in the early days of radio, it appears probable that experimenters will in the near future become increasingly interested in the merits of this type of coil which can be made easily. A single-layer torus of circular cross section is illustrated in Figure 3. The dimensions of interest are the axial radius (R), the turns radius (r), and the number of turns (N). The inductance of this coil may be determined by means of the formula:

$$(4)\quad L = 0.00495\ N^2\left[R - \sqrt{R^2 - r^2}\right]$$

Where L is the inductance in microhenries,
N the number of turns,
R the axial radius (inches), and
r the turns radius (inches).

Illustrative Example: What is the inductance of a toroid coil of circular cross section having an axial radius of 2½ inches, a turns radius of ½ inch, and 230 turns?

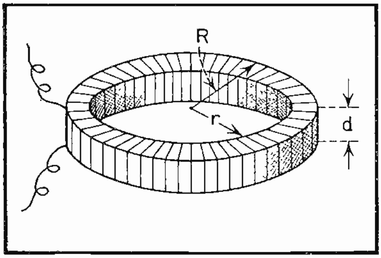


Fig. 4. Dimensions of toroid of rectangular cross section.

$L = 0.00495(230)^2 \times$
$\left[2.5 - \sqrt{2.5^2 - 0.5^2}\right] =$
$0.00495\ (52{,}900) \times$
$\left[2.5 - \sqrt{6.25 - 0.25}\right] =$
$261.8(2.5 - \sqrt{6}) =$
$261.8(2.5 - 2.45) =$
$261.8(0.05) = 13.09$ uh.

Figure 4 shows a single-layer toroidal coil having rectangular cross section. An advantage of using a rectangular form for winding a toroid is the greater ease with which the turns may be pulled and held tightly in place during the process of hand winding. The important dimensions of this coil are the outer radius (R), inner radius (r), depth (d), and number of turns (N). The inductance of the rectangular toroid may be determined by means of the formula:

$$(5) \quad L = 0.00461\ N^2 d \log_{10} \frac{R}{r}$$

Where L is the inductance in microhenries,
N the number of turns,
R the outer radius (inches), and
r the inner radius (inches).

Illustrative Example: Calculate the inductance of a single-layer toroid of rectangular cross section having an outer radius of 3 inches, inner radius of 2¼ inches, depth of ¾ inch, and 500 turns.

$L = 0.00461(500)^2 0.75 \log_{10} \frac{3}{2.25} =$
$0.00461(250{,}000)0.75 \log_{10} 1.335 =$
$1152.5(0.75)0.125841 =$
$1152.5(0.0944) = 108.8$ uh.

Core and Shield Effects

The presence of dielectrics (cores or winding forms) in the field of radio-frequency coils introduces losses which are in-phase in nature and therefore appear as resistance. The effect of resistance is to lower the coil Q. For this reason, air-wound coils are superior to those wound on solid forms. Where the use of a form is unavoidable, a low-loss material, such as Polystyrene or ceramic is used.

Cores of magnetic metals (solid iron, high-permeability alloys, etc.) are not suitable for use in coils at high radio frequencies, although their increased permeability over air increases coil inductance tremendously at low frequencies. At radio frequencies, somewhat comparable inductance multiplication is afforded by cores of powdered iron, the particles of which are separately insulated. Modern **ferrites** (magnetic ceramics) are superior to powdered iron and provide material for cores which are efficient at very high frequencies.

Cores of non-magnetic metals (copper, brass, etc.) are subject to eddy current losses and by this mechanism reduce the inductance of any coils into which they are inserted. Because they are "losser" devices, these cores reduce the coil Q at the same time. Nevertheless, such cores in the form of movable slugs often are used for tuning coils in applications where the Q reduction can be tolerated.

Coils may be tuned with movable slugs either of magnetic or non-magnetic metal and are available commercially in both types. The amount of inductance variation provided depends upon the nature and constitution of the slug material and upon its dimensions.

The purpose of shields is to confine the magnetic field to the immediate vicinity of the coil and thereby to prevent interference with and coupling into other portions of the circuit in which the coil operates, or into adjacent circuits. Since such shields are constructed of metal, their presence in the coil environment will tend to reduce the inductance and Q as a result of eddy current losses in the shield. For this reason, it is necessary to keep the walls of the shield as far as possible from the coil. This means that the best shields are large in comparison to the coils they house. A good practical rule is to make any shield of such size that its inside diameter is at least twice the outside diameter of the coil, and its height above the coil (and, if possible, below as well) is at least equal to the coil diameter. These are **minimum** dimensions. If the shielded coil stands too close to the shield walls, the coil efficiency will be reduced markedly. If the shield can be made larger than the minimum dimensions given, it will have less adverse effect upon the coil characteristics.

In order for a shield to be effective, its walls must be thick. Skimpy shields made of very thin sheet metal are hardly worth the time required to build them. A good shield also is closed on all sides. A shield full of holes and gaps is analogous to a sieve.

The foregoing discussion regarding reduction of inductance and Q by losses in metallic cores and shields applies also to any other such metallic object within the field of a coil. For example, operating a coil too close to a chassis, baffle plate, transformer, metal cabinet wall, or any other metal mass has a similar detrimental effect. Coils should be either mounted in the clear or well shielded for best results.

Inductance Measurements

Maxwell Bridge. The Maxwell bridge is very handy for inductance measurement. Its chief merit is that it requires no standard inductor for comparison. Instead, the unknown inductance is checked against a standard capacitor. An accurately-known capacitor is more readily available to the experimenter than is a standard inductor. The Maxwell bridge may be assembled easily from laboratory or shop parts.

Figure 5 shows the Maxwell bridge circuit. L is the unknown coil, R_1 a ratio-arm resistor (several values such as 1, 10, 100, 1000, and 10,000 ohms must be available), R_2 a resistance-calibrated 10,000-ohm potentiometer, R_3 a resistance-calibrated 100,000-ohm potentiometer, and C a standard capacitor (several values, such as 0.001, 0.01, and 0.1 ufd. should be available).

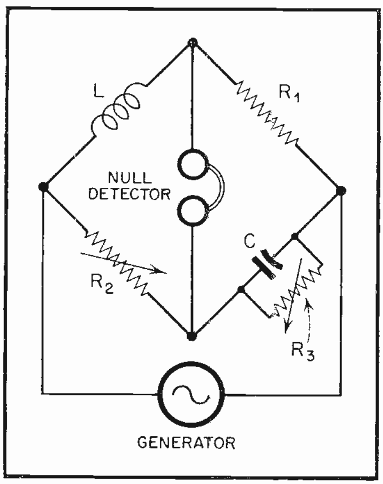


Fig. 5. Circuit of Maxwell bridge.

The generator preferably is a transformer-coupled 1000-cycle audio oscillator. The null detector may be headphones, a. c. vacuum-tube voltmeter, or oscilloscope.

The bridge is balanced for null by adjustment of potentiometer R_2. Potentiometer R_3 then is adjusted for improvement of the null. The operator works back and forth between the two potentiometers until exact null results. At complete null, the inductance (L) and equivalent series resistance (R) of the coil may be determined from the formulas:

(6) $L = R_1R_2C$

Where L is the inductance in henries, R_1 and R_2 the potentiometer settings (ohms), and C the standard capacitance (farads).

(7) $R = \frac{R_2}{R_3}R_1$ All in ohms

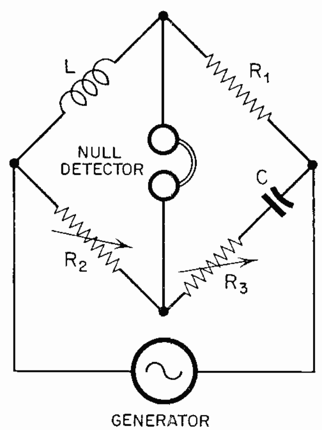
Illustrative Example: In a Maxwell bridge with a ratio resistor (R_1) of 1000 ohms and a standard capacitor (C) of 0.01 ufd. (0.00000001 farad), null is obtained at the 5000-ohm setting of potentiometer R_2 and at the 5000-ohm setting of potentiometer R_3. What are (1) the inductance of the test coil, and (2) the equivalent series resistance of the coil?

$L = 1000(5000)0.00000001 =$ 0.05 henry (50 mh.)

$R = \frac{5000}{5000}1000 =$ $1(1000) = 1000$ ohms.

Hay Bridge. The Hay bridge is particularly useful for checking high-inductance, low-Q coils. Like the Maxwell bridge, this circuit can be assembled from laboratory or shop parts. Figure 6 shows the circuit of the Hay bridge and gives the balance equations for inductance and equivalent series resistance. Note that, unlike the Maxwell bridge equations, a frequency term appears in the Hay bridge formulae.

Resonance Methods. Tuned-circuit methods are handy to the experimenter and service technician for measuring inductance at radio frequencies. The unknown coil is tuned to resonance with an accurately-known mica capacitor. The inductance then is



$$L = \frac{R_1 R_2 C}{1 + R_3^2 (6.28f)^2 C^2} \text{ henries}$$

$$R = \frac{R_1 R_2 R_3 (6.28f)^2 C^2}{1 + R_3^2 (6.28f)^2 C^2} \text{ ohms}$$

In both equations, R is in ohms, C in farads, and f in cycles.

Fig. 6. Circuit of Hay bridge.

calculated from the capacitance and frequency values. Two schemes are illustrated in Figure 7.

In Figure 7(A), the coil is connected in series with the known capacitor and coupled to a variable-frequency r. f. oscillator. An a. c. vacuum-tube voltmeter is connected **by short leads** across the capacitor. The oscillator is tuned through its range, starting at its lowest frequency and tuning upward, until the resonant point is located, as shown by peak deflection of the meter. At exact

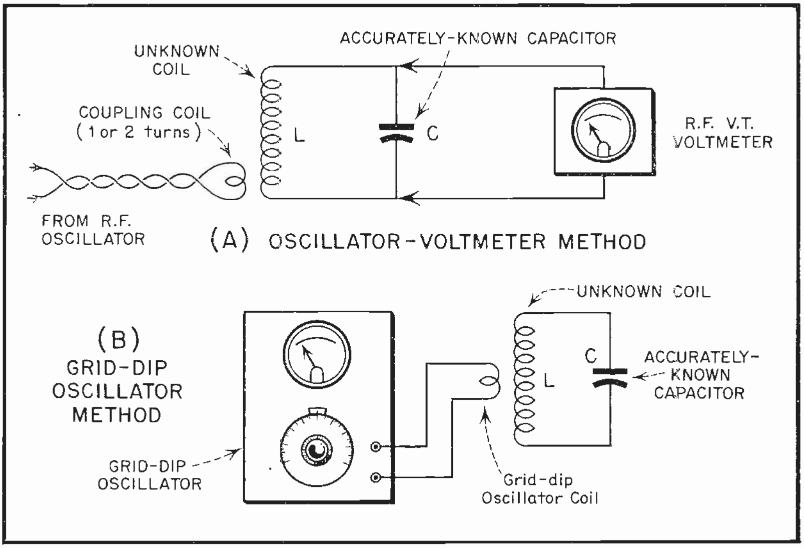


Fig. 7. Resonance methods of checking inductance.

resonance, the frequency is read from the oscillator, and the inductance calculated by means of the following formula:

$$(8) \quad L = \frac{25,400}{f^2C}$$

Where L is the inductance in microhenries,
f the resonant frequency (megacycles), and
C the capacitance (uufds.)

Illustrative Example: An unknown coil resonates with a 100-micromicrofarad capacitor at 2.5 Mc. What is its inductance?

$$L = \frac{25,400}{2.5^2(100)} = \frac{25,400}{6.25(100)} = \frac{25,400}{625} =$$
40.6 uh.

Figure 7(B) shows how a grid-dip oscillator may be used for inductance measurement by the resonance method. The unknown coil (L) is connected in series with an accurately-known capacitor (C). The grid-dip oscillator is loosely coupled to the coil and tuned through its ranges, **starting at its lowest frequency and tuning upward.** At exact resonance, as indicated by a sharp dip of the meter, the frequency (f) is read from the oscillator dial. The unknown inductance then is calculated by means of Formula (8).

Illustrative Example: An unknown coil is connected to a 250-uufd. capacitor. A grid-dip oscillator is loosely coupled to the coil. Exact resonance is obtained when the oscillator is tuned to 1500 kc. (1.5 Mc.). What is the inductance of the coil under test?

$$L = \frac{25,400}{1.5^2(250)} = \frac{25,400}{2.25(250)} = \frac{25,400}{337.5} =$$
75.4 uh.

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