Optimum Wire Size for RF Coils

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There are applications for inductors in electronic circuitry where the inductor Q is of little or no importance. In many other applications, the Q is secondary only to the value of the inductance. Among these are tank circuit coils, impedance matching circuit coils, and virtually all coils involved in loading or tuning antennas.

The Q of an inductor is the ratio of its reactance (X_L) to its ac resistance (R_{ac}) at the operating frequency.

$$X_L = 2\pi FL \qquad \text{(Eq 1)}$$

and

$$Q = \frac{X_L}{R_{ac}} \qquad \text{(Eq 2)}$$

then

$$Q = \frac{2\pi FL}{R_{ac}} \qquad \text{(Eq 3)}$$

where
π = 3.1416
Q = quality factor
F = frequency in Hz
L = inductance in henrys
R_{ac} = ac resistance of coil

The Q of an inductor is proportional to frequency. Less obvious is that the resistance to alternating current is also a function of frequency and of several other factors we will discuss.

RF In A Conductive Sheet

A sheet of conductive material has a resistance at high frequencies that is higher than the resistance measured with direct current. The difference is caused by *skin effect*. That is, the current is carried not by the entire cross section of the material, as in direct current, but by a thin layer of conductor lying at the surface. For example, in a sheet of copper at 1.8 MHz, the current density at a depth of about 0.001 inch is only 0.37 of that at the surface. The current density continues to decrease exponentially with depth. At 30 MHz, the depth is 0.0005 inch.

The depth at which the current density is down to 0.37 of the surface density is called the *skin depth*. It is a mathematical concept in that the sheet's resistance at RF is equal to the dc resistance of a layer of the skin thickness (0.37 is 1/e, where e is the base of the natural logarithms, 2.718).

The skin depth, and consequently the ac resistance, can be calculated by

$$D_s = \frac{0.3937}{\sqrt{\pi \mu F \sigma}} \qquad \text{(Eq 4)}$$

where
D_s = skin depth in inches
F = frequency in Hz
μ = magnetic permeability ($4\pi \times 10^{-9}$ for non-ferrous materials)
σ = conductivity in mhos per centimeter cube (5.8×10^5 for copper)

Since F, μ and σ appear under the square root sign in the denominator of Eq 4, the skin depth varies inversely as the square root of their values.

The higher the frequency, and the higher the permeability, the thinner the skin. Therefore, ferromagnetic metals such as iron, steel, and nickel make poor RF conductors. Non-ferrous metals such as copper, silver, aluminum, and gold have a permeability essentially that of free space. These materials make better, but not equally good, RF conductors.

The higher the conductivity, the thinner the skin. The advantage of using silver over copper is not as great as the ratio of their dc conductivities might conclude. The conductivity of silver is 6% better than that of copper, but is only about 3% better at RF.

Q In A Straight Round Wire

If the conductor is not flat, but has a surface curvature (round wire), then all of the direct inverse square root relationships become more complex. In wire of small diameter, the skin depth is greater. And because a larger portion of the wire conducts, the skin effect is not as severe. The *ratio* of ac resistance to dc resistance is smaller. A large straight wire has a smaller ac resistance than a small wire, but again the advantages are less than might first be thought.

For the reasons stated earlier, large copper, silver (or silver plated), and aluminum wires are used as high-frequency conductors. Silver's surface corrosion products are conductive, and it provides for a good contact. It has a slight advantage over copper's less conductive corrosion products. Aluminum is light and sometimes larger-dimensioned materials can compensate for its somewhat poorer conductivity.

Q In A Coil

When a piece of wire is wound into a coil, three additional factors come into play. First, the wires of adjacent turns are in close proximity, and the current is not distributed uniformly over the surface. Therefore, some parts of the skin carry a higher-current density than other parts, and since the power loss is proportional to the square of the current, the effective resistance is increased. This is called the *proximity effect*.

Second, the coil's magnetic field induces eddy currents in the wire material. The loss incurred by these currents are reflected as more loss resistance in the coil. Smaller wires have less material for eddy current induction and (for the same turns per inch) less proximity effect. The combination of these two effects can combine to overcome the lower ac resistance of the larger wire in its straight form.

The third factor occurs when a coil is wound on a form. Loss in the coil form material may occur. This factor is usually of less concern in the HF range unless poor form material is used, particularly if it is subject to water absorption.

Each factor interacts in an extremely complex manner to yield a multiplying factor that is the ratio of the ac resistance of a coil to its dc resistance. If a coil is wound with a specific diameter, length, and number of turns, we have a sort of dilemma. If the wire is too small, the ac resistance is unnecessarily high in spite of a low multiplying factor because of its high dc resistance. If the wire is too large, the ac resistance is unnecessarily high in spite of its low dc resistance because of a high multiplying factor.

As it turns out, for any coil of a given diameter, length, and number of turns, there is an optimum wire size. That wire size is not the largest that can be accommodated. When a coil specification says *closewound* enameled wire, be assured that the coil will have more loss than it could have. Formulas that minimize dc resistance do not apply at radio frequencies.

Butterworth researched this problem.[1] A fairly simple equation yields the optimum wire diameter for a simple single-layer solinoidal coil wound of round wire. All the complexities described went into the calculation of factor A in Table 1.

$$d_o = \frac{LA}{N} \qquad \text{(Eq 5)}$$

where
d_o = optimum wire diameter
L = length of coil
D = diameter of coil
N = number of turns
A = from Table 1

(These terms are expressed in the same units.)

[1]Notes appear on page 7.

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Table 1

Machine-Wound Coil Specifications

$\frac{L}{D}$	A
0.4	0.702
0.6	0.666
0.8	0.637
1.0	0.615
2.0	0.551
4.0	0.508
8.0	0.478
10.0	0.474
∞	0.450

Let's Try An Example

For a 160-m antenna construction project, we want a coil two inches in diameter and four inches long.[2] It should be closewound with no. 14 enameled wire, with an inductance of 80 μH, and a measured Q of 110. (That dictates a loss resistance of 8.7 Ω at 1.9 MHz.) Now, 60 closewound turns of no. 14 enameled wire should fit in four inches and yield an inductance of approximately 80 μH. But is that the optimum wire size for maximum Q and minimum loss and heat? No! Applying Eq 5, we calculate L/D = 4/2 = 2. From Table 1, A = 0.551 and

$$d_o = \frac{LA}{N} = \frac{4 \times 0.55}{60} = 0.0367 \text{ inch} \qquad \text{(Eq 6)}$$

Consulting a wire table, we find that 0.0367 inch in diameter lies between values listed for no. 18 and no. 19 wire. Number 18 wire is used because no. 19 is not commonly available. We space 60 turns of no. 18 wire to occupy the four inches of winding length. Expect the Q to be about 200 or better. This cuts the 1.9 MHz loss resistance from 8.7 Ω to 4.8 Ω or less. You can get less loss with less copper.

Improving Q

It is generally accepted that coils having a length similar to their diameter optimize Q with little difference over the range of lengths of from one half to two times the diameter. With longer lengths the increased coil form loss (if any) also adds to the loss.

If we consider a coil with a specific length-to-diameter ratio, loss can further be reduced by increasing the coil size. If we maintain the same ratio of length to diameter, the Q increases as the square root of the ratio of the diameters, providing that for each coil size we use the optimum wire size for that coil. Larger coils have larger optimum wire sizes. Thus, if the coil in our example were increased to four inches in diameter and eight inches in length, with 44 turns (for the same 80-μH inductance), the optimum wire size would be no. 10 and we'd expect the Q to be 280 or better (4/2 = 2, $\sqrt{2}$ = 1.414, 200 x 1.414 = 280). The 1.9 MHz loss resistance would be reduced to 3.4 Ω or less.

For those interested in the low-frequency experimental band at 160-190 kHz, Litz wire can be used to increase Q. For most amateurs, however, Litz wire is of no advantage; its effect disappears at frequencies above about 0.8 MHz. Hard drawn copper wire should not be used for high-Q coils—its conductivity is only about 59% of that of soft drawn copper wire.

Some commercial loaded antennas use closewound coils. I can only conjecture that the higher loss is tolerated to provide a tradeoff for wider SWR bandwidth. In fact, the manufacturer of one popular antenna states in his packaged instructions, "Do not be concerned if resonators appear to warm up. Efficiency will not be affected." Wow! Perhaps they meant "efficiency will not be effected"!

Notes

[1]S. Butterworth, Effective Resistance of Inductance Coils at Radio Frequencies, *Exp Wireless and Wireless Eng,* vol 3, Apr 1926, May 1926, Jul 1926, Aug 1926. Eq 5 is adapted from Terman, *Radio Engineers Handbook*, 1943, p 77-83, incorporating his Table 22 data into his Eq 100, all based on S. Butterworth, loc. cit.

[2]D. DeMaw, "How to Build A 160-Meter Shortie," *QST*, Nov 1986, p 26.

Bits

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