Iron Powder Cores for High Q Inductors

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SUBJECT: A brief overview will be given of the development of carbonyl iron powders. We will show how the magnetic properties of the iron affect inductor performance and will show, through example, how the physical size of a core along with its winding details interact to affect Q Vs frequency characteristics.

INTRODUCTION: As a circuit designer you are faced with a need for inductors and transformers. Whether you plan to build or buy these components, it is valuable to have a practical understanding about the parameters affecting performance.

In the last century the use of solid magnetic material for DC electromagnetics and then laminated magnetic materials for low frequency applications led to the need for materials that would operate efficiently at higher and higher frequencies. With the original thick laminations it was discovered that the apparent permeability or inductance decreased as frequency increased and, at the same time, losses became prohibitive. It was found that by using thin sheets of material insulated from one another that better results were obtained. This is primarily due to an effect known as eddy-current shielding. As frequency increases, the depth of magnetic penetration decreases for any given material. Thus by having thin sheets, effectively more of the core body is utilized. This progression worked toward thinner laminations and grain oriented alloys to meet the higher frequency needs.

While the thin oriented laminations were useful for broadband audio transformers, they were unable to meet the need for selective circuits where high Q is required. While at low frequency the magnetic field in a coil is in its axial direction, at high frequency, each turn generates its own field concentric with the wire. These fields are coupled with fields from adjacent turns and are coupled to the core through axial fields rather than one central field. This type of field requires cores laminated in all directions in order to minimize losses and thus maintain reliable inductance and Q versus frequency.

There are two basic classes of iron powders available. The hydrogen reduced irons which have low resistance, and relatively large particle. This type of powder produces the highest permeabilities, (up to 100μ), has low losses at low frequency, but the losses increase significantly at high frequency, producing very low Q at RF. Cores from this powder are commonly used for differential-mode chokes in line filters and DC output chokes in switching power supplies.

The carbonyl irons on the other hand have a particle that is formed by the decomposition of pentacarbonyl iron vapor. This produces a spherical particle with an onion skin structure. This laminating affect of the onion skin produces resistivity of individual particles much higher than that of pure iron. This high resistance in conjunction with the very small particles (3 to 5 microns) greatly enhances the high frequency performance. Carbonyl iron powders permeability, and thus its inductance can be manufactured to very tight tolerance and remaining extremely stable with frequency, temperature, and applied signal level. All of this is important in high Q selective circuits.
The distributed air-gap characteristic of the carbonyl iron powder produces a core with permeabilities ranging from 4 to 35. This feature in conjunction with the inherent high saturation point of iron makes it very difficult to saturate at high power RF. Normally, high power applications are limited by temperature rise due to core loss.

In the middle 1930's the first ferrite's were investigated. The development of these materials produced higher permeability than that attainable with iron powder and at the same time had reasonable losses. In many applications the ferrite's higher permeability is a distinct advantage. However, in the case of high frequency, high Q tuned circuits, high permeability is not nearly as important as attainable Q and good stability with varying environmental and electrical conditions. Ferrites are typically manufactured to a +/- 20% tolerance.

INDUCTANCE: The inductance per turn of a closed magnetic structure, like a toroidal core, is described by:

$$\frac{L}{N^2} = \frac{4\pi\mu A}{\ell}$$

Where: L = Inductance (nH)
μ = Permeability
A = Cross-sectional area (cm2)
l = Path length (cm)
N = Number of turns

This illustrates that the inductance per turn of a core is directly related to its permeability and the ratio of its cross-section to path length. Core manufacturers provide an inductance rating for their cores. There are 3 different descriptions commonly used, nH/t, mH/1000t and μH/100t. Because the inductance varies squared with turns, the three compare according to this example.

5nH/t = 50 μH/100 turns = 5mH/1000 turns

These ratings are used to calculate required turns for a desired inductance as follows.
If A_L is in nH/t:

$$\text{required turns} = \left[\frac{\text{desired L (nH)}}{A_L}\right]^{1/2}$$

If A_L in mH/1000 turns:

$$\text{required turns} = 1000\left[\frac{\text{desired L (mH)}}{A_L}\right]^{1/2}$$

If rated in μH/100 turns:

$$\text{required turns} = 100\left[\frac{\text{desired L }(\mu\text{H})}{A_L}\right]^{1/2}$$

For example, if we need 3μH on a core with an inductance index (A_L) of 49uH/100 turns then:

$$\text{required turns} = 100\left[\frac{3}{49}\right]^{1/2} = 24.7 \cong 25 \text{ turns}$$

Q CONSIDERATION: We will now take a look at some of the considerations in producing high Q inductors. We will first look at what Q is… In a simplified view, $Q = \tan\theta = \omega L/R$ where θ is the phase angle, ωL is the inductive reactance and R is the effective series resistance. In the case of an ideal inductor, the phase angle is 90° and the Q is infinite. Likewise, an inductor with a Q of 1 has a phase angle of 45 degrees and thus its reactive and resistive elements are equal. A Q of 150 has a phase angle of 89.6 degrees.

The factors that make up the effective resistance are quite complex. They involve both the core and winding losses. The core losses vary with material, frequency, flux density and core size. The winding losses involve wire resistance, turn to turn, and turn to core Capacitive effects which are all frequency and size dependent. There are rigorous analysis of these inter-relationships available, but in general are far too complex to be of much practical use when it comes to designing a high Q, high frequency inductor. We will discuss the basic trends of these inter-relationships as they relate to frequency. The examples will use toroidal or donut shaped cores, but the principles can be applied to other shapes.

Optimum Q will occur when the combined core loss equals the total winding loss. It has been shown by Legg that in general maximum attainable Q is directly related to a cores physical size for any given material. It has also been shown that the frequency at which this maximum attainable Q occurs is, in general, inversely proportional to permeability, core size, and the square root of core loss.

Figure 1 illustrates the basic relationship that, for a given core material, carbonyl E, (u = 10) with a recommended frequency range of .25 to 10 MHz that the physically large cores provide higher peak Q than physically small cores and that the frequency at which this peak occurs is indeed inversely proportional to core size. That is to say large cores reach their optimum at lower frequency than small cores.

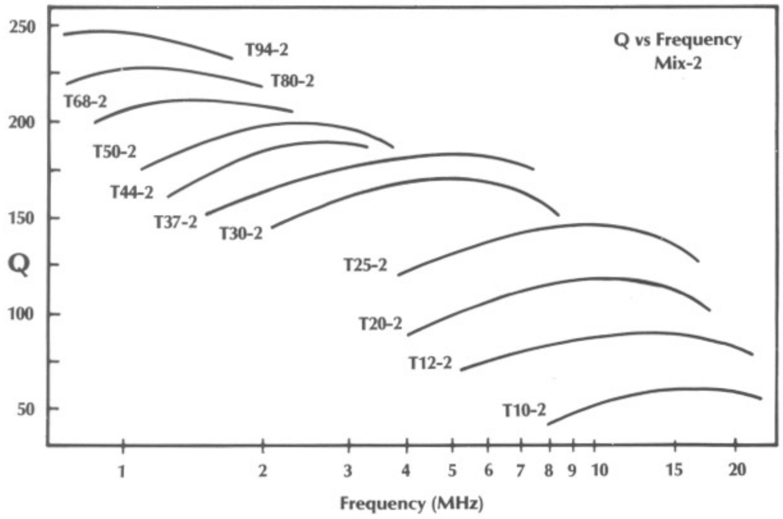


Figure 1

Figure 2 illustrates how for the same physical size core, T50, which is a ½ inch core, that the frequency at which the peak Q values occur increases with decreasing permeability. Eddy current losses also are involved in determining this optimum frequency.

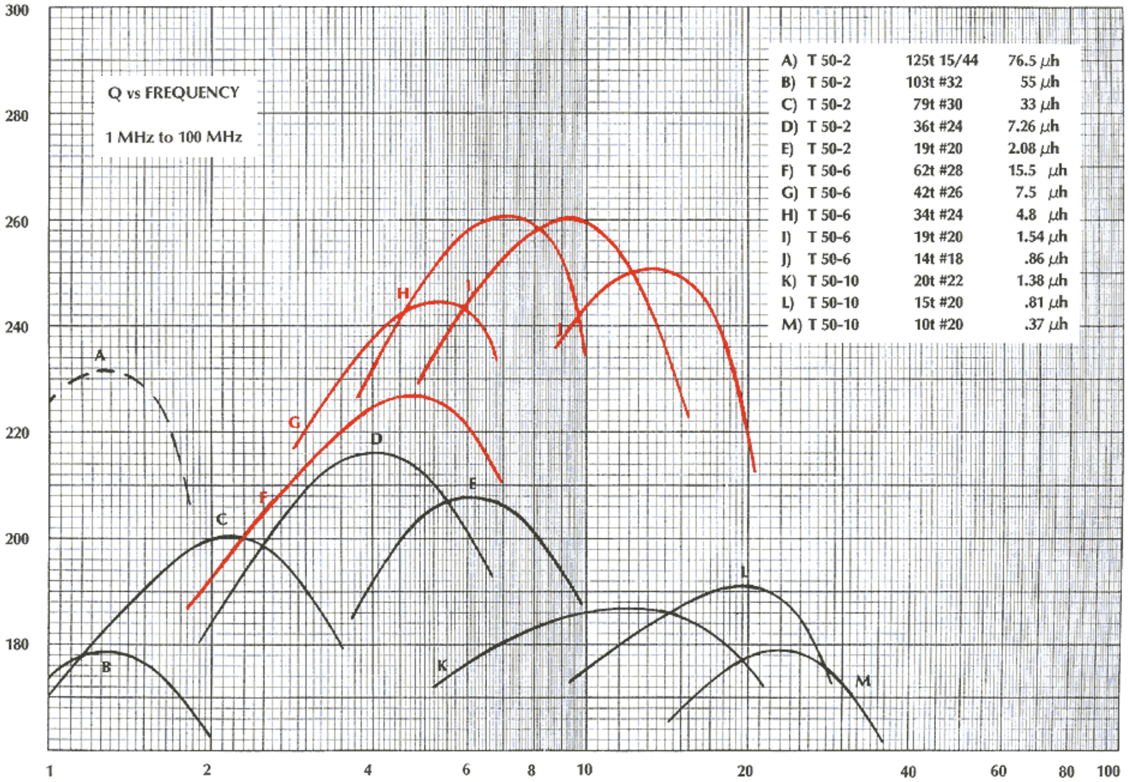


Figure 2

In the comparison made, the inductance has been a variable in order to approach an optimized Q at an optimum frequency. Figure 3 shows a series of Q curves for the T44-2 and T50-3 cores with different single layer windings. These curves show that the frequency at which the Q peaks, decreases as the number of turns, and thus the inductance, increases. It also shows that there is a point at which we obtain a peak-peak.

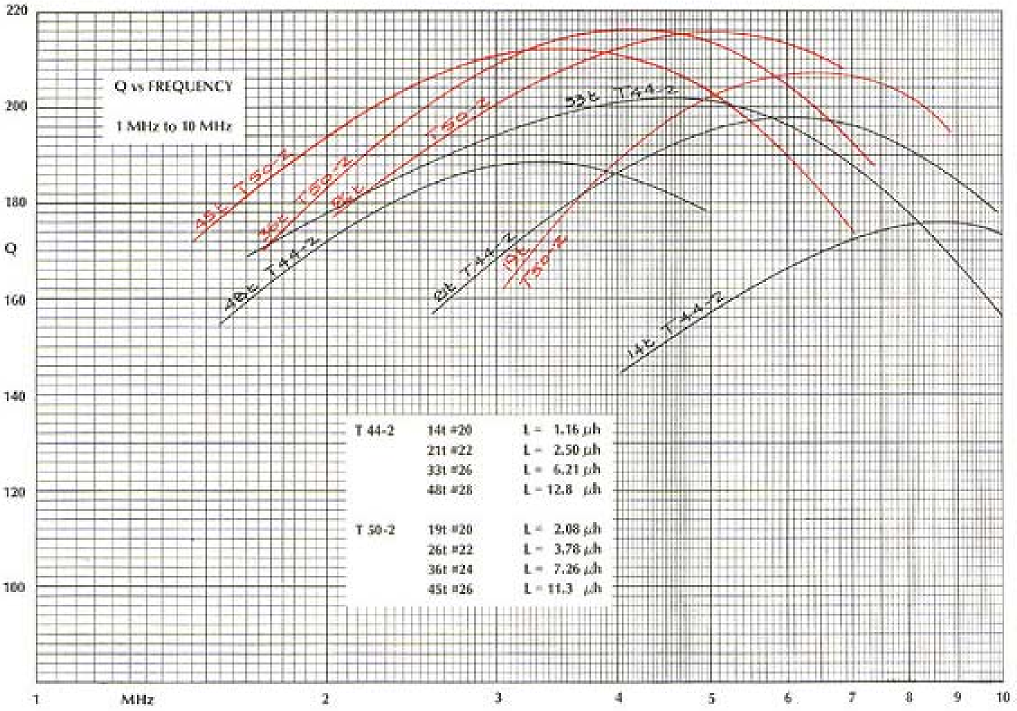


Figure 3

Another interesting comparison is to set the inductance fixed at some value and see how the core size, core material and required windings interact. Figure 4 shows this. While these are not optimized coils, this still illustrates that even with fixed inductance, with the same core material, larger cores produce higher Q at lower frequency than small cores.

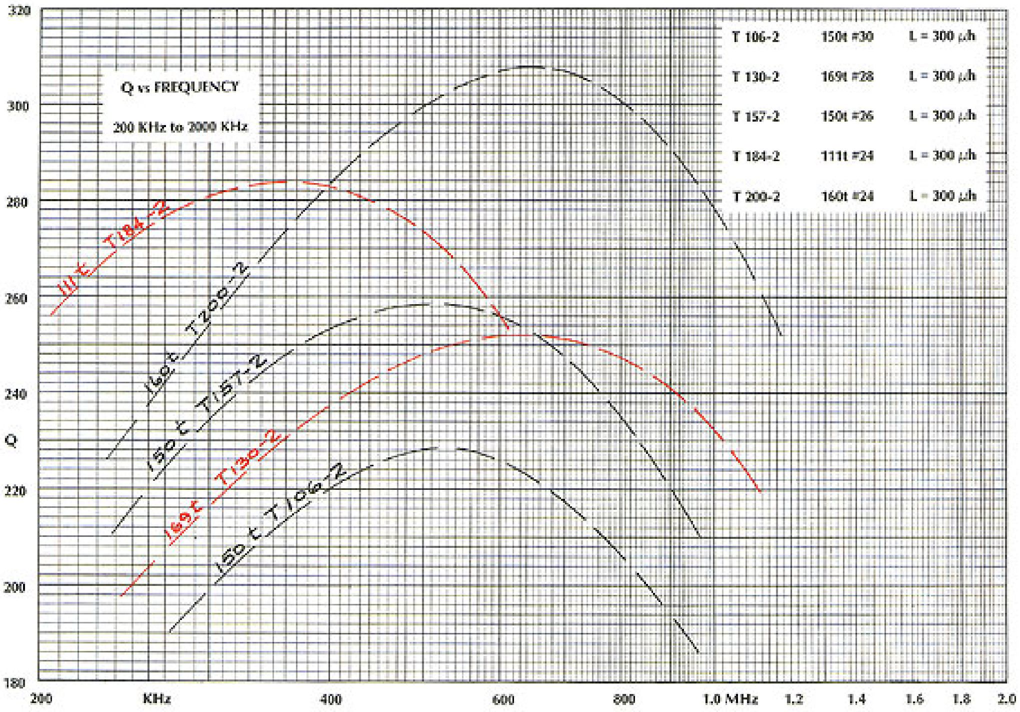


Figure 4

Thus far, we have not paid too much attention to the winding details but have looked at the interaction of core size and material as it relates to Q and frequency. In the examples shown, the windings have all been a full single layer. We will now look at the effects of different types of windings and their implications versus frequency.

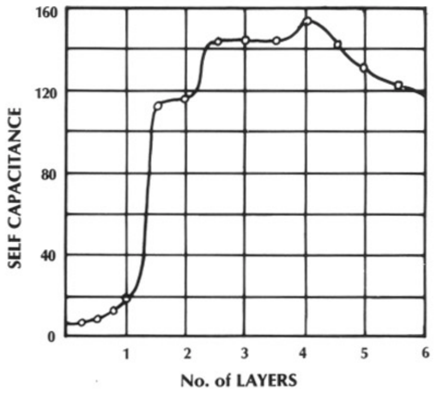
WINDING CONSIDERATIONS: In arriving at the best winding for a given coil, there are two basic effects which reduce Q to be considered: resistive and capacitive.

The resistance of copper wire at very low frequency is the same as its DC resistance. The skin depth of an AC current is inversely proportional to the square root of the operating frequency. Thus the AC resistance of a conductor is proportional to $f^{1/2}$. Because of this, the increased resistance due to skin effect will begin to come into play at higher frequencies for smaller wire and at relatively low frequency for large wire. As an example #30 wire will begin to see increased resistance as low as 300kHz and #40 wire is affected around 3MHz. This resistance is further increased in the case of wound coils due to the proximity effect of adjacent turns.

In order to help the AC resistance of a conductor approach its DC resistance at moderate frequency, Litz wire can be used. Litz wire is formed by a number of strands of small insulated wire connected in parallel at the ends and completely interwoven. The interweaving is essential in order for the various strands to equally share the current. There is a significant difference between true Litz sire and stranded wire.

Practical Litz wire is very effective at frequencies up to 1MHz. As frequency increases, however the benefits begin to disappear. At very high frequency the reduced resistance due to the interwoven stranding is more than offset by the capacitive build-up between the strands. Since most of the work in RF today is at frequencies above 1MHz the use of Litz wire has become rather uncommon.

In a winding, the self-capacitance that is built up is a result of the turn-to-turn capacitance of adjacent wires as well as turn to core capacitance. The turn to turn capacitance is affected by wire size, number of turns, and the spacing and positioning of the turns. In general, capacitive effects on Q become increasingly important with frequency squared (f^2). For a toroidal coil, one of the most important factors in controlling capacitive build-up is to limit the winding to a single layer. Figure 5 from Welsby shows how the self-capacitance of a toroidal coil varies with the number of layers. It is seen that the addition of even a partial second layer dramatically increases the self-capacitance.



CAPACITANCE OF TOROIDAL WINDINGS AS A FUNCTION OF THE NUMBER OF LAYERS

Figure 5

This capacitive effect is evident in Figure 6. In this example all coils are wound with #28 wire and essentially the same number of turns. Curve #1 is a single layer winding and has a peak Q of 244. Curve #2 is what results by adding only 2 turns on a second layer. The resulting Q is 7% lower. Curve #3 is a randomly wound coil and exhibits even lower Q. And the worst of the group is Curve #4 that has 60 turns on the first layer and 40 turns on the second layer. In this case the capacitive effects have lowered the Q by over 25%.

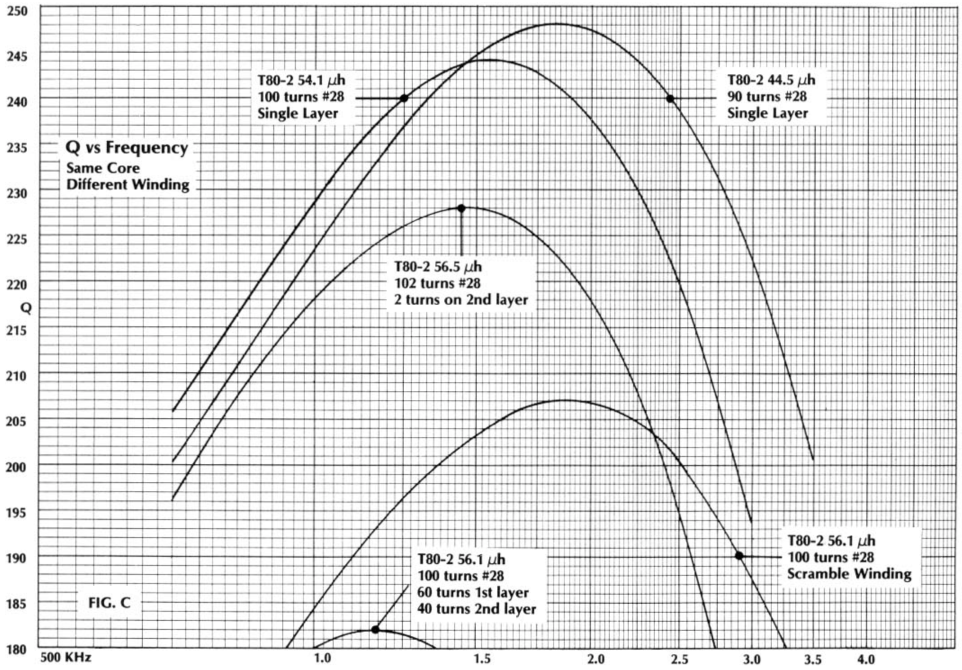


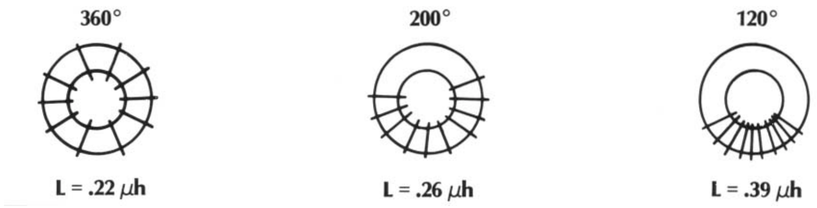
Figure 6

Since our objective is to minimize both resistance, which implies larger conductors and thus multi-layers, and at the same time to minimize capacitance, which implies single layers with good spacing. It is valuable to keep in mind that the importance of resistance varies with $f^{1/2}$, and the importance of capacitance varies with f². This indicates that at low frequencies resistance is the dominant factor and that at high frequency capacitance is the most important.

Aside from the affect that coil capacitance has on Q, it also affects the self resonant frequency and apparent inductance of the coil. The greater the coil capacitance, the lower the self-resonant frequency and the higher the apparent inductance.

These coils are also often times either dipped in a material to secure turns or are completely encapsulated. The dielectric characteristics of the material coming in contact with the winding can have a profound effect on the coil capacitance and, therefore, the Q, apparent inductance and self-resonant frequency. In order to minimize shift due to encapsulating, a material with a low dielectric constant must be used.

Another characteristic, which affects the apparent inductance, is leakage inductance. Leakage inductance acts in series with the coils self-inductance. This is a result of uncoupled flux and becomes most apparent in high frequency, low inductance coils particularly when the turns are not evenly distributed around the core. Here is an example where a T50-17 is wound with 10 turns #20 (μ = 4).



In cases like this where it is possible to drastically change the positioning of the turns, and the permeability of the core material is low, very large differences are seen. In higher permeability materials this affect is much less. In a number of applications, toroidal coils are tuned by this means.

SUMMARY: Iron powder is a core material well suited for high Q stable inductors to be used in the 100kHz to 200MHz frequency range.

We showed the following relationships regarding core material and size:

1. For a given material, larger cores produce higher Q at lower frequency.
2. For a given material and size core, Q peaks at lower frequency as turns are Increased, and there is a frequency and winding of Q optimization.
3. For a given core size, the optimum value of Q is inversely proportional to permeability.

We also showed that from the winding standpoint, in order to help optimize Q:

1. At low frequency (<500kHz) that resistive losses are dominant and thus the use of Litz wire is advantageous.

2. At frequencies above 1MHz losses due to capacitive affects begin to dominate and that multi-layering is very detrimental to Q. It can generally be considered that a full single layer will provide the best result.

In order to help the design engineer in his efforts to build high Q inductors, we have put together an extensive series of Q Vs frequency curves for Micrometals iron powder cores and is called the Q-Curve Book. In studying this information it can be seen that when high Q is required at a particular frequency, and physical size is limited by required packaging, that when possible, it is best to optimize the coil for Q and adjust the value of external resonating capacitors rather than select the desired inductance and then have to sacrifice Q in order to achieve it.

Another application for which iron powder is receiving increased attention is for use in very high frequency broadband matching applications. The extremely linear frequency response of iron powder even in our 35 permeability material makes it useful for transformers above 50MHz. The primary attraction of iron powder being its repeatability at the extremely high frequencies. Full characterization of these materials for broadband applications up to 1GHz will be available in the future.