A method for estimating the impedance of a ferrite cored toroidal inductor at RF

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Abstract

This article presents a method for estimating the impedance of a ferrite cored inductor at RF from manufacturer's data, and a simple method for identifying ferrite material based on manufacturer's data.

1. Using manufacturer's data

Taking an example of an FT140-43 or Fair-rite 5943002701 with 10 turns at 21MHz.

Inductance of an inductor wound on a high permeability core can be given as $L = N^2.A_l$ where $A_l = \frac{\mu A}{2\pi r}$, N is the number of turns, A is the cross section area of the core, r is the radius of the core, and μ is the permeability of the core. μ=μ0*μr where μ0=4πe-7 and μr is the relative permeability.

The impedance of an ideal inductor can be expressed as $Z = j\omega L$, or $Z = j2\pi fL$. Substituting for L, $Z = j2\pi fN^2A_l$.

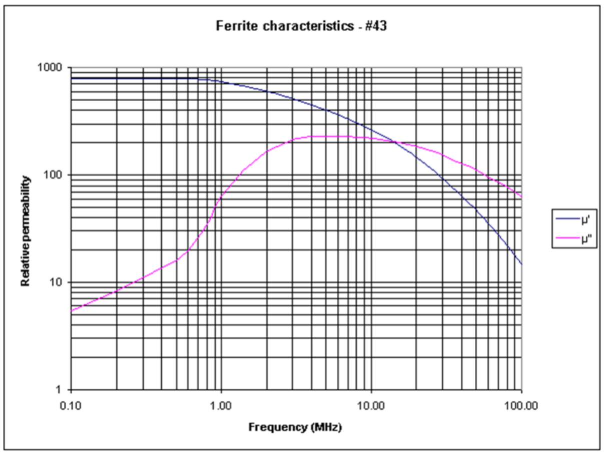

Figure 1: Characteristics of Fair-rite #43

Relative permeability can be expressed as a complex quantity to capture both the ability of the core to increase flux and the core loss. The figure above taken from the data sheet gives μ' and μ" over a range of frequencies.

The published data for the core gives A_l=885e-9, but A_l is based on the permeability at low frequencies (initial permeability, μi) where it is relatively constant, and must be adjusted for higher frequencies by multiplying by $\frac{\mu' - j\mu''}{\mu_i}$.

So, we now have $Z = j2\pi fN^2A_l\frac{\mu' - j\mu''}{\mu_i}$.

Let us put some numbers around that.

From the graph above, at 21MHz μ'=140 and μ"=180, and from the datasheet, μi=800.

Z=j*2*π*f*N^2*A_l*(μ'-jμ")/μi.

Z=j*2*π*21e6*10^2*885e-9(140-j180)/800= 2627+j2044Ω. Note this is quite a different answer to calculation based simply on uncorrected A_l, which suggests an inductance of 88μH and an impedance therefore of 0+j11680Ω.

Inductors such as these exhibit self resonances, and their two terminal impedance is affected as frequency increases towards the first resonance. The effect can usually be approximated well around the first resonance by addition of a small shunt capacitance to the model.

If for example the inductor calculated to have Z=2627+j2044Ω is shunted with 2pF of equivalent self capacitance, the impedance of the combination is given as 1/(1/(2627+j2044)+j2πf*2e-12)=3792-j1270Ω. Note that the effect of the self capacitance is to make this inductor look like a high resistance with a series capacitive reactance, not what is perhaps expected of an inductor.

Some manufacturers publish graphs of R,X vs f for a single turn for specific cores. These can be multiplied by turns squared, but the effects of equivalent self capacitance need to then be factored in as above.

2. Calculators

The Internet abounds with calculators that purport to calculate the impedance of ferrite toroidal cored inductors, but sadly, most do not reconcile with measurement of the inductors. The reasons become obvious when the lack of input parameters is considered.

2.1 Calculation from A_l, μi, μ' and μ"

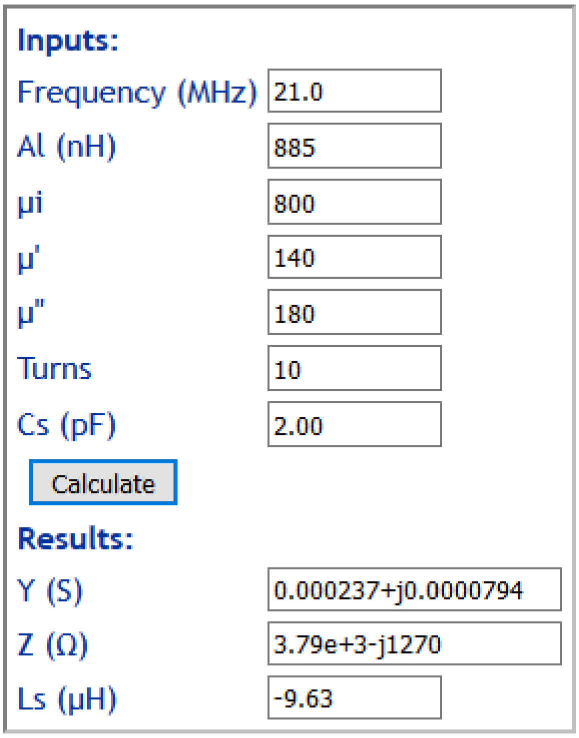

Figure 2: Calculation from A_l, μi, μ' and μ".

The negative value for Ls is due to the effect of the equivalent self capacitance.

Power lost in the core can be calculated as I^2R (R=real(Z)) or V^2G (G=real(Y)).

The method described does not capture dimensional resonance effects.

The above calculator implements the method described in this article, it and related calculators are available online at:

- http://owenduffy.net/calc/toroid.htm ;
- http://owenduffy.net/calc/toroid2.htm ; and
- http://owenduffy.net/calc/toroid3.htm .

3. Identifying ferrite materials

One often wants to identify the type of material used in a ferrite core for use at radio frequencies.

The most common method is to make some measurements to determine the initial permeability μi, usually at audio frequencies, and to compare that to a table of μi for common core materials. This method might well indicate several mixes that have similar μi, but each may be quite different at higher frequencies.

The suitability for use at RF usually depends much more on complex permeability at radio frequencies than it does on μi at say, 10kHz.

Figure 1 from the Fair-rite data book shows the complex permeability characteristic of #43 ferrite material.

In fact, the data presented in Figure 1 is measured on a toroidal core with a small winding, the datasheet states that in this case it was "[m]easured on a 17/10/6mm toroid using the HP 4284A and the HP 4291A", and probably using just one turn.

This characteristic means that a small inductor wound on a core of #43 material so that there is very little flux leakage will have a complex impedance with X/R=μ'/μ". The frequency at which R=X is a good 'signature' for the material type, #43 crosses over at about 14MHz in Figure 1.

It is vital that this measurement is done with as few turns as necessary to give a reliable and accurate reading on the measuring instrument. More turns means decreased self resonant frequency and the impedance will no longer obey the simple model X/R=μ'/μ". On the other hand, measuring an impedance of the order of ohms with the ubiquitous MFJ-259B does not give accurate results.

If the inductor has appreciable flux leakage (eg a rod or low μ), then the flux leakage results in a departure from X/R=μ'/μ".

The technique is not so applicable to powdered iron materials as they usually have much lower loss than ferrites, and grading by μi remains the best option.

Note that ferrite materials are subject to manufacturing tolerances and variation with temperature, do not expect 1% accuracy in applying datasheets to real world cores.

Table 1: Selected Fair-rite data

Mix	Frequency where R=X (MHz)	μi
31	3.6	1500
33	4.5	600
43	14	800
52	30	250
61	43	125
73	2.3	2500
77	1.7	2000

Table 1 shows the cross over frequency and μi for some common Fair-rite materials. It can be seen that although #33 and #43 have similar μi, their RF performance is quite different, due in part to the fact that #33 is MnZn ferrite and #43 is NiZn ferrite. If one was to classify an unknown core of type #43 or #33 based on μi alone, allowing for manufacturing tolerances, temperature and measurement error, it would be very easy to wrongly classify it.

Likewise, other manufacturers may have cores of fairly similar materials, and measuring μi alone gives little indication of the RF performance, or a valid comparison with a known core.