LOSSES IN FERRITE ROD ANTENNAS

The losses in ferrite rod antennas are much higher than predicted by the accepted theory. This article shows that the increased loss is due to an increase in the copper losses in the winding rather than losses in the ferrite itself.

1. INTRODUCTION

When a ferrite rod is introduced into a coil its inductance increases considerably, and if the only increase in loss was in the ferrite a very large increase in Q would result. But experiment does not support this, and one of the first to notice this was Polydoroff (1960, ref 1) who found that 'the increase of loss due to the insertion of the core is many times greater than the iron loss, proper' (he was using dust iron cores). In one of his experiments the loss resistance introduced by the magnetic core was nearly 100 times the value he had calculated, but despite an extensive investigation he was unable to locate the additional loss.
Surprisingly the situation has not improved much over the subsequent half century, and textbooks still assume that the all the additional loss is in the magnetic core. For instance the 'Antenna Engineering Handbook', Johnson & Jasik (ref 2, Chapter 5) gives the 'resistance due to the core loss' as :

$$R_m = \omega\, (\mu_{rod} / \mu')^2 \mu''\mu_0\ F_r N^2 A / lc \qquad 1.1$$

Where μ' is the ferrite permeability, μ'' its loss permeability, N is the number of turns, A is the cross-sectional area of the ferrite and *lc* the coil length. For the calculation of μ_{rod} the theory of demagnetisation is used, derived from the theory of permanent magnets (see Payne ref 4). F_r is an empirical factor needed to get the equation to agree with experiment, and this ranges from about 0.1 to 0.6 but even then the equation is not accurate because F_r is derived from 'averages of experimental data' (ref 2).
The reason for this inaccuracy is in the assumption that the wire resistance remains the same as in the air cored coil, and that the only additional loss when a ferrite core is introduced is that in the ferrite itself. However the wire loss increases considerably, and this is the topic of this article.

The total loss is the sum of the conductor loss and the ferrite loss, and these are considered below starting with the ferrite loss.
In this report the most significant equations are highlighted in red.

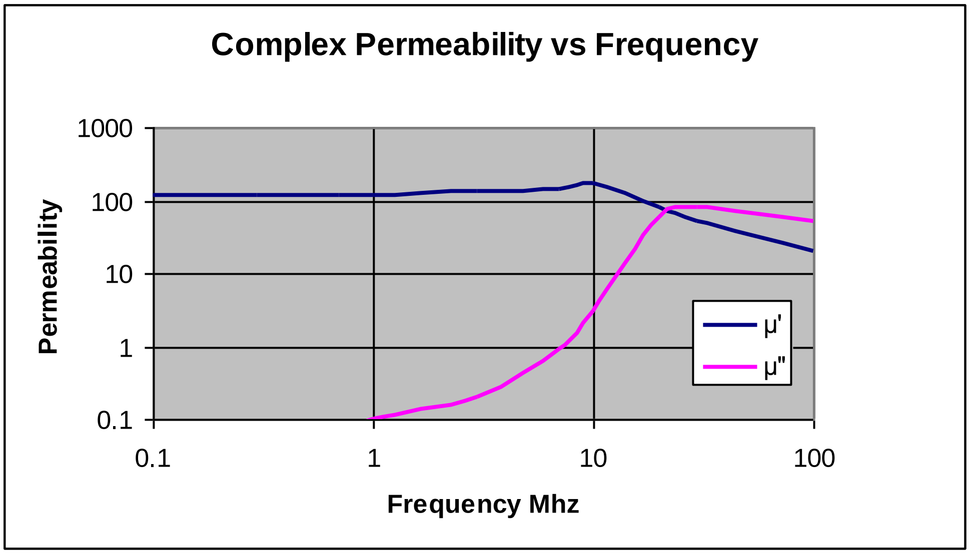
2. FERRITE LOSS

2.1. Closed core and Open core

Most magnetic circuits are termed 'closed', in that the ferrite forms a complete magnetic circuit containing the entirety of the flux, and the most common example is the transformer. Sometimes an air gap is included but this is generally very short so that any leakage flux is very small. In contrast the ferrite antenna is an 'open' magnetic circuit having a very large leakage flux, but the same theory can be used to evaluate the ferrite losses, so the analysis below starts with closed cores.

2.2. Losses in Closed Cores

The permeability of a ferrite is designated by μ' and its loss and by an imaginary permeability μ''. These both change with frequency and so are often given by the manufacturer as a graph similar to the one below:



The Q of a ferrite is given by the ratio of these two:

$$Q_m = \mu' / \mu'' \qquad 2.2.1$$

In the graph above the Q of the ferrite at10 MHz is Q_m = 57 (i.e. 170/3).
If a coil is wound around a closed ferrite, such as a toroid, and measurements made of the inductance and resistance then the overall Q is equal to the ratio of reactance to resistance $Q = \omega L / (R_w + R_f)$, where R_w is the loss due to the wire and R_f that due to the ferrite. If the wire resistance is subtracted this gives the Q of the magnetic circuit (the ferrite) which is designated here as Q_m :

$$Q_m = \omega L / R_f \qquad 2.2.2$$

[NB for a closed magnetic circuit such as a toroid, it is assumed that the wire loss is not affected by the inclusion of the ferrite. This seems to be essentially true when the permeability of the ferrite is high, so that any leakage flux from the ferrite cutting the wire is very small. However, there is evidence that if the permeability is small this may not be true, and then the wire loss can increase (see Polydoroff ref 1, p72)].

Equating the above two equations gives :

$$Q_m = \mu' / \mu'' = \omega L / R_f \qquad 2.2.3$$

So ferrite manufacturers usually determine μ’ and μ’’ by winding a coil around a toroid of the material and measuring the *increase* in inductance and the *increase* in resistance due to the core.

2.3. Losses in Closed Cores with an Air Gap

When an air gap is included in the magnetic circuit, the overall permeability reduces and so does the loss. If the new permeability is μ'_e , then the new loss factor is (Snelling ref 3, equation 4.48) :

$$Q_{m\ gapped} = Q_m . (\mu'-1)/ (\mu'_e -1) \qquad 2.3.1$$

As an example, if a ferrite toroid with a permeability μ’ =200, and Q_m =100, has inserted into it an air gap of such a width as to reduce the effective permeability μ'_e to say 50, then the new Q of the magnetic circuit will rise to $Q_{mgapped}$= 406.

At first sight this result may be surprising, since by adding an air gap it might be expected that both μ' and μ'' will reduce by the same amount, so that the Q would be unchanged. This *would* be true if the air gap was also lossy with the same loss as the ferrite, but the air gap has no loss.

2.4. Losses in Open Cores

Considering now the ferrite rod antenna. When the rod is inserted into the coil the inductance increases by an amount significantly less than the permeability μ', because of the diluting effect of the large air gap. For instance the inductance may only increase by a factor of 6 times even though the ferrite has a permeability of say 250. This ratio by which the inductance *actually* increases, L_f/L_{air} , is often given the label μ_{coil}, so to apply Equation 2.3.1 to the open core we substitute μ_{coil} for μ_e :

$$Q_{m\ open} = Q_m\,(\mu'-1)/\,(\mu_{coil}-1) \qquad 2.4.1$$

The ratio $(\mu'-1)/(\mu_{coil}-1)$ is normally very large and in the absence of any other loss a large increase in Q could be expected. So if the ferrite material in the above example had a Q of 100 then the Q of the ferrite rod antenna would be 5000 [ie = 100*(250-1)/(6-1)].

2.5. μ_{coil}

The above equation needs a value for μ_{coil}, but the accepted equations for this are inaccurate. The author has derived an accurate equation (Payne ref 4) which can be approximated to :

$$L_f/L_{air} \approx x\,(1+C') \qquad 2.4.2$$

where

$$x = 5.1\,[l'/d_c]/[1+2.8\,(d_c/l')]$$

$$l' = l_c + 0.45\,d_c$$

$$C' \approx 0.7\,[(l_f - l_c)/d_c]\,/\,[\,Ln\,\{2\,(l_f + d_f)/d_f\}-1]$$

This equation should be accurate enough for practical purposes if the antenna meets the following conditions:

a) the coil is no longer than twice its diameter and is centred on the ferrite rod.
a) the inner winding radius of the coil is not too different from that of the ferrite
b) the ferrite permeability is greater than 100
c) the ferrite rod is no longer than 12 times its diameter.

In applying this equation it should be noted that in the author's experience the permeability of ferrite rods is around half that quoted by manufacturers. For the measurement of the permeability of ferrite rods see ref 4.

2.6. Ferrite loss alone

Equations 2.4.1 and 2.4.2 give the loss in the ferrite, but this is only a fraction of the total loss as the following experiment shows : a coil of 32 turns of 0.6mm dia enamelled copper wire, was wound over a length of 20mm on a former of 10 mm dia., and gave a Q_c of 156 at 3Mhz. When a ferrite rod was introduced having a length equal to that of the coil, the above equations give a Q of 615, but the measured Q was only 62.

[Details of experiment were : When the ferrite was introduced the inductance increased by 6.38 (= μ_{coil} = L_f/L_{air}). So if there was no loss in the ferrite and the winding loss was unaffected, the Q would increase to 995 (ie 156 x 6.38). In fact the Q of the ferrite was 29, and its permeability 300, both at 3 MHz. So from Equation 2.4.1 the Q of the *open* core $Q_{m\ open}$ was 1612.
We could therefore expect the overall Q to be that of a Q of 995 in parallel with a Q of 1612, so
$Q_t = Q_1 Q_2/(Q_1+Q_2) = 615$, but measurements gave a Q of only 62].

So the loss in the ferrite was only a small fraction of the total loss and we need to look for a large additional loss.

3. POSSIBLE LOSS MECHANISMS

In an effort to locate the extra loss the author considered many possible loss mechanisms, but most were discounted because if present they would also be present in a toroid, and since this is used to determine the loss in the ferrite $Q_m = \mu' / \mu''$, any such loss would already be included. The loss mechanism had to be unique to the open core, and not present in the toroid.

Two mechanisms were good candidates. The first was that there was a circulating flux around the core. This could arise because it has been reported that at high frequencies in open cores the flux tends to form a tube, with little flux in the centre of the core (Polydoroff ref 1 page 2).When flux traveling down this outer tube arrives at the end of the ferrite rod it will not necessarily flow into the air, because there is a much lower reluctance path it can take. This path is across the end face of the ferrite and then in the reverse direction down the center core of the ferrite. This could lead to a large re-circulating flux giving high losses, with a much smaller flux propagating into the air. This seemed an excellent candidate and so was investigated in great depth, but its predictions did not correspond with measurements.

The second candidate was increased loss in the *wire* due to the large increase in the fields cutting the wire, and the theory developed for this mechanism did agree with experiment and it is this which is described in this article.

4. INCREASED COPPER LOSSES

4.1. Copper Losses at High Frequencies

So consideration must be given to the losses in the wire and how they are affected by the presence of the ferrite.

It is well known that the resistance of isolated conductors at high frequency is much larger than the dc resistance due to the skin effect, so-called because at sufficiently high frequencies the current penetrates into the conductor only a small amount and flows in only a thin skin down the outside of the conductor.

Skin effect arises because of the magnetic field which the conductor produces around itself, but if this field also intercepts other conductors this will also increase its resistance. In particular if the wire is wound into a coil, each turn of the wire induces loss-making eddy currents into adjacent turns, indeed even of turns some distance away in that it contributes to an overall field down the coil. The power lost in these eddy currents must come from the wire(s) responsible for the magnetic field, and so these wires have an apparent increase in their resistance. In addition, as flux passes down the coil only a part of it reaches the end, and a proportion leaks away into the wire, particularly towards the ends of the coil, and this sets up further eddy currents. In Figure 4.1 this leakage flux is shown exiting the coil, but as it cuts the wires the resultant eddy currents tend to cancel this flux. This cancellation is especially pronounced at high frequencies and with close wound coils, and then little if any flux exits from the sides.

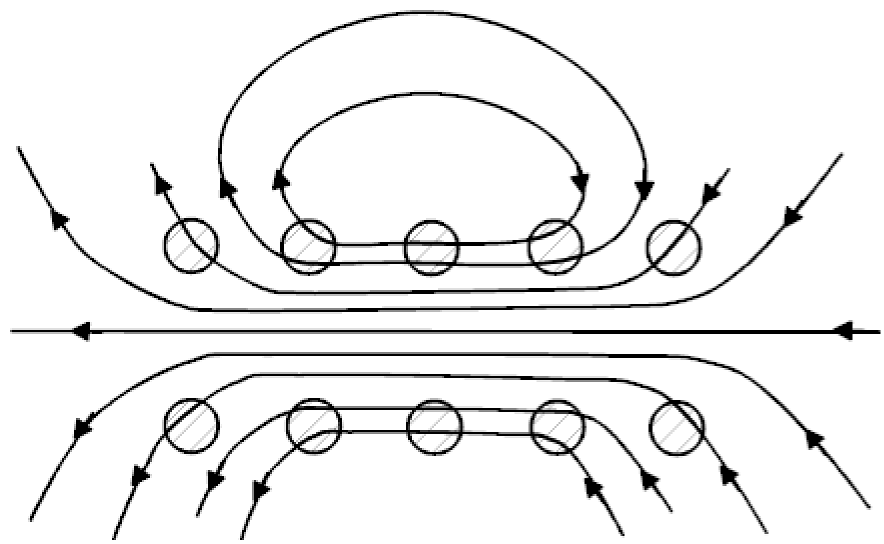


Figure 4.1 Flux Distribution in an Air Coil

4.2. Loss due to Magnetic Field

The apparent resistance of the wire therefore increases, and if this extra resistance is called R_φ, then the power lost in the coil is:

$$Pt = I^2 R_0 + I^2 R_\varphi \qquad 4.1.1$$

The first term is the power lost in the wire when the external field is absent. The second power loss is due to the magnetic field cutting the wire, and if this has an intensity H amps/m the power loss due to this cause is (Welsby ref 5 p53):

$$W\varphi = I^2 R_\varphi = 4\pi^2 R_{dc} d^2 H^2 G \text{ watts} \qquad 4.1.2$$

Where R_{dc} is the dc resistance of the wire, G a numerical factor which allows for the skin depth, and d the diameter of the wire.
The additional power loss is therefore proportional to H^2, and when the ferrite is introduced H increases by L_f/L_{air} and so the power loss increases as $(L_f/L_{air})^2$. Since this extra power loss occurs *without an increase in the current I*, it must come from an apparent increase in the resistance, and so the resistance of the wire will increase by $(L_f/L_{air})^2$.
Therefore to a first approximation the wire loss increases by $(L_f/L_{air})^2$, and this goes a long way to explaining Polydoroff's additional loss described in the Introduction.

5. CONDUCTOR LOSS IN AIR COILS

The inclusion of the ferrite therefore increases the resistance of the air coil, and so it is air coils which are considered first.
The alternating current resistance of single layer air coils wound with round wire presents serious mathematical difficulties and was attempted by Butterworth in the 1920's, but his analysis has been shown to be not very accurate for the important case of close wound coils (Medhurst ref 6). In 1951 a more

accurate theory was developed by Arnold (ref 7), but again the analysis is complicated and the resulting equations difficult to use.
Recently Payne (ref 8) has produced a new analysis which leads to the following equation for the resistance of the wire, and this equation has the advantage that it can be readily programmed into spread-sheets:

$$R_{wire} = R_{ow} + R_{ow} k_r K_n^2 + R_{wall} N^2 32 \pi (1- K_n) (d_w / p)_{av} M^2 (l_e / l_c)^2 (a_{coil} / l_{coil}) / (w_2 / w_1) \qquad 5.1$$

{The individual factors are defined later}.

The above equation is of the form :

$$\mathbf{R_{wire} = R_{ow} + R_{Aw} + R_{Rw}} \qquad \mathbf{5.2}$$

R_{ow} is the high frequency resistance of the unwound wire conductor, and R_{Aw} and R_{Rw} are the added resistances due to the axial and radial components of the fields cutting the conductor (see Figure 5.1).

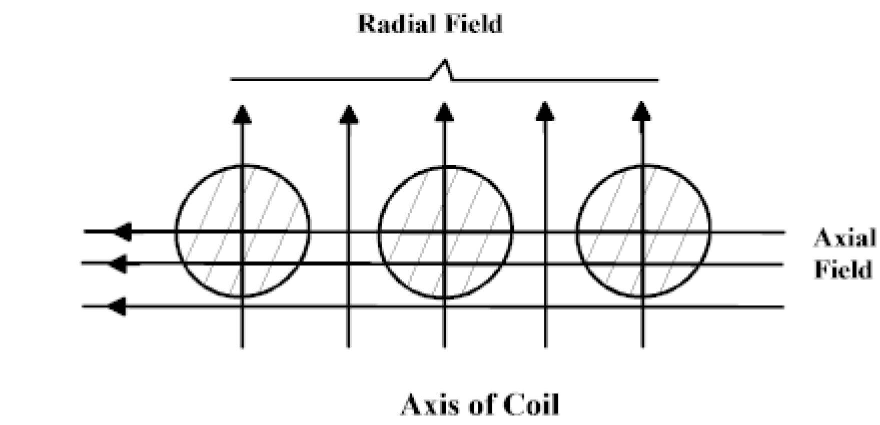


Figure 5.1 Axial and Radial Fields

When the ferrite is added these axial and radial fields are changed, and this changes the values of R_{Aw} and R_{Rw} as detailed below.

6. EQUATIONS MODIFIED FOR FERRITE ANTENNAS

6.1. Flux Distribution in Ferrite Cored Coil

When the ferrite is introduced into the air coil the main effect is that the magnitude of the flux increases by L_f/L_{air}, and if this were the only change then the loss components R_{Aw} and R_{Rw} would be increased by $(L_f/L_{air})^2$ [see Section 4]. However, the shape of the field also changes, as shown in Figure 6.1.

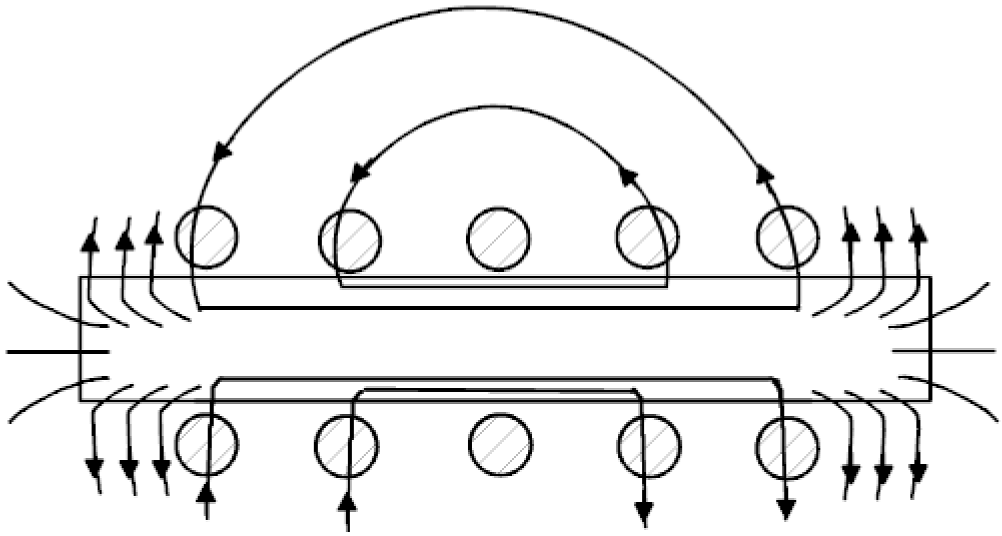


Figure 7.1 Flux Distribution in Ferrite Coil

The key difference in the shape is that the magnetic flux takes the course of least reluctance which is through the ferrite, so the *axial* field through the wires is very much smaller than in the air coil. The effect of this change is considered below.

6.2. The Conductor Loss due to the Axial Field

In the air coil the current in the wire is concentrated onto the side of the wire closest to the centre of the coil. This arises because the axial field is stronger on the inside of the coil than on the outside (Figure 4.1), and so a filament of the wire on the outside is enclosed by more flux that a filament of wire on the inside. The outside filament therefore has a higher inductance and its current is reduced.

The axial field is reduced considerably when the ferrite is introduced, and indeed if the ferrite permeability is high it can be assumed that the field is close to zero, and that current flows over the whole circumference of the wire. Thus $R_{Awf} \approx 0$ for high permeability. Notice that this is a *reduction* in resistance.

There are two other factors in Equation 5.1 which are dependent on the axial field : $(d_w /p)_{av}$ and (w_2 / w_1). The first of these is *apparent* ratio of the wire diameter to the pitch, and this differs from the actual ratio because of currents induced in the wire by the axial field. When the axial field is zero $(d_w /p)_{av} = (d_w /p)$. The second factor (w_2 / w_1) becomes unity when there is no axial field.

6.3. The Conductor Loss due to the Radial Field

When the ferrite is introduced the loss resistance R_{Rw} can be expected to increase to :

$$R_{Rwf} \approx R_{Rw} (L_f/L_{air})^2 \qquad 6.3.1$$

The coil diameter will be slightly greater than that of the ferrite, and so the flux leaving the ferrite will have a lower density when it reaches the coil, by the ratio of their areas $(a_c/a_f)^2$. So Equation 7.3.1 becomes :

$$R_{Rwf} \approx R_{Rw} (L_f/L_{air})^2 (a_c/a_f)^2 \qquad 6.3.2$$

There is also another adjustment to be made : those factors in Equation 5.1 which describe the intensity and shape of the flux [Kn, M and l_e / l_c] are now describing this within the ferrite (over the length of the coil) and so in the calculation of these it is the *ferrite* diameter which must be used rather than that of the coil. In this respect it is as if the coil was projected onto the surface of the ferrite.

6.4. Loss in the Ferrite

The series loss resistance due to the ferrite itself has to be added to the above conductor loss. The Q of the open ferrite is given by Equation 2.4.1, so the series resistance due to this is loss is given by

$$R_f = \omega L_f / (Q_{m\ open}) \qquad 6.4.1$$

where $\omega = 2\pi f$
L_f is the inductance with ferrite
$Q_{m\ open}$ is given by Equation 2.4.1

7. Overall Loss Equation with Ferrite Core

From the previous section the overall resistive loss is given by :

$$R_{wire\ t} = R_{ow} + R_{Rw}\ (L_f/L_{air})^2\ (a_c/a_f)^2 + \omega L_f / (Q_{m\ open}) \qquad 7.1$$

where L_f/L_{air} is given by Equation 2.4.2
L_f is the inductance with ferrite (Payne ref 4)
l_{coil} is the length of the winding (see para 8.1)
$Q_{m\ open}$ is given by Equation 2.4.1

R_{ow} is the loss of the unwound straight wire, and if $(2\pi\ a_{coil}\ N)^2 >> l_{coil}^{\ 2}$ (the normal case) is given by (see Payne ref 8) :

$$R_{ow} \approx R_{wall}\ 2\ a_{coil}\ N^2 / [l_{coil}\ (d_w/p)] \qquad 7.2$$

where d_w is the effective wire diameter (see below)
p is the pitch of the winding
N is the number of turns
a_{coil} is the radius of the winding to the centre of the wire
$R_{wall} = \rho / \delta$ where ρ is the resistivity and δ the skin depth of the conductor. For copper $R_{wall} = 0.264\ 10^{-3}\ f^{\ 0.5}$, where f is in MHz

R_{aw} is the loss due to the axial field and is given by :

$$R_{Rw} = R_{wall}\ N^2\ 32\ \pi\ (1 - K_n)\ (d_w/p)\ M^2\ (l_e / l_c)^2\ (a_{coil}\ / l_{coil}) \qquad 7.3$$

where $K_n \approx 1/ [\ 1 + 0.45\ (d_f / l_{coil}) - 0.005\ (d_f / l_{coil})^2\ ]$
$M \approx d_f / [\ (2\ d_f)^2 + (\ l_{coil})^{\ 2}]^{\ 0.5}$
$(l_e / l_c) \approx K_n\ (1 + 0.05\ d_f / l_{coil}\ )$
d_f is the diameter of the ferrite

The effective diameter of the wire is smaller than its physical diameter because the current recedes from the surface by one half of the skin depth (see Wheeler ref 9). This effect can be very large, and for instance a wire with a physical diameter of 0.2 mm will have an effective diameter 33% less at 1 MHz.

So $d_w = d - \delta$, where d is the physical diameter and δ the skin depth which for copper is equal to 66.6 /$f^{0.5}$ where f is in Hz. This is accurate to within 5.5% for wire diameters greater than twice the skin depth ($d_w / \delta > 2$).

8. EXPERIMENTAL RESULTS

8.1. General

In the following a comparison is made between experiment and the theory given above. To avoid any errors in the calculation of the ratio L_f/L_{air}, this ratio was derived from the measurements, and used in the calculation of loss resistance.

The calculated resistance is very sensitive to the values of the coil diameter and length, and the diameter of the wire, and this sensitivity is discussed later. The definition used here for these parameters is :

Wire diameter is the physical diameter minus the skin depth. Skin depth is 0.036 mm in copper at 3.4 MHz and the wire diameter was measured at 0.55 mm after burning off the insulation.

The coil diameter is the mean diameter of the winding ie the diameter of the former on which the wire was wound plus one wire diameter

The coil length is N times the pitch, where N is the number of turns. Notice that this is greater than the distance from the first turn to the last turn and represents the equivalent length of the current sheet (see Grover ref 10, p149).

8.2. Comparison of Theory and Experiment

A coil of 17 turns was wound onto a low loss former with 0.55mm dia wire, over a current sheet length of 22.6mm, so the ratio d_w/p was 0.39. The mean winding diameter to the centre of the wire was 11.84mm. Its air inductance was measured at 1.55 µH, and corrected at each frequency for its self-resonant frequency SRF, using Equation 9.1.1. (SRF was measured as 75 MHz). This corrected value of L_{air} was used to calculate the ratio L_f/L_{air}.

Nickel- Zinc ferrite rods of various lengths up to 120mm were inserted into this coil, each rod having a diameter of 10mm, but with two flats along the sides. The effective diameter was estimated at 9.42 mm.

At each length the inductance, series resistance and SRF of the coil were measured at 3.4 MHz, and the values corrected for the SRF (measured for each rod length) according to Equations 9.1.1 and 9.1.2

The frequency of 3.4 MHz was chosen because the Q of this particular ferrite was only 35 at this frequency (see below), and thus the ferrite would give a fairly high loss resistance, enabling this aspect to be evaluated.

In the graph below the measurements of the total loss resistance are shown in blue and the calculated total loss (Equations 7.1, 7.2 and 7.3) is in red. Also shown in green is the calculated contribution to the total loss by the ferrite (Equation 6.4.1):

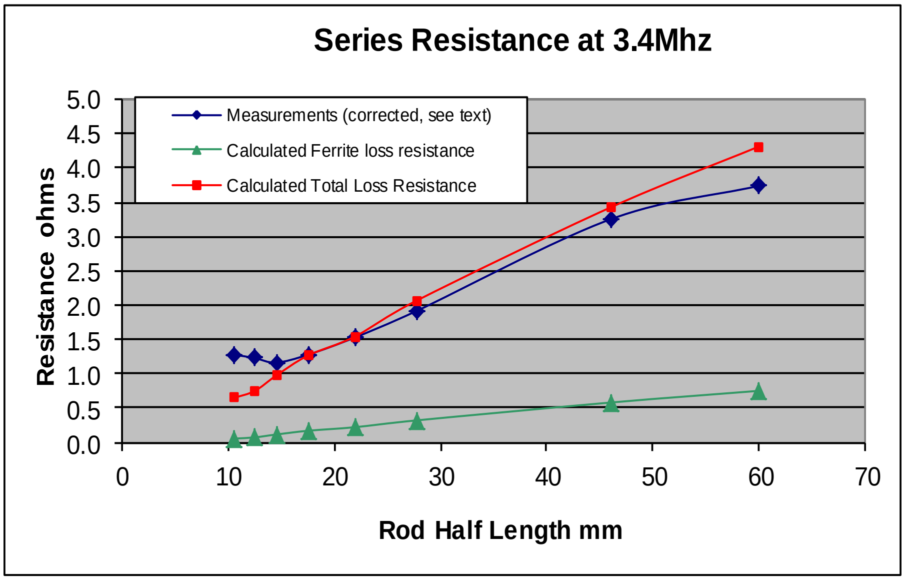


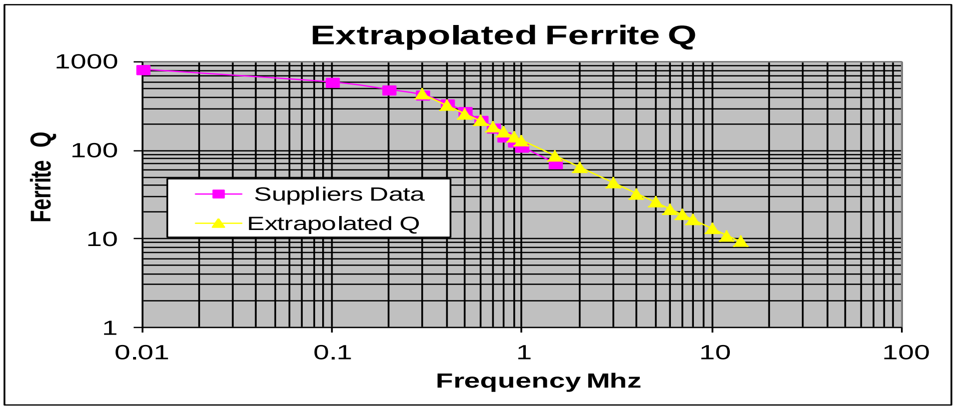
Figure 8.2.1 Comparison of Measured and Calculted Resistance

The agreement is very good given the possible measurement errors, and the need to extrapolate the ferrite parameters to this frequency (see below). Notice that the ferrite loss is a small part of the total loss, despite the fact that this ferrite was being operated above its normal frequency range so its loss was unusually high.

There is larger error at small values of the ferrite length when the ferrite is the same length as the coil or just a little longer. This is because the calculations do not account for the very high radial field at the end of the ferrite intercepting the coil at these shorter lengths. Although the equations could be extended to cover this it would be of little practical value because it is easy to avoid this high loss situation by making the ferrite longer than the coil by 2 ferrite diameters or more.

8.3. Ferrite Loss

The ferrite loss was given by the supplier up to a frequency of 1.5 MHz and was extrapolated to 3.4 MHz as shown below :



The closest agreement with the data supplied with the ferrite was with Q decreasing as $1/f^{1.2}$, giving an extrapolated value at 3.4 MHz of Qm = 28. However the theory of domain movement in ferrites which leads to the loss, gives Q reducing as 1/f (see Hamilton ref 11), and this gives a Q of 35 and this extrapolation is shown in the curve above and was used in the calculations for Figure 8.2.1.

8.4. Parameter Sensitivity

The sensitivity of the calculated results to errors in the coil parameters was assessed by increasing each by 5% from the values used in Section 8.2 and noting the change in the calculated resistance ΔR, as follows:

Coil diameter : $\Delta R = +9\%$
Coil Length : $\Delta R = -7\%$
Wire Diameter : $\Delta R = +4\%$

So for accurate calculation it is important to measure these as accurately as possible, according to the definitions given in Section 8.1.

9. MEASUREMENT METHOD

9.1. Correction for SRF

For each measurement the self resonant frequency f_r of the coil, or coil + ferrite was measured, and this was used to correct the measured inductance L_c and the measured resistance R_c using the following equations (see Welsby ref 5, p 37)

$$L = L_c \, [\, 1- (f / f_r\,)^2] \qquad 9.1.1$$

$$R = R_c \, [\, 1- (f / f_r\,)^2]^2 \qquad 9.1.2$$

This correction is accepted practice and is based on the assumption that coils have a self capacitance, and that this increases the *apparent* resistance and inductance when the coil is used in a series resonant circuit. However the author has shown that the change in inductance and resistance with frequency is a real change (Payne ref 14), and so the above factors should therefore be part of the *theory*, rather than a correction of the measurements. However for the purpose of comparing measurements with theory it doesn't matter particularly whether this 'correction' is applied to the theory or the measurements, and since the latter is accepted practice this was done here.

9.2. Measurement of Inductance and Resistance

Measurements were made with an Array Solutions AIM 4170 analyser, with the impedance of the connection leads calibrated out. The resistance measurements were subject to large uncertainties because of the presence of the very high inductive reactance, particularly when the ferrite was present, and so this reactance was tuned out with a high quality variable capacitor. This had silver plated vanes and wipers, and ceramic insulation and had a resistance given by (see Payne ref 12) :

$$R_{cap} = 0.01 + 800/\,(f\,C^2) + 0.01\,f^{\,0.5} \qquad 9.2.1$$

Where C is in pf, and f in MHz

This resistance was used to correct the measured results but it was always very small compared with the overall measured resistance.

The resistance values were below 5 Ω, and the analyser accuracy is guaranteed as only 1Ω, however a calibration resistor measured at dc as 2.1 Ω on a meter with a resolution of ±0.05Ω was measured by the analyser as being between 1.97 and 2.1Ω at frequencies up to 3.4 MHz, implying an accuracy of 1%.

10. SUMMARY

Ferrite rod antennas are shown to have a large loss in the wire, in addition to the expected loss in the ferrite. The author's equations for the loss in air cored coils is extended to give the loss with the ferrite added, and experiment shows good agreement with the theory given.

It is clear that the major loss is in the conductor rather than in the ferrite and so Litz wire should be used where possible (Payne ref 13). Also the coil should be made shorter than the ferrite by at least two diameters, to minimise the loss due to the radial flux from the ends of the ferrite.

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