

Inductance of Magnetic Plated Wires as a Function of Frequency and Plating Thickness

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Abstract: This paper analyzes the magnetic behavior of electroplated wires. For this purpose the resistance and inductance of single turn loops and coils have been simulated and measured. The measurement is delicate due to the influence of a stray capacitance. We show that the quality factor of magnetic plated loops and coils can be tuned easily by the plating thickness. In addition the quality factor of the plated material is larger than that of its pure constituents. The relative permeability of electroplated nickel seems to be either inferior to that of pure nickel or frequency dependent above 10 MHz.

Keywords: Magnetic wires, quality factor, azimuthal induction current application mode, time-harmonic analysis type.

1. Introduction

Several companies fabricate magnetic-coated wires for various properties such as high tensile strength or high temperature resistance. These wires can be used as watch coils or in core-wound motors. Other magnetic-plated wires are used for high frequency coils or delay lines. The losses are reduced by about 10% compared to conventional copper coils, according to the application notes of a Japanese wire manufacturer. This company argues that the reduction is due to magnetic shielding. They claim that the electric current density of plated wires is more homogeneous, the effective resistance therefore reduced.

In collaboration with a Swiss company, which also produces such wires, we tried to reproduce and understand the above mentioned shielding phenomena. We measured the quality factor Q of various coils fabricated with different wire materials. The measurements were compared to FEM calculations. The magnetic shielding can be understood in terms of classical electrodynamics and skin effect. In this paper we present COMSOL Multiphysics results and their experimental validation. We discuss the electric current distribution in the wires as a function of

frequency and plating thickness and its implication on the effective resistance and the inductance of a current loop and of coils.

In the past fifteen years magnetic wires have been investigated by several researchers. The term "giant-magneto-impedance" (GMI) was created for the magnetic behavior of wires, ribbons and multilayered soft ferromagnetic thin films [e.g. 1, 2]. GMI material can be used for magnetic shielding, strain sensors or fluxgate sensors to measure small magnetic fields [3]. In order to exhibit GMI various conditions must be satisfied: The material should be magnetically soft and display hysteresis cycles. The magnetic behavior should be anisotropic. An a.c. current must be applied perpendicular to the magnetic easy axis. The magnetic material should have a small resistivity ($\leq 100 \mu\Omega \text{ cm}$).

The wires presented here are suited to display the above mentioned giant magnetic inductance. However we investigated only their classical inductive and resistive behavior when formed to loops or coils.

The paper is organized in the following sections: We present our experimental setup in section two. In the third section the numerical models are presented. A brief introduction to theory and approximations are given in section four. Section five discusses the single loop results. Section six explains the real coil calculations and their experimental validation. We conclude with a summary in the final section seven.

2. Experiment

For the experimental validation of our simulations we used a commercial coil [4] of 8.0 mm in diameter and 2.7 mm in length. The coil consisted of 30 turns of a wire with a diameter of 80 μm . The nonmagnetic copper core was electroplated with a 1.5 μm thick nickel layer by the wire manufacturer. An optical micrograph of the cross section of the wire is shown in Figure 1. The complex impedance of

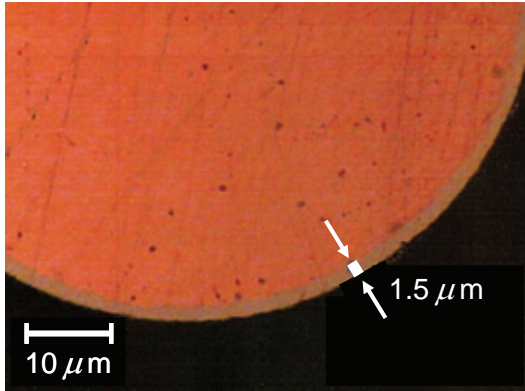


Figure 1. Cross section of a magnetic-plated wire with 80 μm in diameter. The magnetic surface layer is nickel and has a thickness of 1.5 μm . The non-magnetic core consists of copper. This wire was used in coils to validate the numerical simulation.

the coils was measured with the Network / Spectrum Analyzer HP4195A in the frequency range from 10 Hz to 100 MHz. The quality factor Q was calculated from the phase angle φ of the impedance.

3. Numerical Models

To understand the inductance and resistance of magnetic-coated wires we studied two models: a single loop and a coil. We chose the loop wire in the model much thicker than the real coil wire. This allowed for detailed analysis of the current density at the wire surface and in the vicinity of the Cu-Ni junction.

3.1 Single Loop Model

With the single loop model we could easily vary the plating thickness and still keep the number of mesh elements moderate. The loop has a diameter of 8 mm and the wire an overall diameter of 1.2 mm. The surface Ni-layer requires at least two elements across to resolve the skin penetration of the a.c. current at high frequency. This requirement increases the number of elements at small layer thickness. Figure 2 shows the COMSOL 2D model of the single loop. We set two outer subdomains (air 1 and 2) to estimate the adequate domain size and compared their magnetic field energies. The magnetic energy of the outer subdomain (air 1) is 0.1 per cent of the inner domain energy.

Therefore the outer domain contributes little to the inductance calculated via the magnetic field energy (see below).

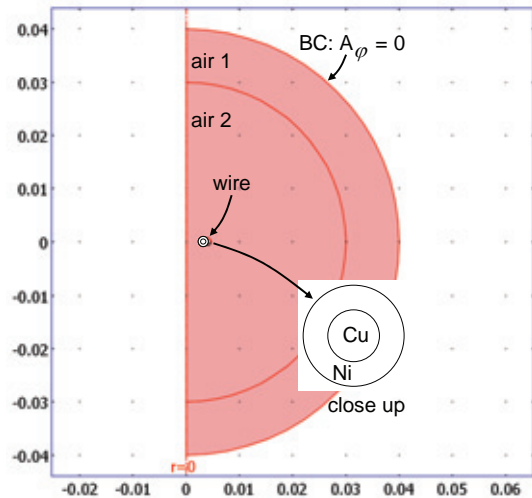


Figure 2. COMSOL model of a wire loop with axial symmetry. The simulation domain is a sphere with a radius of 4 cm. The outer shell (air 1) was used to confirm the adequate size of the simulation domain.

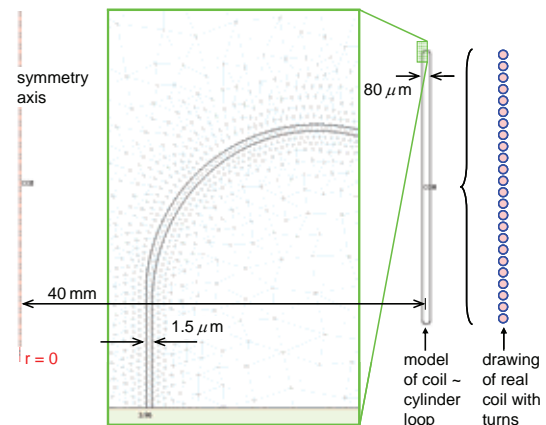


Figure 3. Details of the mesh of the coil model within the green rectangle. The model is set up in axial symmetry. Instead of simulating real turns we simplified the 30 turns to a single loop as shown on the right hand side of the figure. The true values of voltage and current needed to be considered when calculating the inductance and the resistance of the coil (see text).

3.2 Coil Model

The real coil consists of 30 turns of a Ni-plated wire. We consolidated the 30 turns to a single cylinder loop, as sketched in figure 3. The concentration of mesh elements in the Ni-layer can also be seen in figure 3. The Ni-plating of the commercial coil is 1.5 μm thick. The coil's overall wire diameter is 80 μm .

3.3 Simulation Parameters

We used the Azimuthal Induction Current application mode of the AC/DC Module and solved time harmonic (a.c. sine-excitation) and parametric for different frequencies f from 10 Hz to 10 GHz. The dependent variable was the phi-component of the magnetic vector potential A_ϕ . A loop potential V_{loop} was applied to the wire cross section and to the coil cross section, respectively. The domain boundaries were set to magnetic insulation $A_\phi = 0$, or axial symmetry. The computed magnetic flux density, the phi-component of the total current together with the applied loop voltage led to the determination of the loop inductance and resistance according to the following equations:

$$\text{inductance: } L_e = \text{imag} \left(\frac{V_{\text{loop}}}{I_{\text{phi}} \cdot 2\pi f} \right) \quad (1)$$

or

$$L_m = 2 \cdot \frac{E_{\text{mag,field}}}{I_{\text{phi}}^2} \quad (2)$$

$$\text{resistance: } R = \text{real} \left(\frac{V_{\text{loop}}}{I_{\text{phi}}} \right) \quad (3)$$

where V_{loop} is the applied loop voltage, I_{phi} is the phi-component of the total current, f is the a.c. frequency and $E_{\text{mag,field}}$ is the magnetic field energy of the simulation domain.

The total current and the field energy were obtained by subdomain integration of "Jphi_emqa" and "Wmav_emqa", respectively. The loop voltage applied to the overall coil cross section (see figure 3) needed to be multiplied by the number of turns and the phi-component of the total current ought to be divided by the number of turns in order to emulate correctly the real coil.

4. Theory and Approximations

The frequency dependence of the resistance R and the inductance L of a loop or a coil is due to the penetration of the electrical current into the wire, the so called skin effect. The analytical expression for the skin depth δ is given by [Chapter 8 of Ref. 5]:

$$\text{skin depth (theory): } \delta = \sqrt{\frac{1}{\mu_0 \cdot \mu_r \cdot \pi f \cdot \sigma}} \quad (4)$$

where $\mu_0 = 4\pi \times 10^{-7}$ T·m/A, μ_r is the relative permeability, f is the a.c. frequency and σ is the conductivity of the material, in our case copper and nickel.

Alternatively to Eq. (3) the resistance of a wire loop can also be calculated by means of the skin depth δ at high frequency:

$$R \approx \frac{1}{\sigma} \cdot \frac{D\pi}{d\pi \cdot \delta} = \frac{D}{d} \sqrt{\frac{\mu_0 \cdot \mu_r \cdot \pi}{\sigma}} \cdot \sqrt{f} \quad (5)$$

where D is the diameter of the loop and d the diameter of the wire.

It can be seen from Eq. (5) that the resistance will increase with the square root of f at high frequency. Similarly one finds:

$$L_e (\delta \leq \ell) \sim \frac{1}{\sqrt{f}} \quad (6)$$

$$L_m (f \rightarrow \infty) \sim \text{const.} \quad (7)$$

where ℓ is the plating thickness.

The behavior (5) to (7) will be observed in the simulation results (sections five and six).

The quality factor Q of the simulation is defined as the impedance ratio of the inductance to the resistance.

$$\text{quality factor (simulation): } Q = \frac{2\pi f \cdot L}{R} \quad (8)$$

Replacing L and R in Eq. (8) by the expressions (5) to (7) we find Q to be constant at intermediate frequencies ($\delta \leq \ell$) and to increase as the square root of f at high frequencies.

The quality factor Q of the measured coils was computed from the network analyzer data via the equation:

$$\text{quality factor (measurement): } Q = \tan(\varphi) \quad (9)$$

where φ is the phase angle of the complex impedance of the experimental setup (coil plus mounting board).

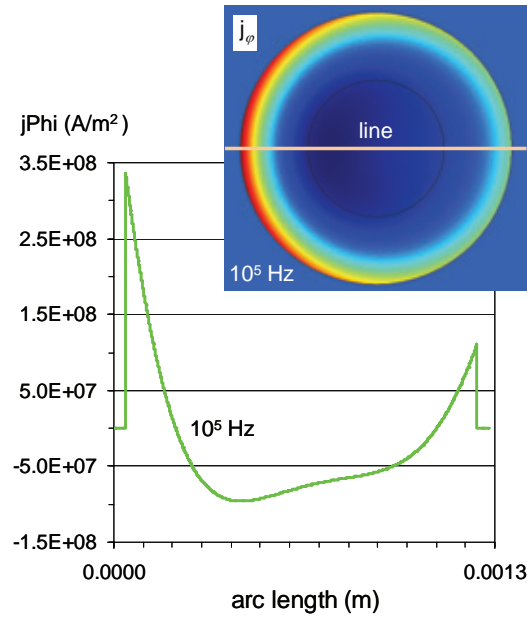


Figure 4. Top: Surface plot of the phi component (real part) of the total current density of a copper loop at 10⁵ Hz. The red color represents positive values, dark blue is negative, i.e. the current is inverted compared to the exciting voltage. Bottom: Line plot of j_{φ} vs. arc length across the diameter of the wire.

5. Single Loop Results and Discussion

5.1 Current Density and Skin Depth

Fig. 4 shows the real part of the current density in the pure copper wire of a single loop at 10⁵ Hz. Calculation of the skin depth yields $\delta \approx 200 \mu\text{m}$, which is compatible with the j_{φ} vs. arc length graph of figure 4.

5.2 Quality Factor Q versus Frequency f

The quality factor Q vs. frequency f has been computed for a number of different plating

thicknesses ℓ (green curves in Fig. 5). The overall wire diameter is $d = 1.2 \text{ mm}$, the loop diameter is $D = 8 \text{ mm}$. Q vs. f of a pure copper loop (red) and a pure nickel loop (blue) are also shown in figure 5. The Ni-curve displays an S-shape, the Cu curve has a kink at 30 kHz. It is interesting to notice that the plated wires do not behave just "in between" the Cu and Ni curves. They have their own characteristic shapes with a local Q -maximum. The frequency of the maximum varies as a function of plating thickness. All plated loops display a range of Q -values larger than both, the pure copper and nickel loop by almost an order of magnitude.

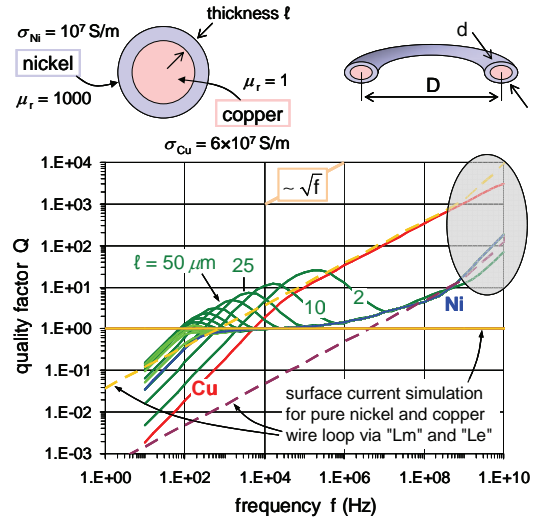


Figure 5. Quality factor Q versus frequency f of a single wire loop (wire diameter $d = 1.2 \text{ mm}$, loop diameter $D = 8 \text{ mm}$). The plating thickness of nickel varies from $\ell = 2 \mu\text{m}$ to $\ell = 500 \mu\text{m}$ (green curves). A local maximum can be discerned for thin Ni layers. The behavior of a pure Cu loop (red curve) and a pure Ni loop (blue) are shown for comparison. The surface current simulation for pure Cu and Ni are displayed as dashed lines (orange and violet). The horizontal orange line corresponds to Q calculated via L_c and surface current simulations. The values in the gray area are not reliable due to numerical limitations.

6. Coil Model and Validation

Wire coils have been simulated for plated layers with different relative permeability. The plating thickness is $\ell = 1.5 \mu\text{m}$. The simulated data and Eq. (8) yield the quality factor Q as a function of frequency which is displayed in

figure 6 for $\mu_r = 100$ (pink line) and $\mu_r = 50$ (orange line). The measured Q of a plated Ni-Cu coil (blue line) and a pure Cu coil (green line) is also shown in Fig. 6. Notice the pronounced decrease of Q of the Ni-Cu coil starting just below 60 MHz. The real coil constitutes also a stray capacitance. The capacitance is included in the Q value obtained by Eq. (9). Other measurements show that the coil exhibits an L-R-C resonance at about 62 MHz. This resonance masks the Q value calculated by means of Eq. (8). Therefore the simulated ($\mu_r = 50$, orange line) and the measured (blue line) Q values disagree above 40 MHz, but they agree well below 40 MHz. The electroplated coils seem to comprise a much smaller permeability than expected at first (see loop simulation with $\mu_r = 1000$). The noise in the measured data above 10 MHz is due to the experimental setup and is reproduced for all coils, wound with pure wire or plated wire.

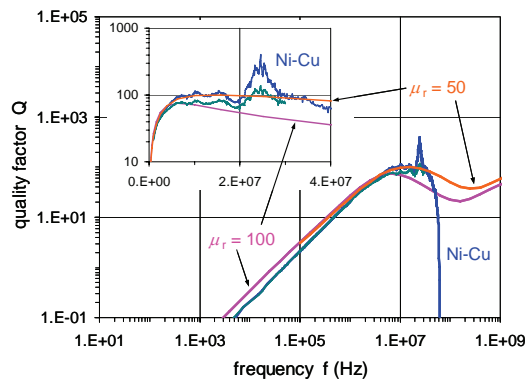


Figure 6. Quality factor Q versus frequency f of 30 turn coils (coil diameter $D = 8$ mm, wire diameter $d = 80$ μm). The pink ($\mu_r = 100$) and orange ($\mu_r = 50$) line correspond to simulated Q values for the plated wire coil (plating thickness $\ell = 1.5$ μm). The green curve is the measured pure copper coil, blue the measured nickel plated coil. The latter displays a sharp drop starting at about 40 MHz. This is due to the stray capacitance of the real coil. Together with the inductance and resistance of the coil, the capacitance forms an L-R-C circuit with a self parallel resonance at 62 MHz (see text).

7. Conclusions

The resistance, the inductance and the quality factor of plated single turn loops and of coils can be simulated with the classical electrodynamics AC/DC module of COMSOL. Interestingly, there exist frequency regimes where the Q value of the plated loop is larger than those of its pure constituents copper and nickel. The possibility to tune the Q values by means of the plating layer thickness might find application in the recently discovered power transfer by magnetic resonance [6]. The comparison of the measured to the simulated Q values allows to determine the relative permeability of the electroplated layer. To our surprise, the μ_r value for the nickel layer is rather low, namely $\mu_r \approx 50$; or frequency dependent above 10 MHz. Due to the close L-R-C resonance the experimental determination of the Q value in the frequency regime from 10 - 40 MHz is rather difficult. The simulated results of the coil and the measurements agree well below the resonance frequency.

8. References

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9. Acknowledgements

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