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Investigation of planar coil for eddy current conductivity measurements in wide frequency range

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***Abstract*-**Several planar coil designs have been investigated for the application in accurate AC conductivity measurements in the wide frequency range. The measurement method is based on the eddy-current probe-coils solutions proposed by Dodd and Deeds [1]. The coil parameters affecting the performance of the model in the specified frequency range from 30 kHz to 720 kHz have been investigated.

Different designs have been used including coils on a printed circuit board (PCB), coils on a flexible substrate and on-site manufactured coils winded from a copper wire. The goal was to reach the inductance of the different coils to match the best-accuracy of the measuring instrument. Amongst the others, the important factor was to keep the diameter of the coils suitable for the practical applications.

Keywords: Conductivity, impedance, eddy-current, measurement, planar coil.

I. Introduction

Electrical conductivity measurements are widely used by industry in production and inspection of metals. For example in aviation the electrical conductivity measurement is used to identify defects in metal parts e.g. aircraft wings. The electrical conductivity measurements are used in the coinage industry for quality assurance and for detecting of counterfeited coins. Owing to the wide range of interest in the measurement of electrical conductivity, the non-destructive testing techniques are still acute.

Several research groups have investigated methods to establish accurate electrical conductivity measurements with inductive sensors. The results obtained are in many cases applicable within the narrow frequency range only and with the moderate measurement uncertainties [2, 3], limited mostly by the coil design and measurement accuracy of the coil parameters used in the mathematical model. Furthermore, it has been observed that there is a considerable difference in between the electrical conductivity value measured by using DC [4] and those for measured using AC techniques in the frequency range up to 100 kHz [4, 5].

The purpose of this paper is to present the investigation of the different coil designs used in electrical conductivity measurements in the wide frequency range. We describe the parameters of the coils studied and present the measurement results of the electrical conductivity obtained when taking into account the equivalent circuit for the real inductor.

II. Method description

The eddy current conductivity measurements are based on the measurement of an impedance change of a coil. The theoretical derivation of an impedance change ΔZ of an air-core coil located above a conducting nonmagnetic half-space with the constant conductivity σ can be found elsewhere [1]. The relation for the change in impedance of an air-core coil located above a conducting nonmagnetic half-space with constant electrical conductivity σ derived in [1] has the form described in [6].

Formulas (1) – (4) are used for calculations. Here h_2 and h_1 are the distances from the bottom and the top of the coil to the conductive half-space, r_{out} and r_{in} are the outer and inner radii of the coil, respectively, ω is the frequency, μ_0 is the magnetic constant and $J_1(\xi)$ is the Bessel function of the first kind of order one.

$$Z_{ind}^{T} = j\omega\pi\mu_0 \frac{N^2}{(r_{out}-r_{in})^2(h_2-h_1)^2} W, \qquad (1)$$

$$W = \int_0^{\infty} \frac{\lambda - q}{\lambda^6(\lambda+q)} (e^{-\lambda h_2} - e^{-\lambda h_1})^2 g^2(r_{in}, r_{out}, \lambda) d\lambda, \qquad (2)$$

$$q = \sqrt{\lambda^2 + j\omega\sigma\mu_0}, \qquad (3)$$

$$g(r_{in}, r_{out}, \lambda) = \int_{\lambda r_{in}}^{\lambda r_{out}} \xi J_1(\xi) d\xi, \qquad (4)$$

$$\Delta^2 = \frac{\left(X_{ind}^{E} - X_{ind}^{T}\right)^2}{\left(X_{ind}^{E}\right)^2} + \frac{\left(R_{ind}^{E} - R_{ind}^{T}\right)^2}{\left(R_{ind}^{E}\right)^2}. \qquad (5)$$

The electrical conductivity σ can be determined from the measurement results of the reactance X and the resistance R and solving the inverse problem. In our method, we minimize the norm of the difference between theoretical predictions and experimental measurements where the subscripts T and E denote the theoretical and experimental values, respectively. It is assumed in the present paper that the inverse problem is solved when the two parameters, namely, the conductivity and the lift-off, are unknown. Solutions of the forward and inverse problems required for calculation of the electrical conductivity value have been realized by software specially developed at our laboratory [7].

III. Studied planar coils

Six measurement coils with different parameters have been investigated. The properties of the tested coils are presented in the Table 1. The dimensional measurements were carried out by the measurement microscope. The measurement uncertainty of dimensional measurements was 20 µm (coverage factor $k = 2$). The inner and outer diameters of the coils ranged from (1…18) mm and (48…52) mm respectively.

All the investigated coils have the inductance of about 220 µH ±10 %. This is required for the measurements matching the best accuracy of the measurement equipment. The number of turns of the investigated coils varies from 82 to 111.

The inductance and resistance values of the coil presented in Table 1 are measured at 30 kHz. The impedance of the studied coils has been measured by a LCR meter calibrated in the specified frequency range by the traceable capacitance and resistance standards assuring the measurement uncertainty to be less than 0.1 %. The temperature during the electrical and dimensional measurements was kept constant (23.5 ± 0.5) °C and (22.4 ± 0.5) °C respectively.

Table 1. Properties of the tested coils

Coil ID	**Inductance *L*, µH**	**Resistance *R*, Ω**	**Distributed capacitance *C*, pF**	**Quality factor *Q***	**Resonance frequency f_0, MHz**
W92	240.8	9.17	0.935	4.95	10.6
B1	202.1	26.02	1.953	1.46	8.0
B11	242.5	44.97	1.875	1.02	7.5
B16	202.2	68.42	1.785	0.56	8.4
Z3	222.7	116.2	3.335	0.36	5.9
Z2	221.7	282.5	2.330	0.15	7.0

The studied coils differ from each other by the design and the substrate, the coils denoted as Z2 and Z3 are manufactured on the flexible substrate, the substrate for the coils denoted as B1, B11 and B16 is PCB. The coil denoted as W92 is made from a copper wire with the diameter 0.15 mm and is made onto an adhesive layer. The coil W92 is manufactured on-site while the rest of the coils are commercially available from the different electronic board manufacturers.

IV. Results and discussion

An ideal coil is a purely inductive element having no resistance and capacitance. However, the real inductors dissipate energy due to resistive losses and at some frequency become resonators because of distributed capacitance. A simplified lumped element equivalent circuit of the real coil is shown in Figure 1, where L, R and C are the inductance, resistance and capacitance respectively. The resistance and inductance listed in Table 1 have been measured at the lowest investigated frequency of 30 kHz by the precision LCR meter. The quality factor Q better describing the performance of the coil is used to present the obtained results hereinafter (6), where Im(Z) and Re(Z) are the real and imaginary parts of the impedance.

$$Q = \frac{|\mathrm{Im}(Z)|}{\mathrm{Re}(Z)}. \tag{6}$$

The parasitic capacitance has been determined by the measurement of the resonance frequency from the equation (7), where ω_{SRF} is the resonance frequency and L is the inductance of the coil.

$$C = \frac{1}{(\omega_{SRF})^2 L}. \tag{7}$$

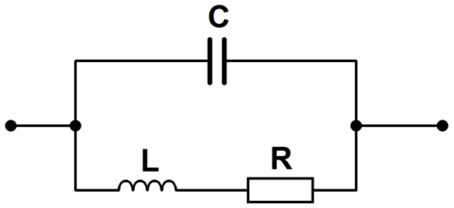

Figure 1. The equivalent circuit for the real inductor

The effect of the parasitic parameters R and C on the determination of the electrical conductivity value has been studied by measurements of the impedance of each coil over the wide frequency range using the precision LCR meter. The conductivity is determined by the program based on the Dodd and Deeds theory [1] requiring two impedance measurements of the coil: in the air and with a metal plate above the coil.

In Figure 2 the AC conductivity value of a 14 MS/m sample plate determined by six different coils is presented as a deviation from the DC conductivity value determined by using the accurate Van der Pauw technique [8].

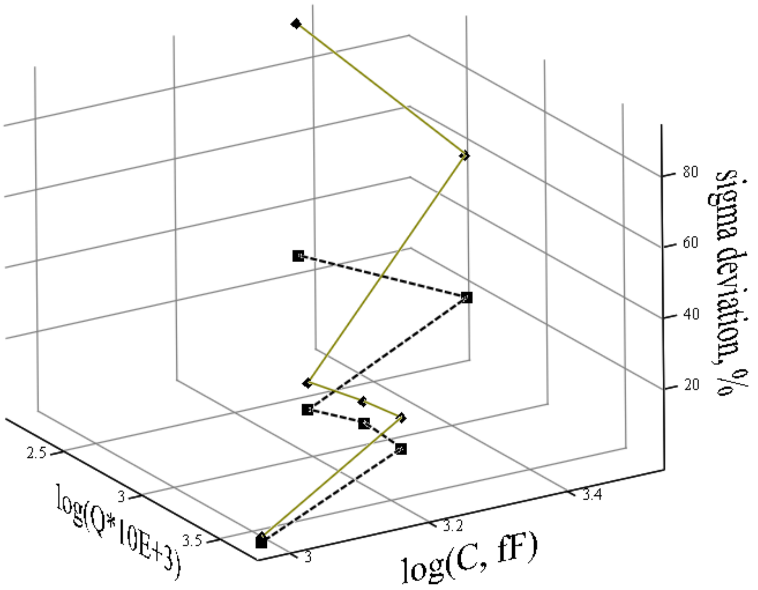

Figure 2. Conductivity deviations from the DC value determined for six measurement coils at the frequencies of 30 kHz (dashed line) and 720 kHz (solid line) as the function of the quality factor measured at 30 kHz and distributed capacitance

The eddy-current measurements were performed at 8 frequencies in the range from 30 kHz to 720 kHz. In this paper the results are presented at two frequency points, i.e. at 30 kHz and 720 kHz, as the measurement results at the intermediate frequencies fall in between the values obtained with those frequencies.

As it can be concluded from Figure 2, the difference of the DC electrical conductivity value from that of determined by the eddy-current method strongly depends on the coil resistance and capacitance. Therefore, the high quality factor and low distributed capacitance should be kept closely to the ideal inductor when designing a sensor for accurate absolute conductivity measurements. The data obtained for the sigma deviation denoted as $f(x)$ can be approximated by the power function having the form of the equation 8, where A is a constant and z is the power of x, where x is the two parameter function $x = f(Q, C)$.

$$f(x) = \frac{A}{x^z}. \tag{8}$$

By designing a coil with carefully selected parameters, the AC conductivity deviation less than 1.1 % relative to the DC reference values can be achieved over the frequency range from 30 kHz to 720 kHz. In Figure 3 the conductivity value of three metal plates has been determined by the coil denoted as W92 having the lowest parasitic parameters. The measurements have been performed in the air-thermostat with the temperature stability better than 0.1 °C.

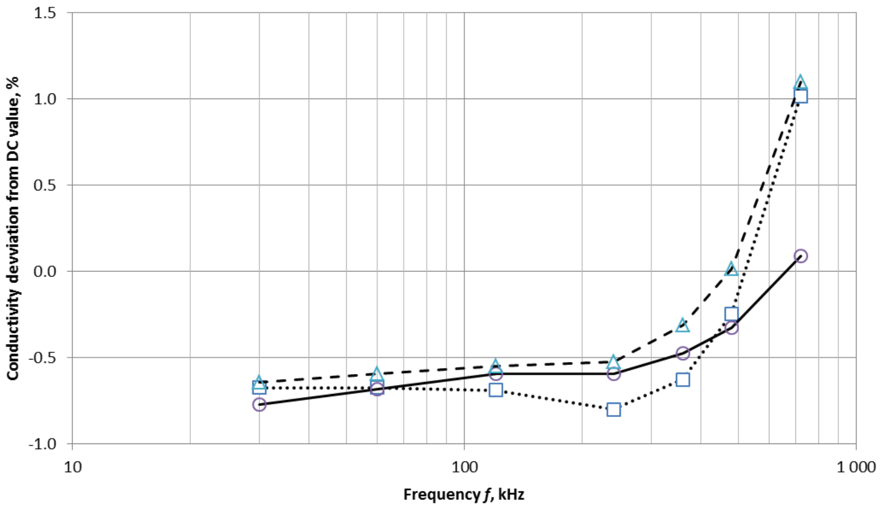

Figure 3. Conductivity deviations from the DC value determined with measurement coil denoted as W92 at frequencies of 30 kHz to 720 kHz against different absolute electrical conductivity measurements. 14.28 MS/m (dotted line), 9.57 MS/m (dash line), 2.172 MS/m (solid line)

V. Conclusion

The measurement coils produced by three technologies having different coil quality factors, has been studied for application in the accurate electrical conductivity measurement. The quality factor and distributed capacitance being the most critical parameters affecting the accuracy in determination of the AC conductivity value by the eddy-current method has been investigated.

It has been shown that by designing a coil with the carefully selected parameters, a good agreement between the AC and DC conductivity values can be achieved in the wide frequency range. In combination with accurately measured dimensional parameters of the coil and stable temperature conditions the characterized coil can be applied for the traceable calibration of electrical conductivity standards at the AC current.

The conductivity of three metal plates in the range from 2 MS/m to 14 MS/m has been determined in the frequency range from 30 kHz to 720 kHz with the deviations from the DC value less than 1.1 % of the measured value.

VI. Acknowledgement

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