Comprehensive electromagnetic testing of the properties of functional metal coatings, including multilayer, and its metrological assurance in aerospace industry

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Abstract

In the aerospace industry in recent years has significantly increased the range of metal coatings, the main task of which is to provide a large range of functional properties, in some cases contradictory. The traditional testing of only their thickness does not allow to judge their quality.

On the basis of simulation results the structure and parameters of electromagnetic transducers and measuring system allowing to control electrical conductivity, magnetic permeability and thickness of coatings and bases of standards and products designed to work in particularly harsh conditions of ultra-high temperatures and loads with the provision of specified functional electromagnetic, geometric and mechanical properties were developed.

The results of modeling, methods of calculation of parameters and operating modes of measuring transducers, description of developed standards of coating and base properties, as well as the structure and parameters of the reference complex for metrological assurance of measurement results are presented. Metal coating thickness reference standards (measures of thickness of conductive coatings on conductive base) are described, for which not only geometric but also electrophysical parameters are normalized, such as electrical conductivity and complex relative magnetic permeability of the base, electrical conductivity of the coating.

1. Introduction

At present, the aerospace industry uses a large number of metal products with a variety of coatings, which should provide not only protective, but also various functional properties. The functional properties of products and metal coatings in most cases are determined by their coating thickness and the specified values of the electrophysical parameters of metal coatings and bases.

In the production of these products is widely used a large number of dissimilar metals and alloys. Requirements for the quality of coatings are increasing, more complex technological tasks are being solved, many different application technologies are used, which complicates the process of quality control. Traditionally, one of the main parameters of the coating quality is its thickness T_c, the measurement range of which can range from tenths of a micrometer to several millimeters. In the conditions of actively developing high-tech industries, the task of increasing the accuracy of T_c measurements becomes more and more urgent, with the required electrophysical parameters of the base and coating materials.

To measure the thickness of metal coatings and their electrophysical properties, it is optimal to use eddy current amplitude, phase and amplitude-phase methods of measurement based on the analysis of the electromagnetic field of eddy currents induced in the object of control and dependent on the group of parameters: electrophysical (specific electrical conductivity of the coating materials σ_c and the base σ_b, as well as the relative magnetic permeability of the base material μ_b) and geometric (T_c, roughness, radius, etc.).

To ensure the unity of measurements, coordination of the work of metrological services, manufacturers and consumers of eddy current instruments, it is necessary to ensure traceability to the state reference standards through the verification scheme, which includes as secondary standards (measures of the thickness of metal coatings on metal bases - MCMB) with known specified electrical and geometric parameters. Such standards are necessary for calibration, primary and periodic verification, as well as for calibration of eddy current thickness gauges when performing measurements in production conditions.

It is obvious that the lack of information about the electrophysical parameters of the standards does not allow their full use in order to ensure the unity of measurements in the field of thickness of coatings, coordination of the work of metrological services, manufacturers and consumers of eddy current instruments. Consider the features of measuring the electrical parameters of MCMB, as well as requirements for their design and manufacturing technology.

2. Measurement of electrical conductivity of base metals of MCMB

Traditionally, bases of MCMB are made in the form of a cylinder or a parallelepiped. In accordance with[(1)] thickness of the measure base T_b is selected from the condition: $T_b \geq \delta_0$, where δ_0 - the standard depth of penetration of eddy currents at a given frequency f of the excitation current of the primary measuring transducer.

Since the value of σ_b does not depend on f, it is of interest, especially in the case of ferromagnetic conductive metals and alloys, the use of direct measurement σ_b by van der Pau method, which establishes relations for the cross-resistance of a flat conductive sample and is a variant of the four-probe method[(2)]. The results of modeling and calculations show that to ensure correct measurements (eliminating the influence of the shape and width of the contacts), the optimal design is the base of the measure presented in figure 1. Also, to ensure the specified accuracy of measurements, the base of the measure should be a polished plane-parallel plate, the opposite sides of which have a nonparallelness of not more than ± 0,05 mm and a surface roughness of Ra < 3,2 µm.

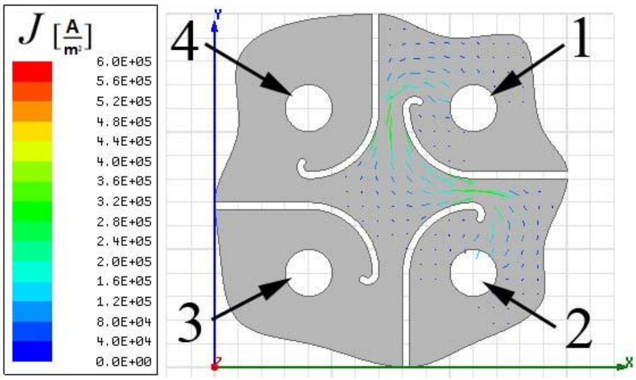


Figure 1. The base of the measure with pads 1- 4 and shaped cuts and the pattern of the current flow between the contacts 1-2 on the simulation results

The connection of the current source 5, the Ohmmeter 6 and a Voltmeter 7 to the contacts is performed in accordance with figure 2.

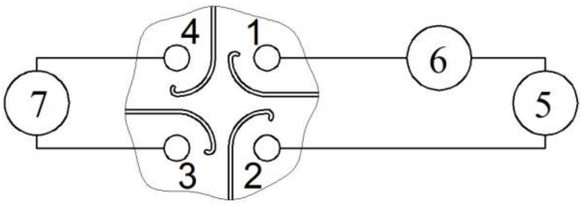


Figure 2. Connection of contacts of the basis of standard to the current source and measuring devices: 1, 2 – contact platforms for connection of a current source; 3, 4-contact platforms for connection of the voltmeter; 5- current source; 6-Ohmmeter; 7-Voltmeter

In this case, the current I_{12} from contact 1 flows sequentially through the isthmus of the base, formed by figured cuts, the working area and the second isthmus to the contact 2 (figure 1). The voltage drop U_{34} is measured on the opposite contacts of the base (in this case, 3 and 4). Measurement I_{jk} and U_{mn} are carried out four times with sequential shift elements of the circuit of the contacts by one step. According to the results of four measurements, in accordance with[(2)], is calculated

$$\sigma_c = \frac{4\ln(2)}{\pi\bar{h}\left(\frac{U_{34}}{I_{12}}+\frac{U_{41}}{I_{23}}+\frac{U_{12}}{I_{34}}+\frac{U_{23}}{I_{41}}\right)} \quad (1)$$

where $\bar{h}$ – the average value of the thickness of the base.

3. Measurement of relative magnetic permeability of base metals of MCMB

For low-frequency magnetic fields, traditionally, the relative magnetic permeability of ferromagnetic materials is calculated by the formula

$$\mu_r = \frac{\mu}{\mu_0} \quad (2)$$

where μ is the absolute magnetic permeability of the metal,
μ_0 - magnetic constant, $4\pi 10^{-7}$ H/m.
However, since in most applications eddy current instruments operate at *f* to 10 MHz, the relative magnetic permeability should be considered as a complex value

$$\bar{\mu}_r = \mu_1 - j\mu_2, \quad (3)$$

where μ_1 – valid, "elastic" component of characterizing reversible processes in ferromagnetic material, and μ_2 – the imaginary, the "viscous" component, describing the irreversible energy dissipation during the magnetization reversal, is proportional to *f*. In practice, it is convenient to use the value of the tangent of the angle magnetic losses

$$\mathrm{tg}\delta_\mu = \frac{\mu_2}{\mu_1} \quad (4)$$

In this regard, in the manufacture and calibration of MCMB, you must have the ability to determine μ_1 and μ_2 of base of MCMB in the above mentioned range *f*. It should also be taken into account that most of the primary measuring transducers of eddy current instruments use very low values of the magnetic field, and therefore it is necessary to determine the value of the initial complex magnetic permeability

$$\bar{\mu}_r = \mu_{1\mathrm{int}} - j\mu_{2\mathrm{int}} \quad (5)$$

The highest measurement accuracy is achieved by using ring samples (cores) and creating an alternating ring magnetic field inside them, since it is the ring-shaped ferromagnetic cores that have the demagnetizing factor that affects the results of measurements the least, and the level of magnetic fields of dispersion is minimal and approaches the theoretically achievable limit.

Measurements in the frequency range up to 2 MHz are optimally carried out using a Permeameter. The design of the Permeameter, ensuring the fulfillment of the above conditions, with respect to the task, is shown in figure 3.

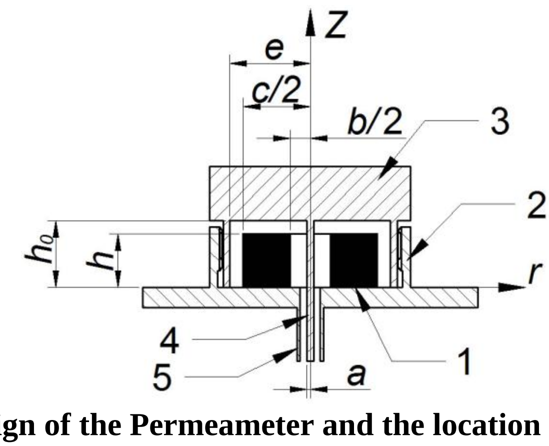


Figure 3. The design of the Permeameter and the location of the sample in the measurements: 1-ring sample, 2-base, 3-cover, 4-pin cover, 5-ring contact base

When installing the ring sample in the Permeameter, it turns out to be an almost ideal inductor, which is a single toroidal coil of the conductor formed by the base 2 and the cover 3, around the ring test sample 1, the magnetic field of scattering of which is negligible. The pin 4 located in the center of the cap 3 passes through the hole of the test specimen and the hole in the center of the base 2. Pin 4 with ring pin 5 located on the base form a coaxial connector through which the Permeameter is connected to the impedance meter.

The intrinsic inductance of the Permeameter is determined by the equation:

$$L = \frac{1}{I}\int B\mathrm{d}s = \int_{a}^{e}\int_{0}^{h_0} \frac{\mu_1}{2\pi r}\mathrm{d}r\mathrm{d}z \tag{6}$$

where B - the effective value of magnetic induction in the internal volume of the Permeameter, I - the effective value of the current flowing through its toroidal coil.

Revealing the equation (6) we obtain:

$$L = \int_{\frac{c}{2}}^{e}\int_{0}^{h_0} \frac{\mu_0}{2\pi r}\mathrm{d}r\mathrm{d}z + \int_{\frac{b}{2}}^{\frac{c}{2}}\int_{0}^{h} \frac{\mu_0\mu_1}{2\pi r}\mathrm{d}r\mathrm{d}z + \int_{\frac{b}{2}}^{\frac{c}{2}}\int_{h}^{h_0} \frac{\mu_0}{2\pi r}\mathrm{d}r\mathrm{d}z + \int_{a}^{\frac{b}{2}}\int_{0}^{h_0} \frac{\mu_0}{2\pi r}\mathrm{d}r\mathrm{d}z \tag{7}$$

After simplification:

$$L = \frac{\mu_0}{2\pi}\left(\left(\mu_1 - 1\right)h\ln\frac{c}{b} + h_0\ln\frac{e}{a}\right) \tag{8}$$

Transforming the expression (8) to calculate μ_1 we obtain the formula:

$$\mu_1 = \frac{2\pi(L - L_{ss})}{\mu_0 h\ln\frac{c}{b}} + 1 \tag{9}$$

where L_{SS} is the intrinsic inductance of the Permeameter without the test sample installed in it, equal to:

$$L_{ss} = \frac{\mu_0}{2\pi}h_0\ln\frac{e}{a} \tag{10}$$

The test sample placed in an alternating magnetic field of Permeameter, causes a change in reactive ωL and active R components of the impedance Z of the circuit, through which current flows, where $\omega = 2\pi f$ - circular frequency of alternating field magnetization. By their change can be judged on the characteristics of the magnetic material.

Since for the inductive-resistive electrical circuit impedance can be written by the expression:

$$\bar{Z} = R + j\omega L = j\omega(\frac{R}{j\omega} + L) \quad (11)$$

when given the magnetic loss is fair in the formula (9) replacing *L* in the formula (9) transform:

$$\bar{\mu}_r = \frac{2\pi(\bar{Z} - j\omega L_{ss})}{j\omega\mu_0 h \ln\frac{c}{b}} + 1 \quad (12)$$

Since the Permeameter used to measure the magnetic parameters of the ring samples is a physical device of finite size, and its composition includes connectors and connecting cables that are part of the electrical circuit, the measurements occur parasitic phenomena that must be considered in the calculations.
For figure 4 shows a General view of the Permeameter and its equivalent electrical circuits during measurements with test sample and without it.

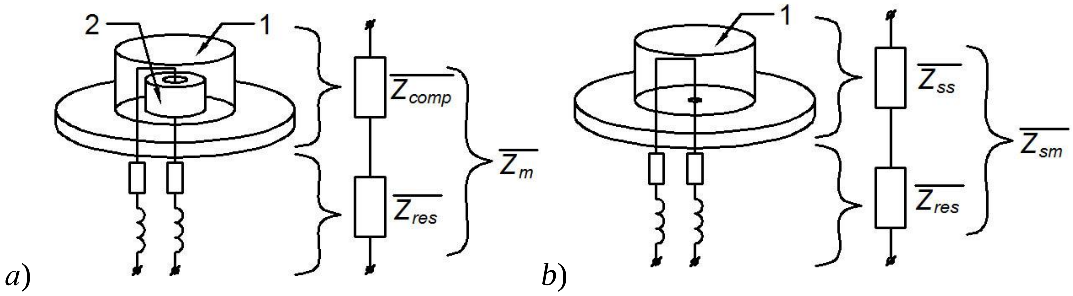


Figure 4. The Permeameter, the scheme of the General view and the equivalent circuit diagram: *a*) with the set of the test sample, *b*) without a test sample installed. 1-Permeameter, 2 - ring test sample

For those shown in figure 4 circuits:

$$\bar{Z}_{res} = \bar{Z}_{sm} - \bar{Z}_{ss} \quad (13)$$

where $\bar{Z}_m$ is the value of the total impedance obtained during the measurement with the test sample.

Since $\bar{Z}_{ss} = j\omega L_{ss}$, the expression (9) can be given to the form:

$$\bar{\mu}_r = \frac{2\pi(\bar{Z}_m - \bar{Z}_{sm})}{j\omega\mu_0 h \ln\frac{c}{b}} \quad (14)$$

To conduct research in variable magnetic fields, the Permeameter must be connected to the immittance meter, which is based on the circuit of the auto-balanced bridge (figure 5).

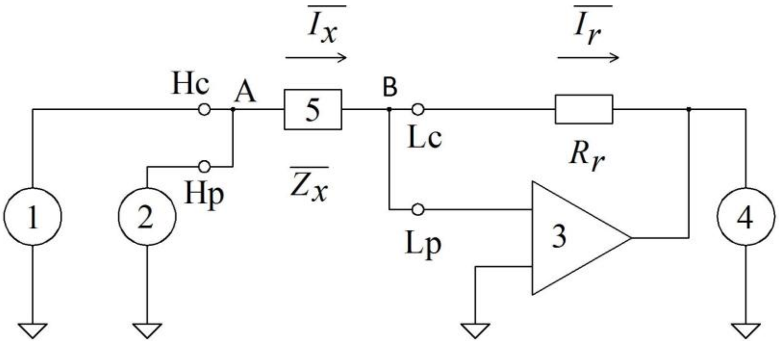


Figure 5. Structural diagram autobalancing bridge connected Permeameter. 1-sinusoidal current generator; 2, 4 – Voltmeters; 3-current-voltage Converter; 5-Permeameter with the test sample installed; Hc and Lc-current terminals of high and low (zero) potential, respectively; Hp and Lp-potential terminals of high and low (zero) potential, respectively

The immitance meter contains a AC generator 1, which generates a sinusoidal current of a given amplitude I_x and frequency *f*. The sinusoidal current flows through the measured Z_x circuit, which sets the resistor R_r and is compensated by the current-voltage Converter built on the basis of the operational amplifier 3. Voltmeter 2 measures the potential $\overline{U}_x$ on the measured circuit at point A, at point B zero potential is maintained, and voltmeter 4 measures the potential $\overline{U}_x$ on the reference resistor R_r, proportional to the current $\overline{I_r} = \overline{I_x}$. The impedance of the measured circuit (Permeameter 5) is calculated by the formula:

$$\bar{Z}_x = \frac{\bar{U}_x}{\bar{I}_x} = R_r \frac{\bar{U}_x}{\bar{U}_r} \tag{15}$$

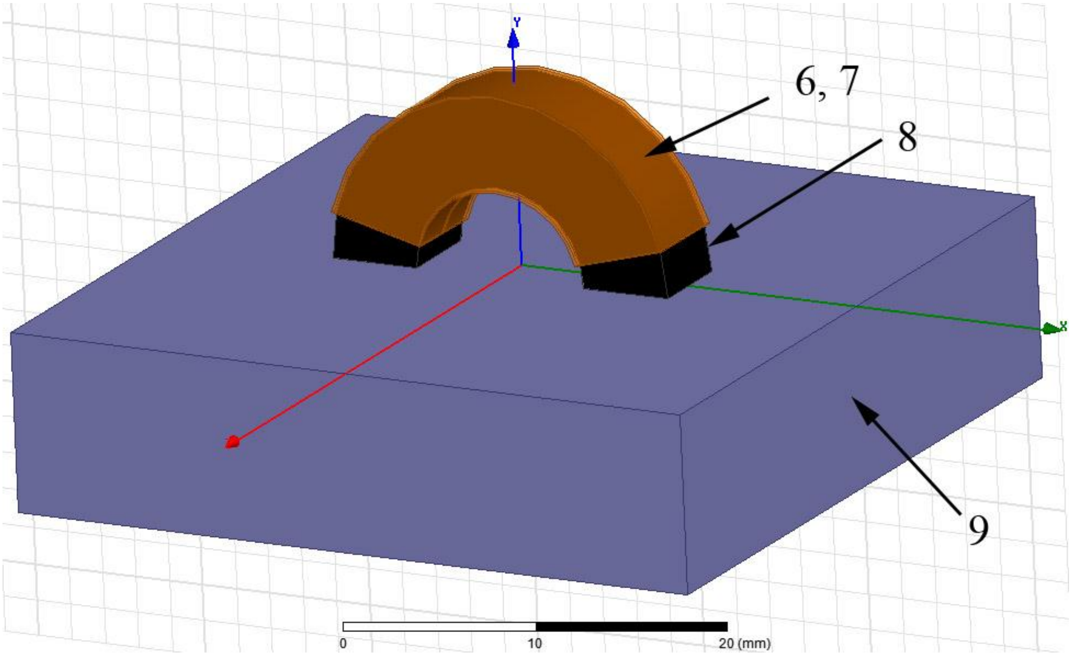
The measurement result is obtained as a complex impedance value $\bar{Z}$ of the measured circuit or as (R_x; $2\pi f L_x$) for given *f* and *I*.

In the real high-frequency immitance meter instead of the Converter current-voltage 3 it is necessary to use the zero-detector consisting of the phase detector, the integrator and the vector modulator providing high accuracy of measurements at frequencies more than 1 MHz.

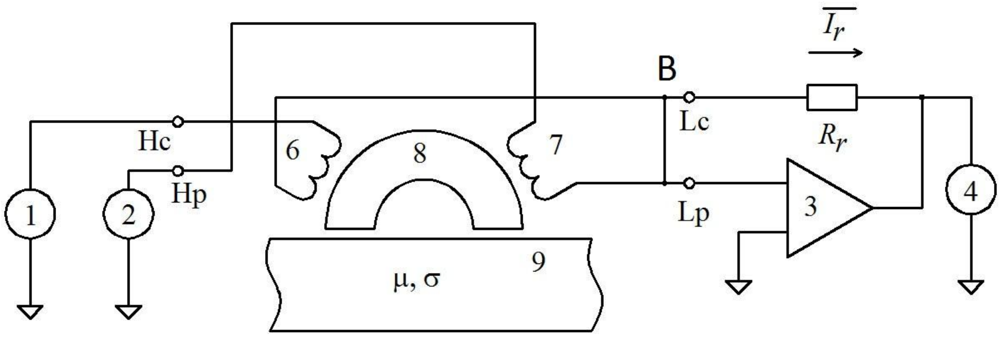
Ring samples for measuring the magnetic properties of the material according to the above procedure are not suitable for the manufacture of measures of the base thickness of coatings. For this reason, the value of them is transmitted to the bases of measures of cylindrical or other shape with a flat surface, which can be coated with a galvanic coating, the thickness of which is measured by eddy current thickness meters.

To transfer the value of the relative magnetic permeability can use the overlay eddy current transformer with a U-shaped core forming a closed magnetic circuit with the ring sample or base of standard. The core shall be made of a charge metal having the highest magnetic permeability in weak magnetic fields. A direct calculation $\bar{\mu}_{rint}$ in the same way as is done in the measurement of ring specimens, it is impractical due to the large number of uncontrolled confounding parameters associated with a significantly large number of magnetic stray fields of the transmitter and its complex geometric factors that must be considered in the calculations. For this reason, the eddy current transducer with a U-shaped core must be calibrated on a set of ring measures with values $\bar{\mu}_{rint}$ defined by the above procedure. Due to the curvature of the U-shaped eddy current transducer, the set must consist of at least three pieces.

Figure 6 shows an overhead eddy current transducer with a U-shaped core on a ferromagnetic plane-parallel base: a graphical representation of the finite element model (*a*) and the block diagram (*b*).



a)



b)

Figure 6. Superimposed eddy current transducer with U-shaped core: *a*) image of the finite element model, *b*) block diagram. 1-sinusoidal current generator; 2, 4-Voltmeters; 3-current-voltage Converter; Hc and Lc – current terminals of high and low (zero) potential, respectively; Hp and Lp-potential terminals of high and low (zero) potential, respectively; 7 – measuring winding; 6 – excitation winding wound on top of the measuring winding; 8 – core; 9 - base metal

Input contact of the excitation winding 6 of the eddy current Converter is connected to the source of harmonic current 1 with the given *f* and *I* (connector H_c of the immittance meter). Input contact of the measuring winding 7 is connected to the H_p connector of the immittance meter. The output contacts of both windings are connected to point B, which supports zero potential. Voltmeter 2 measures the potential $\bar{U}_x$ on the measuring winding, and voltmeter 4 measures the potential $\bar{U}_r$ on the setting resistor R_r, proportional to the excitation current of the eddy current transducer. The output signal of the Converter is its equivalent impedance $\bar{Z}_{\mathrm{ECT}}$, calculated by the formula:

$$\bar{Z}_{\mathrm{ECT}} = R_r \frac{\bar{U}_x}{\bar{U}_r} \tag{16}$$

The real and imaginary components of $\bar{Z}_{\mathrm{ECT}}$ are analyzed. It is assumed that the real and imaginary components $\bar{\mu}_{r\mathrm{int}}$ affect, respectively, the imaginary and the real component $\bar{Z}_{\mathrm{ECT}}$ independently.

The dependence of the imaginary component $\bar{Z}_{\mathrm{ECT}}$ on the real component of the magnetic permeability with sufficient accuracy is approximated by a cubic expression:

$$\mu_{1\mathrm{int}} = a * \mathrm{Im}(\bar{Z}_{\mathrm{ECT}})^3 + b * \mathrm{Im}(\bar{Z}_{\mathrm{ECT}})^2 + c * \mathrm{Im}(\bar{Z}_{\mathrm{ECT}}) \tag{17}$$

where $\mathrm{Im}(\bar{Z}_{\mathrm{ECT}})$ - the imaginary component $\bar{Z}_{\mathrm{ECT}}$, *a*, *b* and *c*-interpolating coefficients necessary for the construction of the calibration characteristics calculated by the formulas:

$$a = \frac{M_a}{M_z}, b = \frac{M_b}{M_z}, c = \frac{M_c}{M_z} \tag{18}$$

where M_a, M_b, M_c, M_z – determinants of matrices:

$$M_z = \begin{vmatrix} (\mathrm{Im}(\bar{Z}_{\mathrm{ECT1}}))^3 & (\mathrm{Im}(\bar{Z}_{\mathrm{ECT1}}))^2 & \mathrm{Im}(\bar{Z}_{\mathrm{ECT1}}) \\ (\mathrm{Im}(\bar{Z}_{\mathrm{ECT2}}))^3 & (\mathrm{Im}(\bar{Z}_{\mathrm{ECT2}}))^2 & \mathrm{Im}(\bar{Z}_{\mathrm{ECT2}}) \\ (\mathrm{Im}(\bar{Z}_{\mathrm{ECT3}}))^3 & (\mathrm{Im}(\bar{Z}_{\mathrm{ECT3}}))^2 & \mathrm{Im}(\bar{Z}_{\mathrm{ECT3}}) \end{vmatrix} \tag{19}$$

$$M_a = \begin{vmatrix} \mu_1 1 & (\mathrm{Im}(\bar{Z}_{\mathrm{ECT1}}))^2 & \mathrm{Im}(\bar{Z}_{\mathrm{ECT1}}) \\ \mu_1 2 & (\mathrm{Im}(\bar{Z}_{\mathrm{ECT2}}))^2 & \mathrm{Im}(\bar{Z}_{\mathrm{ECT2}}) \\ \mu_1 3 & (\mathrm{Im}(\bar{Z}_{\mathrm{ECT3}}))^2 & \mathrm{Im}(\bar{Z}_{\mathrm{ECT3}}) \end{vmatrix} \tag{20}$$

$$M_b = \begin{vmatrix} (\mathrm{Im}(\bar{Z}_{\mathrm{ECT1}}))^3 & \mu_1 1 & \mathrm{Im}(\bar{Z}_{\mathrm{ECT1}}) \\ (\mathrm{Im}(\bar{Z}_{\mathrm{ECT2}}))^3 & \mu_1 2 & \mathrm{Im}(\bar{Z}_{\mathrm{ECT2}}) \\ (\mathrm{Im}(\bar{Z}_{\mathrm{ECT3}}))^3 & \mu_1 3 & \mathrm{Im}(\bar{Z}_{\mathrm{ECT3}}) \end{vmatrix} \tag{21}$$

$$M_c = \begin{vmatrix} (\mathrm{Im}(\bar{Z}_{\mathrm{ECT1}}))^3 & (\mathrm{Im}(\bar{Z}_{\mathrm{ECT1}}))^2 & \mu_1 1 \\ (\mathrm{Im}(\bar{Z}_{\mathrm{ECT2}}))^3 & (\mathrm{Im}(\bar{Z}_{\mathrm{ECT2}}))^2 & \mu_1 2 \\ (\mathrm{Im}(\bar{Z}_{\mathrm{ECT3}}))^3 & (\mathrm{Im}(\bar{Z}_{\mathrm{ECT3}}))^2 & \mu_1 3 \end{vmatrix} \tag{22}$$

where $\bar{Z}_{\mathrm{ECT1}}$, $\bar{Z}_{\mathrm{ECT2}}$, $\bar{Z}_{\mathrm{ECT3}}$ are the values of the equivalent impedance of the transducer installed on the first, second and third calibration ring piece, respectively, $\mu_1 1$, $\mu_1 2$, $\mu_1 3$ are the values of the real component of the relative magnetic permeability of the first, second and third calibration ring piece, respectively.

Similarly, the imaginary component of the magnetic permeability is calculated by the formula:

$$\mu_{2\mathrm{int}} = d * \mathrm{Re}(\bar{Z}_{\mathrm{ECT}})^3 + e * \mathrm{Re}(\bar{Z}_{\mathrm{ECT}})^2 + g * \mathrm{Re}(\bar{Z}_{\mathrm{ECT}}) \qquad (23)$$

where $\mathrm{Re}(\bar{Z}_{\mathrm{ECT}})$ - the real component$\bar{Z}_{\mathrm{ECT}}$, d, e, g - interpolating coefficients necessary for the calculation of the calibration characteristics, calculated by formulas:

$$d = \frac{M_d}{M_y}, e = \frac{M_e}{M_y}, g = \frac{M_g}{M_y} \qquad (24)$$

where M_d, M_e, M_g, M_y – determinants of matrices:

$$M_y = \begin{vmatrix} (\mathrm{Re}(\bar{Z}_{\mathrm{ECT1}}))^3 & (\mathrm{Re}(\bar{Z}_{\mathrm{ECT1}}))^2 & \mathrm{Re}(\bar{Z}_{\mathrm{ECT1}}) \\ (\mathrm{Re}(\bar{Z}_{\mathrm{ECT2}}))^3 & (\mathrm{Re}(\bar{Z}_{\mathrm{ECT2}}))^2 & \mathrm{Re}(\bar{Z}_{\mathrm{ECT2}}) \\ (\mathrm{Re}(\bar{Z}_{\mathrm{ECT3}}))^3 & (\mathrm{Re}(\bar{Z}_{\mathrm{ECT3}}))^2 & \mathrm{Re}(\bar{Z}_{\mathrm{ECT3}}) \end{vmatrix} \qquad (25)$$

$$M_d = \begin{vmatrix} \mu_2 1 & (\mathrm{Re}(\bar{Z}_{\mathrm{ECT1}}))^2 & \mathrm{Re}(\bar{Z}_{\mathrm{ECT1}}) \\ \mu_2 2 & (\mathrm{Re}(\bar{Z}_{\mathrm{ECT2}}))^2 & \mathrm{Re}(\bar{Z}_{\mathrm{ECT2}}) \\ \mu_2 3 & (\mathrm{Re}(\bar{Z}_{\mathrm{ECT3}}))^2 & \mathrm{Re}(\bar{Z}_{\mathrm{ECT3}}) \end{vmatrix} \qquad (26)$$

$$M_e = \begin{vmatrix} (\mathrm{Re}(\bar{Z}_{\mathrm{ECT1}}))^3 & \mu_2 1 & \mathrm{Re}(\bar{Z}_{\mathrm{ECT1}}) \\ (\mathrm{Re}(\bar{Z}_{\mathrm{ECT2}}))^3 & \mu_2 2 & \mathrm{Re}(\bar{Z}_{\mathrm{ECT2}}) \\ (\mathrm{Re}(\bar{Z}_{\mathrm{ECT3}}))^3 & \mu_2 3 & \mathrm{Re}(\bar{Z}_{\mathrm{ECT3}}) \end{vmatrix} \qquad (27)$$

$$M_g = \begin{vmatrix} (\mathrm{Re}(\bar{Z}_{\mathrm{ECT1}}))^3 & (\mathrm{Re}(\bar{Z}_{\mathrm{ECT1}}))^2 & \mu_2 1 \\ (\mathrm{Re}(\bar{Z}_{\mathrm{ECT2}}))^3 & (\mathrm{Re}(\bar{Z}_{\mathrm{ECT2}}))^2 & \mu_2 2 \\ (\mathrm{Re}(\bar{Z}_{\mathrm{ECT3}}))^3 & (\mathrm{Re}(\bar{Z}_{\mathrm{ECT3}}))^2 & \mu_2 3 \end{vmatrix} \qquad (28)$$

where $\mu_2 1$, $\mu_2 2$, $\mu_2 3$ - the values of the imaginary component of the relative magnetic permeability of the first, second and third calibration ring pieces, respectively.

4. Measurement of the electrical conductivity of the coating material of MCMB

For conductivity measurements σ_c of the coating material MCMB can be applied to the contact and non-contact measurements. In particular, one of the methods of eddy current type of non-destructive testing can be used. At the same time, in order that the electromagnetic properties of MCMB base material do not affect the results of σ_c

measurements, it is necessary that the minimum thickness of the coating T_{cm} satisfies the following condition:

$$2{,}5\delta \leq T_{cm}, \tag{29}$$

where δ is the standard depth of penetration of eddy currents determined by the formula:

$$\delta = \frac{1}{\sqrt{\pi f \sigma_c \mu_b}} \tag{30}$$

where f is the excitation current frequency of the eddy current measuring transducer (ECT).

For measuring σ_c coatings of small thickness ($T_{cm} \geq 10$ μm), the corresponding, sufficiently high values of f must be used. At the same time, the conditional boundary at which classical methods of analysis of transmission and processing of electrical signals are applied is considered in the frequency range from 30 to 300 MHz. At high frequencies, wave effects are beginning to appear clearly, for the analysis of which the techniques of radio-wave type of non-destructive testing should be applied. The maximum frequency at which the available on the market immittance meters operate, which are based on the circuit of the auto – balanced bridge, is 120 MHz. At f = 120 MHz, the value of the T_{cm} coating, when measured σ_c which electromagnetic properties of the base material are not affected, is in the range from 15 to 43 μm (at σ_c from 58 to 7 MS/m, respectively). To describe the degree of interaction of ECT with the test sample, it is convenient to use the value of the characteristic frequency or the value of the generalized parameter β, for non-ferromagnetic coatings calculated by the formula:

$$\beta = R\sqrt{2\pi f \mu_b \sigma_c}, \tag{31}$$

where R is the radius of the greater of the windings of the transformer ECT.

To ensure the sensitivity of ECT to the change of σ_c, it is necessary to obtain the value of the generalized parameter β in the range from 3 to 30. Calculations show that for the considered problem of the measurement of the diameter of the ECT should be no more than 0,1...0,15 mm. Technologically such a transducer can be made in the form of a conductor on a printed circuit board. For figure 7 shows the finite element model of overhead transformer high-frequency ECT, consisting of a single-turn excitation and measuring windings.

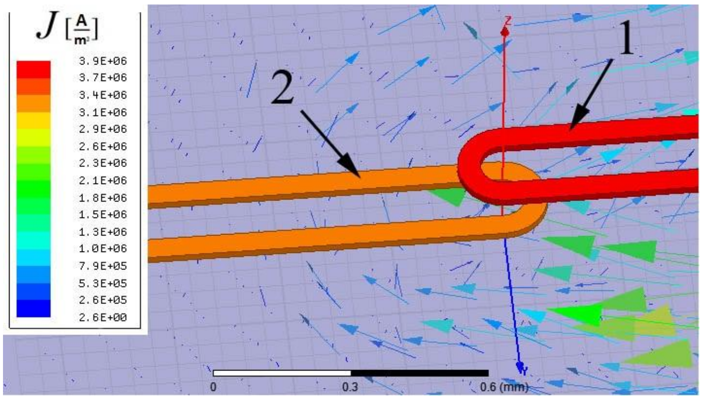


Figure 7. Image of the finite element model of overhead transformer ECT, consisting of single-turn excitation (1) and measuring (2) windings

For this model, the signal level on a single-turn miniature measuring winding will be small for further transformations. In this paper, the impedance meter W65120p by Wayne Kerr Electronics was used. Its measurement error depends on the value of the measured resistance (impedance) and the frequency of the test signal. With the recommended amplitude of the excitation current of 10 mA, the amplitude of the voltage in the measuring winding will be less than 100 μV, which is equivalent to the measurement of impedance is about 10 mΩ. It is obvious that this will be an unacceptable error.

To ensure the signal amplitude sufficient for their further processing, multi-turn windings can be used, but traditional printed multi-turn spiral windings are not suitable for this purpose due to the fact that the outer coils will have an unacceptably large diameter and, as a result, the value of the generalized parameter β for ECT will also be unacceptably large. Multi-layer printed windings are also not acceptable due to the fact that the layers of windings located at a distance of more than 0.1 mm from the surface of the object of control, in this case, will be ineffective. It is interesting to use a conductor forming an equivalent wave-like multi-turn excitation winding 1 as the primary winding of ECT, and as a secondary winding of a straight conductor 2 located symmetrically with respect to the wave-like excitation winding 1. Schematic representation of ECT is shown in figure 8.

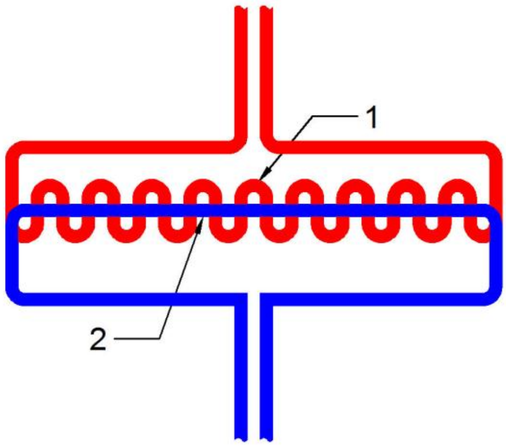


Figure 8. Schematic representation of an ECT with a wave-like excitation winding 1 containing 19 equivalent turns and a straight measuring winding 2

Each bend of the wave-like excitation winding forms an incomplete coil. Each straight section of the measuring winding, crossing the incomplete coil of excitation, perceives a part of the magnetic field of the corresponding incomplete coil of excitation and eddy currents induced by it. The straight-line form of the measuring winding provides the minimum possible value of its inductance and parasitic capacitance. The relatively low efficiency of the applied incomplete turns is compensated by the possibility of scaling ECT. Simulations showed that this approach to the design of the ECT will provide a receipt suitable for further signal processing.

On the basis of this model built, we offer to measure σ_c partitioned ECT containing the equivalent of 240 turns of the primary winding (figure 9).

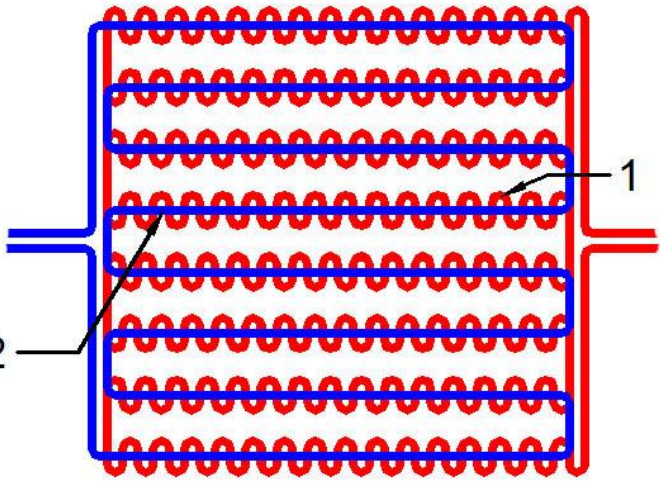


Figure 9. Schematic diagram of a partitioned ECT with wave-like excitation winding 1 containing 240 equivalent turns and measuring winding 2

The calculated hodographs of the ECT signal at the change of the controlled and influencing parameters for *f* = 120 MHz are shown in figure 10.

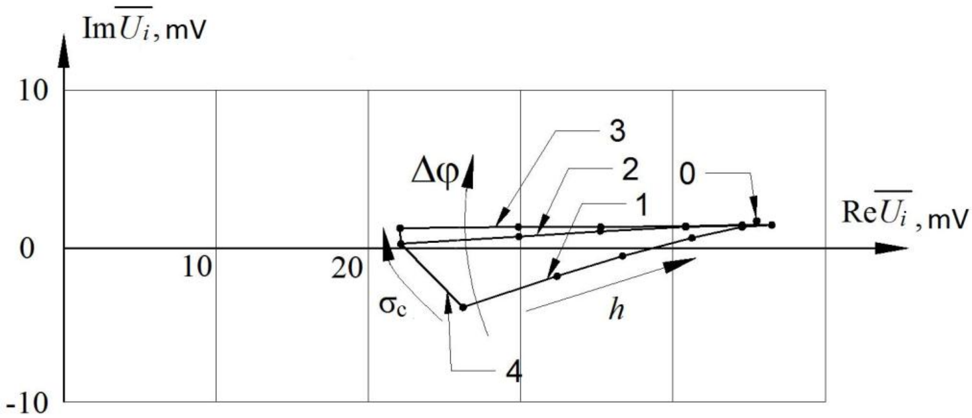


Figure 10. Hodographs of the signals partitioned VTP: 1, 2 and 3 influence lines of the clearance *h* at σ_c = 0,5 MS/m; 5 MS/m and 50 MS/m, respectively (the dots on the lines indicate gaps 0,01; 0,05; 0,1; 0,2 mm); 4 – line impact σ_c when the gap *h* = 0.01 mm between the probe and the surface of the MCMB; Δφ – phase shift of the signal $\overline{U}_i$, measured relative to the point 0

Analysis of hodographs in figure 10 shows that the phase shift Δφ of the signal calculated from the point 0 - the convergence point of the straight lines 1, 2 and 3 should be used as the primary informative parameter for measuring σ_c.

To convert Δφ of signal $\overline{U}_i$ to the value of σ_c must be made calibration of the measuring unit for specific electrical conductivity standards, the value of which corresponds to the range of the measured value σ_c.

5. Construction of thickness reference standards (measures of thickness of conductive coatings on conductive base)

A General view of the developed standards, involving the implementation of the above techniques, is shown in figure 11.

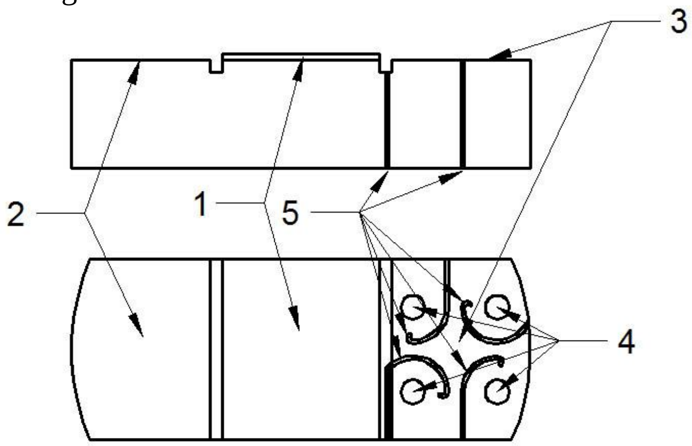


Figure 11. General view of thickness reference standard (measures the thickness of the metal coating). 1 - zone with electroplated coating applied to the work surface; 2 - zone without coating; 3-zone designed to measure the electrical conductivity of the base; 4 - contacts for connecting cables of the current source, Ohmmeter and Voltmeter; 5 - shaped cuts

Three zones are conditionally allocated on the thickness reference standard: 1 – zone with electroplated coating applied to the working surface, 2 – zone without coating. Zones 1 and 2 are intended for installation of eddy current converters of thickness meters on them when using the standard for its intended purpose. In addition, in zone 2, measurements are made when transferring the standard value σ_c. Zones 1 and 2 are also designed to measure the thickness of the galvanic coating with the use of a profilometer. 3-a zone designed to measure the electrical conductivity of the base of the standard. In this area there are the contacts 4 for connection of the cables of the power supply, Ohmmeter and voltmeter, and figure slots 5, forming the optimal shape of the leak area DC when measuring σ_b founded on the method of van der Pau.

6. Measurement of thickness reference standards

When completing the system for measurement, it is necessary to produce and calibrate the necessary sets of ring magnetic permeability pieces and electrical conductivity standards.

The preparatory part should include the calibration of transducer with U-shaped core, designed to measure the magnetic permeability of the MCMB base and the calibration on the measures of the electrical conductivity of the high-frequency transducer ECT, designed to measure σ_c. The procedure for measuring MBMC parameters will consist of the following steps:
- measurement of the thickness T_c of the coating MBMC using profilometer;
- measurement of the electrical conductivity of the base by the method of van der Pau;
- measurement of the magnetic permeability of the MCMB base using transducer ECT with U-shaped core connected to the impedance analyzer;
- measurement of the electrical conductivity of the coating σ_c MCMB using a high-frequency transducer ECT connected to the impedance analyzer;
- processing of the results of all measurements with the help of application software (based on MS Excel).

7. Conclusion

The considered technical solutions and methods, as well as the developed original design of the metal coating thickness reference standards can be used as a basis for the development of a distributed standard for measuring the electrophysical parameters of MCMB, which will be used as standards for calibration and verification of eddy current thickness gauges, which will ensure their accuracy, ensure the reliability of measurements.

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