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ELECTROMAGNETIC MEASUREMENTS

THE USE OF PROJECTION METHODS OF MULTIVARIATE ANALYSIS IN EDDY CURRENT THICKNESS MEASUREMENT

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Multifrequency eddy current measurements of the thickness of non-magnetic metallic materials with dielectric coatings have been carried out. Based on the principal component analysis, the influence of competing factors such as electrical conductivity, thickness of the metal substrate and thickness of the dielectric layer is separated. Using the projection method on latent structures, eddy current measurements have determined the numerical values of the thicknesses of aluminum and copper plates and dielectric coatings.
Keywords: *eddy current method, thickness gauge, multivariate analysis, principal component method.*

The development of new and improved methods for measuring the thickness of product elements and the thickness of protective coatings deposited on them is an urgent task of modern thickness gauging. In indirect non-destructive testing of these parameters of metal materials, the most common are the ultrasonic method and the eddy current method [1, 2]. However, the described methods have a number of disadvantages that limit the scope of the methods. Using ultrasonic thickness gauges, the acoustic signal propagation time from the sensor to the opposite surface of the product or to the interface between the coating and the substrate is measured. For small thicknesses, the acoustic pulse duration is commensurate with the signal transit time, and this method is practically inapplicable. The eddy current method, based on the excitation of eddy currents in a controlled object and measuring their characteristics with a sensor, is deprived of this drawback [3]. In this case, the sensor parameters are simultaneously affected by many competing factors, which must be separated for subsequent accounting and compensation [4].

The output signal of the measurement information, intended for further processing, in the eddy current parametric sensor is the impedance. Various input factors influence the impedance: electrical and magnetic properties of the material [5]; geometric parameters and chemical composition of the product [6, 7]; features of the measuring device and measurement mode [8, 9]. Therefore, in eddy current measurements, an important and urgent task is to isolate the measured value against the background of interfering factors, i.e., the separation of influencing factors.

This problem can be solved in various ways. For example, the thickness of the dielectric coating on a metal is determined with sufficient accuracy as a result of high-frequency measurements (in the megahertz range), since at these frequencies the electrical conductivity and the thickness of the metal substrate practically have no effect. Thus, the separation of factors occurs in hardware by selecting a measurement mode. When measuring with sufficient accuracy the metallization thickness on non-metallic materials, lower frequencies are used so that the thickness of the skin layer is comparable with the thickness of the conductor. However, in this case, it is necessary to specifically stabilize the gap between the sensor and the measured object, and the separation of factors is also carried out in hardware by fixing the value of the gap.

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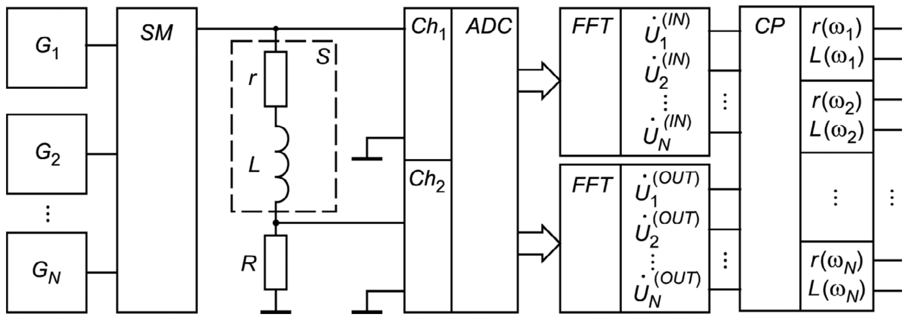

Fig. 1. Block diagram of the measuring device: $G_1, G_2, ..., G_N$ – blocks for specifying harmonic signals; *SM* – adder; *S* – parametric sensor; Ch_1, Ch_2 – channels for digitizing input and output signals, respectively; *ADC* – analog-to-digital converter; *FFT* – discrete Fourier transform block; *CP* – computation unit.

In this paper, we propose a fundamentally different approach to the separation of influencing factors in eddy current measurements. The approach is based on processing a measuring signal using a multidimensional data analysis apparatus [10]. The advantage of this approach is the ability to not only separate factors while data processing (that is, non-hardware), but also to measure with sufficient accuracy not one but several characteristics recorded at the input of the measuring transducer [11– 13]. When using eddy current thickness measurement in addition to traditional measurements of the thickness of the dielectric coating of a conductor, it becomes possible to simultaneously measure the thickness of the coating and the thickness of the conductive metal substrate under the coating. The applicability of this approach to thickness measurement problems was considered in [14] using copper samples with known electrical conductivity as an example. The main influencing factors were the thickness of the metal substrate and the dielectric coating. In this article, the described approach is extended to the case of simultaneous thickness measurements when varying three influencing factors – the electrical conductivities of different materials, the thickness of metal samples and dielectric coatings.

Experimental method. When testing the materials, multifrequency measurements were used, which made the eddy current method most informative [15] and culminated in the construction of experimental hodographs of the *eddy current sensor – controlled sample* system. These hodographs reflect the combined action of the main factors affecting the measurement results. The method of obtaining hodographs is based on the use of an exciting signal of a special form with subsequent digital processing of the recorded output signal [9].

The block diagram of the measuring device is shown in Fig. 1. In blocks $G_1, G_2, ..., G_N$, harmonic signals with fixed frequencies $\omega_1, \omega_2, ..., \omega_N$ are set respectively. These signals are added by the adder Σ and pass through the measuring circuit, consisting of an eddy current parametric sensor *S* and a reference resistance *R*. A parametric sensor represents a series connection of two ideal elements: the equivalent active resistance *r*, which describes the energy losses that occur in the sensor, and the inductance *L*, which characterizes the magnetic flux coupled to the sensor turns during electric current flow. To determine the parameters of the sensor, there is a two-channel synchronous analog-to-digital converter *ADC*. In the first channel Ch_1, the signal supplied to the input of the measuring circuit is digitized, and in the second channel Ch_2, the output signal is taken from the reference resistance. The *ADC* was synchronized to minimize its effect on the phase shift between the two signals. The digitized signals entered the *FFT* blocks, where discrete Fourier transforms were performed. In further calculations, we used only those complex amplitudes that corresponded to frequencies as close as possible to the values of $\omega_1, \omega_2, ..., \omega_N$. The complex amplitudes of the input signal were denoted $\dot{U}_1^{(IN)}, \dot{U}_2^{(IN)}, ..., \dot{U}_N^{(IN)}$, the amplitudes of the output signal were denoted $\dot{U}_1^{(OUT)}, \dot{U}_2^{(OUT)}, ..., \dot{U}_N^{(OUT)}$.

The reactive resistance *X* and active resistance *r* of the parametric sensor at frequencies ω_n ($n = 1, 2, ..., N$) were calculated in the computation block *CP* using the formulas

$$X(\omega_n) = \omega_n L(\omega_n) = R\left(U_n^{(IN)}/U_n^{(OUT)}\right)\sin\left(\varphi_n^{(IN)} - \varphi_n^{(OUT)}\right);$$

$$r(\omega_n) = R\left[\left(U_n^{(IN)}/U_n^{(OUT)}\right)\cos\left(\varphi_n^{(IN)} - \varphi_n^{(OUT)}\right) - 1\right],$$

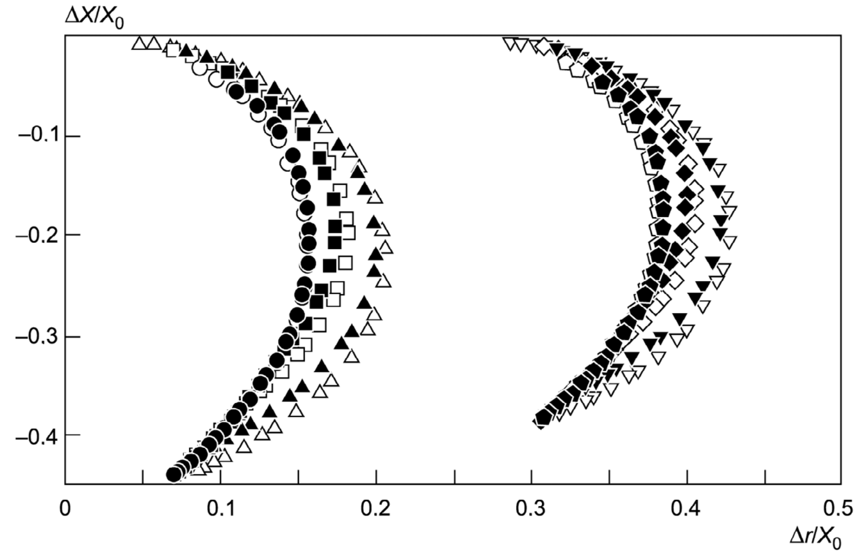

Fig. 2. Experimental hodographs of the sensor – sample system for coatings of various thicknesses for aluminum and copper plates of different thicknesses: △) 1.5 mm, □) 3.0 mm, ○) 7.0 mm (aluminum, coating thickness 0.2 mm); ▲) 1.9 mm, ■) 3.8 mm, ●) 7.5 mm (copper, coating thickness 0.2 mm); ▽) 1.5 mm, ◇) 3.0 mm, ⬠) 7.0 mm (aluminum, coating thickness 0.6 mm); ▼) 1.9 mm, ◆) 3.8 mm, ⬟) 7.5 mm (copper, coating thickness 0.6 mm); for coatings with a thickness of 0.6 mm, abscissa $\Delta r/X_0 + 0.25$.

where $U_n^{(IN)}$, $U_n^{(OUT)}$ and $\varphi_n^{(IN)}$, $\varphi_n^{(OUT)}$ are the moduli and phases of the complex amplitudes $\dot{U}_n^{(IN)}$, $\dot{U}_n^{(OUT)}$, respectively.

The results of multifrequency eddy current measurements were analyzed using hodographs of changes in the sensor impedance $\dot{Z} = r + jX$ at different frequencies ω_n. To construct the hodographs, the relative changes in the active $\Delta r(\omega_n)/X_0(\omega_n)$ and reactive $\Delta X(\omega_n)/X_0(\omega_n)$ resistances of the sensor were calculated, where $X(\omega_n)$, $X_0(\omega_n)$, $r(\omega_n)$, and $r_0(\omega_n)$ are the reactive and active resistances of the sensor, respectively, with and without the sample on the cyclic frequency ω_n. In the presence of a sample, changes in the active and reactive eddy current sensor resistances are determined by

$$\Delta r(\omega_n) = r(\omega_n) - r_0(\omega_n); \quad \Delta X(\omega_n) = X(\omega_n) - X_0(\omega_n).$$

The obtained hodographs are graphically represented in the coordinates $\Delta X/X_0(\Delta r/X_0)$.

The characteristics were measured at frequencies from 100 Hz to 10 kHz at 30 fixed frequencies ω_n. During the tests, a contact parametric sensor in the form of an inductor placed in a half-armored ferrite core with a diameter of 20 mm (ferrite grade 2000MN) was used.

Experimental hodographs. The studies were carried out for non-magnetic metals (copper and aluminum) with different specific conductivities σ. The conductivity σ of the samples, measured by a four-point method with an error of not more than 10%, amounted to 57 ± 5 and 31 ± 3 MS/m for copper and aluminum, respectively. The test samples were in the form of plane-parallel plates of various thicknesses. The thickness of the samples d varied in the range of 1.0–10.0 mm, so that the effect of the skin layer on the recorded parameters could be taken into account. The coating was modeled using dielectric spacers of various thicknesses $h = 0.1$–0.8 mm. The thickness of the sample and gaskets was measured with a micrometer with an instrument error of 0.02 mm.

Typical measurement results in the form of experimental hodographs are shown in Fig. 2. Hodographs for copper and aluminum are qualitatively the same. As the signal frequency increases, the experimental points shift along the axis $\Delta X/X_0$ from the upper part of the hodograph line to the lower part. This is due to the fact that with an increase in the frequency, the rate of change of the magnetic flux generated by the sensor increases, and the density of eddy currents in the metal, and consequently, the inductance of the sensor decreases.

Similarly, the change in electrical conductivity affects the measurement results. The position of the experimental points on the hodograph line for materials with relative magnetic permeability $\mu = 1$ with fixed geometric characteristics of the sample is determined by the generalized eddy current parameter $\beta = a(\mu\mu_0\sigma\omega)^{1/2}$ ($\mu_0 = 4\pi\cdot10^{-7}$ H/m is the magnetic

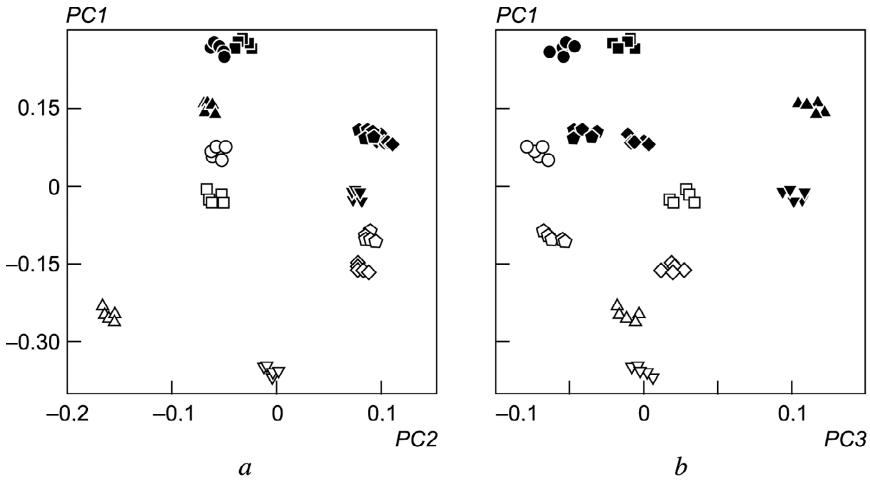

Fig. 3. Projections of the results of eddy current measurements on the plane of the first principal components *PC1–PC2* (*a*) and *PC1–PC3* (*b*); designations are the same as in Fig. 2.

constant; a is the effective radius of the applied parametric sensor) [1]. Therefore, with an increase in σ, the experimental points shift along the hodograph line from the upper part to the lower part, i.e., for copper, which has a higher electrical conductivity than aluminum, the corresponding points are located lower.

As follows from Fig. 2, as the thickness of the dielectric coating h increases, the shape of the hodograph lines changes and these lines approach the axis $\Delta X/X_0$. This is due to a decrease in the influence of the sensor on the substrate metal, which leads to a decrease in the effect on the inductance of the sensor, as well as to a decrease in the density of eddy currents and active losses.

The dependence of the hodographs on the thickness of the conductive plate (Fig. 2) is determined primarily by the ratio between the thickness d of the metal and the depth of the skin layer of the eddy currents, determined by their frequency. So, when switching from 100 Hz to 1 kHz, in copper the thickness decreases from 6.6 mm to 2.1 mm (copper) and from 8.3 mm to 2.6 mm (aluminum). Therefore, when the thickness of the plates is much greater than the depth of the skin layer, there are practically no differences in the values of d on the hodograph lines, and these lines gradually merge at high frequencies.

Separation of influencing factors. From the arrangement of experimental points shown in Fig. 2, it is rather difficult to single out the influence of individual factors on the controlled characteristics. To separate the influencing factors, the obtained hodographs were processed using the principal component method [10]. In accordance with this method, for a particular controlled sample, the entire hodograph in a multidimensional space was described by a single point. The coordinates of this point were the measured values of changes in the active $\Delta r/X_0$ and reactive $\Delta X/X_0$ resistances of the sensor at given frequencies ω_n, forming so-called feature vectors. To reduce the dimensionality of multidimensional space and identify latent patterns, we switched to a new coordinate system in which the first axis (principal component *PC1*) was oriented in the direction of the maximum dispersion of the experimental points, the second axis (principal component *PC2*) was oriented in the direction of the next smaller dispersion of the points, etc. For a graphical presentation of the processing results, projections were used on the plane of the first principal components.

The results of calculations in the form of projections on the plane *PC1– PC2* and *PC1–PC3* are shown in Fig. 3*a*, *b*, respectively. Points describing samples with similar characteristics (thicknesses d, h and specific conductivities) are located in the same region of multidimensional space. These points form a cluster, whose size is determined by the measurement error. Clusters describing copper and aluminum samples and differing in the values of electrical conductivity are linearly separated in both planes along the *PC1* axis. A similar linear separation across the thickness of the dielectric coating is observed on the plane *PC1–PC2*; an increase in h led to a shift of the clusters along the *PC2* axis. The difference in the thickness of metal plates is more pronounced in the plane *PC1–PC3*, where the clusters do not overlap even at large values of d.

Thus, the application of the method of principal components enables a clear separation of the three main factors affecting the results of eddy current measurements.

TABLE 1. Results of Test Measurements of Metal Plate Thickness *d* and Dielectric Coating *h*

Substrate material	Predicted results, mm		Measurement results, mm	
	d	*h*	*d*	*h*
Aluminum	1.40	0.21	1.43 ± 0.05	0.2 ± 0.03
	1.38	0.39	1.43 ± 0.05	0.4 ± 0.03
	1.43	0.58	1.43 ± 0.05	0.6 ± 0.03
	2.95	0.22	2.85 ± 0.05	0.2 ± 0.03
	2.74	0.41	2.85 ± 0.05	0.4 ± 0.03
	3.01	0.59	2.85 ± 0.05	0.6 ± 0.03
	4.21	0.19	4.29 ± 0.05	0.2 ± 0.03
	4.64	0.39	4.29 ± 0.05	0.4 ± 0.03
	4.07	0.57	4.29 ± 0.05	0.6 ± 0.03
Copper	1.78	0.22	1.87 ± 0.05	0.2 ± 0.03
	1.89	0.42	1.87 ± 0.05	0.4 ± 0.03
	1.85	0.59	1.87 ± 0.05	0.6 ± 0.03
	3.91	0.19	3.73 ± 0.05	0.2 ± 0.03
	3.98	0.38	3.73 ± 0.05	0.4 ± 0.03
	3.73	0.56	3.73 ± 0.05	0.6 ± 0.03
	5.98	0.22	5.59 ± 0.05	0.2 ± 0.03
	6.00	0.41	5.59 ± 0.05	0.4 ± 0.03
	6.61	0.59	5.59 ± 0.05	0.6 ± 0.03

Determination of the thickness of the metal substrate and coating. To quantitatively determine the thicknesses of the metal plate *d* and the dielectric layer *h*, we used the projection method on latent structures [10]. According to this method, the transition in a multidimensional space to a new coordinate system, in contrast with the regression to the principal components, is carried out using feature vectors (in this case, the characteristics of experimental hodographs) together with a priori known values of the predicted parameters for the selected group of samples. In the problem under consideration, these parameters are independently measured electrical conductivities σ and thicknesses *d*, *h*, which form the matrix of so-called responses. The totality of these experimental data composes a calibration (training) sample, with the help of which a calibration model is constructed that describes the dependencies between the results of eddy current measurements and controlled parameters. The previously obtained calibration dependencies are then used to calculate the thickness of the metal substrate and the dielectric coating of samples not participating in the construction of the calibration model, i.e., acting as controlled objects with unknown values of *d*, *h*.

In the calculations, to construct the calibration dependencies, we used the experimental data for a group of samples whose properties are described above (cf. Figs. 2, 3). Non-calibrated aluminum and copper plates with dielectric coatings; their *d* and *h* values were considered as test samples. The calculated values of the controlled thicknesses obtained for them are given in Table 1. The values predicted by the projection method on latent structures were compared with the results of independent measurements of the geometric parameters *d* and *h*, also given in Table 1.

Note that the proposed method made it possible to increase the accuracy of the impedance measurements of the measuring eddy current sensor in the frequency range 100–10000 Hz used due to digital signal processing, which caused a decrease in the random error up to 0.1%.

The data in Table 1 establish the influence of individual factors on the measurement result. The electrical conductivity had practically no effect on the results of predicting the thickness of the substrate and coating: the deviation of the forecast results from the measurement results as a whole did not exceed 8% for aluminum samples and 7% for copper (except for a 5.59 mm thick coated sample 0.6 mm thick, for which the deviation was 15%), which, in principle, indicated the limitation of this method by the thickness of the controlled plates.

The thicknesses of metal plates and dielectric coatings were controlled values; an increase in the thickness of the metal sample had practically no effect on the accuracy of determining the thickness of the coating (cf. Table 1), and an increase in the thickness of the dielectric coating increased the error in the predicted thickness of the samples by 3–5%.

Conclusion. The proposed methods for processing experimental data of multifrequency eddy current measurements of the parameters of metal materials with dielectric coatings are based on the mathematical discipline of multidimensional data analysis. The use of these methods allows one to separate the influencing factors and simultaneously measure the thickness of metal products with different electrical conductivities and thickness of coatings applied to these products. At the same time, the range of measuring problems of eddy current thickness measurement is significantly expanded. Note that from the point of view of metrology, the methods under consideration can become an urgent scientific basis for the development of eddy-current thickness gauges of a new generation, which, with sufficient accuracy, could simultaneously measure several characteristics (for example, the thickness of a metal sheet and a protective coating cover).

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