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# Analysis of the influence of controlled and interfering parameters during magnetic testing of coating thickness

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**Abstract**. The magnetic method for measuring the thickness of non-ferromagnetic and, in the general case, electrically conductive coatings on magnetic bases is characterized by a large number of interfering parameters, while the traditionally used principles of magnetic field formation, informative parameters and methods of obtaining measurement information have not undergone significant changes in recent years. However, new software products for modeling primary measuring transducers and modern electronic components allow a new look at the traditional principles of constructing thickness gages and algorithms for their operation when choosing the appropriate optimization criteria, which is the subject of this work.

## 1. Controlled and interfering parameters

Modern industrial production places high demands on the quality of functional and protective coatings. Magnetic induction non-destructive testing using harmonic low-frequency magnetic fields is widely used to measure the thickness $h$ of conductive non-ferromagnetic and dielectric coatings on ferromagnetic substrates or ferromagnetic coatings on conductive non-magnetic or dielectric substrates. The method, in most applications, is based on measuring the amplitude of the EMF $e_2(t)$ induced on the secondary winding $W_2$ of the transformer measuring transducer, proportional to the change in the mutual induction $M_{12}(h)$ of the windings, which depends on the thickness of the coating when the primary winding $W_1$ is excited by a harmonic current $i_1(t)$. In this case, $e_2(t)$ is determined by a change of the penetrating magnetic flux $\Psi_{12}(t)$ [1].

$$e_2(t) = -\frac{d}{dt}\left(\Psi_{12}(t)\right) = -\frac{d}{dt}\left(M_{12} i_1(t)\right) \tag{1}$$

The measurement error when using the method under consideration is determined, among other things, by a large number of interfering parameters:

1. External magnetic fields of the mains voltage from power transformers and power supply devices of power energy equipment (50 Hz network);
2. External pulsed electromagnetic fields from converters of power energy equipment and communication facilities (pulse interference);
3. Pulsed high-frequency pickups along power circuits and communication lines from the central processing unit (pulse pickups of the CPU);
4. Pulse pickups on power circuits and communication lines from pulse converters of the power supply;
5. Temperature drift of environmental parameters and control objects;

6. Roughness $R_z$ of the surface of the base and product;
7. Radius $r$ of curvature of the test object in the measurement area;
8. Thickness $T$ of the product or its wall to which the coating is applied;
9. Distances $L$ from the axis of the transducer to the edge of the product (edge effect);
10. Deviation of magnetic permeability $\mu_{\text{base}}$ base of the product (base) material within one product or batch;
11. The presence of eddy currents in the base material, conductive coating and electrically conductive elements of the design of the measuring transducer, depending on their specific electrical conductivity $\sigma_i$, magnetic permeability $\mu_i$ leading to the emergence of EMF $e_{sec}(t)$ on the secondary winding at frequencies $f > 200$ Hz [2].

All of these interfering parameters have a different level of influence on the measurement result. Some of them can be compensated (reduced to reasonable limits) by optimization:

– design of the primary measuring transducer;
– hardware (secondary measuring transducer);
– algorithms for exciting a magnetic field and processing of primary measurement information.

The geometric and electrophysical interfering parameters listed above are distinguished by the complexity of their suppression and taking into account when processing the measurement results. To assess the effect of each interfering parameter, it seems appropriate to use the finite element modeling tools.

## 2. Analysis of the influence of controlled and interfering parameters in the simulation of primary measuring transducers

Modeling primary measuring transducers over a two-layer structure, in the general case, "non-ferromagnetic electrically conductive coating - ferromagnetic electrically conductive base" allows, first of all, to optimize the geometric characteristics of the primary measuring transducer according to the criterion of "maximum sensitivity with required, in most cases, minimum, overall dimensions", and also to reduce the influence of $r$, $T$ and $L$. Modeling includes the selection and calculation of:

1. the relative position of the windings (radial, radial-axial, axial);
2. the ratio of the geometric parameters of the coils (diameters and heights of the windings)
3. geometric parameters of the ferromagnetic core (diameter, height, radius of the bearing surface);
4. geometric characteristics of the external shield made of ferromagnetic materials (outer diameter $D_s$ and wall thickness in the control zone);
5. the height of the excitation winding.

These parameters determine $M_{12}(h)$, which depends, inter alia, on the relative position of the windings, the number of their turns, the geometric dimensions of the contours of the windings and elements of the magnetic system, as well as on the $\mu_c$ of the core on which they are wound, and $\mu_s$ of the shield.

For high-tech industries, one of the most urgent tasks is to measure the thickness of non-magnetic coatings on small-sized parts and in hard-to-reach places of complex-shaped parts and assemblies. In this case, the key parameters are the diameter $D_s$ of the shield in the control zone and the total height of the transducer while ensuring $L \simeq D_s/2$ [3].

An example of optimization based on the results of modeling is the development of a small-sized primary measuring transducer for measuring the thickness of non-ferromagnetic coatings up to 300 μm thick for aircraft and rocketry.

For this measurement problem, the optimal one is understood as a transducer that provides measurement of the coating thickness with the required total measurement error at the minimum achievable diameter, height and provided the condition $L \simeq D_s/2$. In this case, as the main components of the measurement error, we will consider the random error $\delta_r$ caused by the processing of the measuring signal by the secondary measuring transducer and the influence of external magnetic fields, as well as the systematic error $\Delta_{sys}$ caused by the influence of the overall dimensions of the control objects (edge effect).

The total measurement error is determined by the expression [4]:

$$\delta = \sqrt{\delta_r^2 + \Delta_{sys}^2} \tag{2}$$

where

$$\delta_r = \frac{Range}{sens} \tag{3}$$

where $sens = \frac{\Delta E}{\Delta h}$, $[\frac{mV}{\mu m}]$ is the sensitivity of the magnetic induction transducer to the measured parameter h, determined by the change in the EMF $E$ on the secondary winding of the measuring transducer with a corresponding change in $h$.

*Range*, [mV] is a peak-to-peak signal at the output of the secondary measuring transducer at constant $h$.

The signal swing is influenced by external magnetic fields, external and internal impulse and high-frequency interference. The signal swing (EMF) was determined experimentally when connecting a magnetic induction transducer, conventionally taken as an exemplary one that does not interact with the test object, and amounted to ± 1 mV.

The systematic error caused by the influence of the overall dimensions of the controlled objects is determined by the expression:

$$\Delta_{sys} = \frac{(E_c - E_i)}{sens.} \tag{4}$$

where $E_c$, [mV] is EMF value on the secondary winding of the measuring transducer, obtained during calibration on a reference base at a given thickness reference standards with a thickness $h_s$; $E_i$, [mV] is EMF value on the secondary winding of the measuring transducer, obtained during measurements at the test object using a thickness reference standards with a thickness $h_s$.

As a measuring transducer, we consider a shielded absolute magnetic induction transducer of traditional structure (figure 1).

The transformer consists of a core with two windings enclosed in a magnetic shield. The number of turns of each winding is 1750. The diameter of the magnetic shield $D_s$ is twice the diameter of the core $D_c$, the wall thickness of the shield is 0.25 mm, the height of the core is 10.7 mm, and the core outlet is 0.8 mm.

In the simulation, the value of the EMF on the secondary winding of the measuring transducer was determined using the method of numerical solution of boundary value problems of electrodynamics (finite elements). The problem under consideration is described with satisfactory accuracy by a two-dimensional axisymmetric model (figure 2) [5].

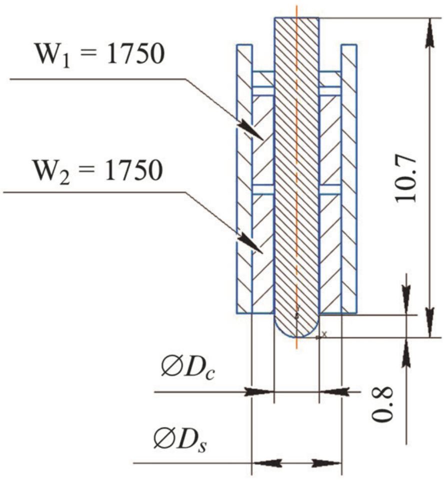

**Figure 1**. Conventional absolute shielded magneto-inductive transducer structure.

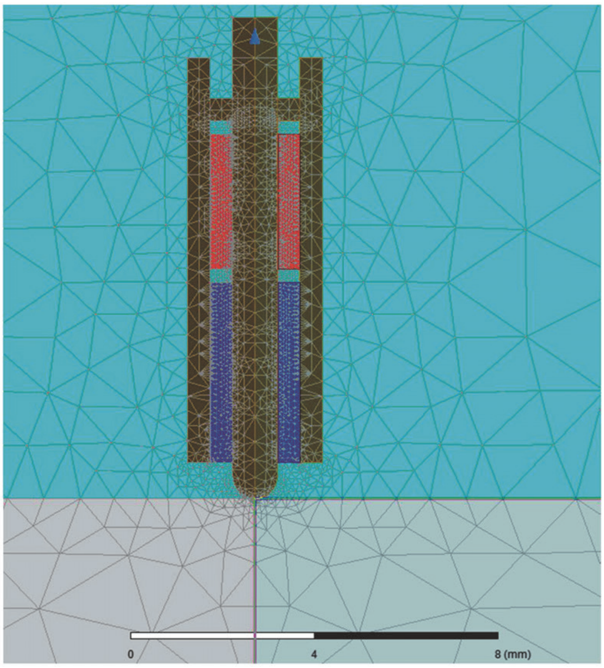

**Figure 2**. Two-dimensional axisymmetric model of an absolute shielded magnetic induction transducer over a ferromagnetic electrically conductive half-space.

In the model, for the core, magnetic shield, magnetic contactor and steel base, the following material parameters are accepted: specific conductivity $\sigma_c = 2 \cdot 10^6$ S/m and initial magnetic permeability $\mu_c = 200$.

The field winding $W_1$ is supplied with a sinusoidal current with an amplitude of 5.5 mA at a frequency of 300 Hz. The amplitude of the induced EMF on the measuring winding $W_2$ (max$E$, mV) acts as the analyzed parameter of the model.

A flat ferromagnetic base with a diameter significantly exceeding the diameter of the transducer (half-space) is used as an object of control for conditional calibration; a flat base with a diameter of 3.5 mm with similar thickness and electromagnetic properties is used as a tested object used to assess the error caused by the edge effect. The thickness of the coating is simulated by the gap between the contact surface of the transducer core and the base; the properties of the gap are equivalent to air.

Simulation of a series of geometrically similar magnetic inductive primary measuring transducers is shown in figure 3.

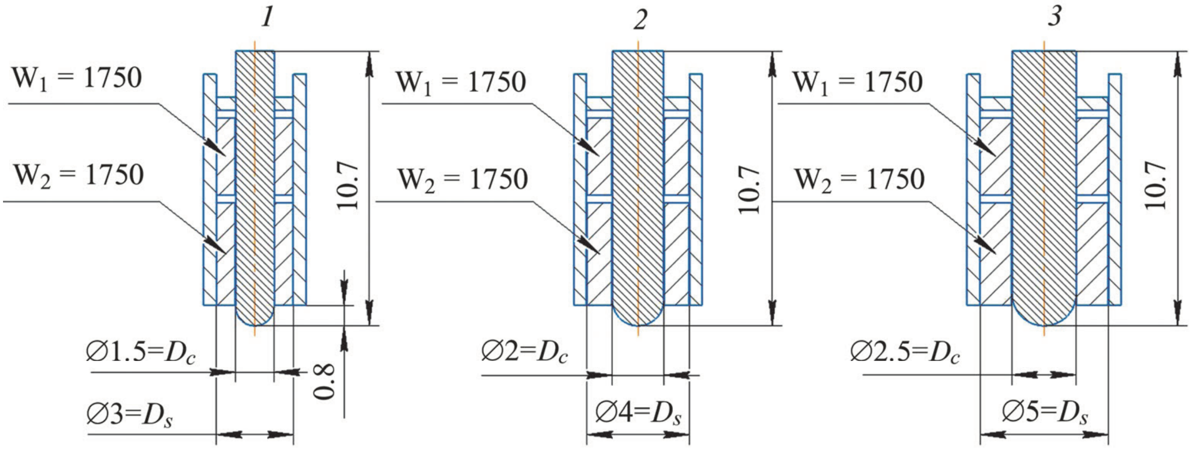

**Figure 3**. Designs of a series of simulated geometrically similar primary measuring transducers.

Figure 4 shows the simulation results of the presented transducers:

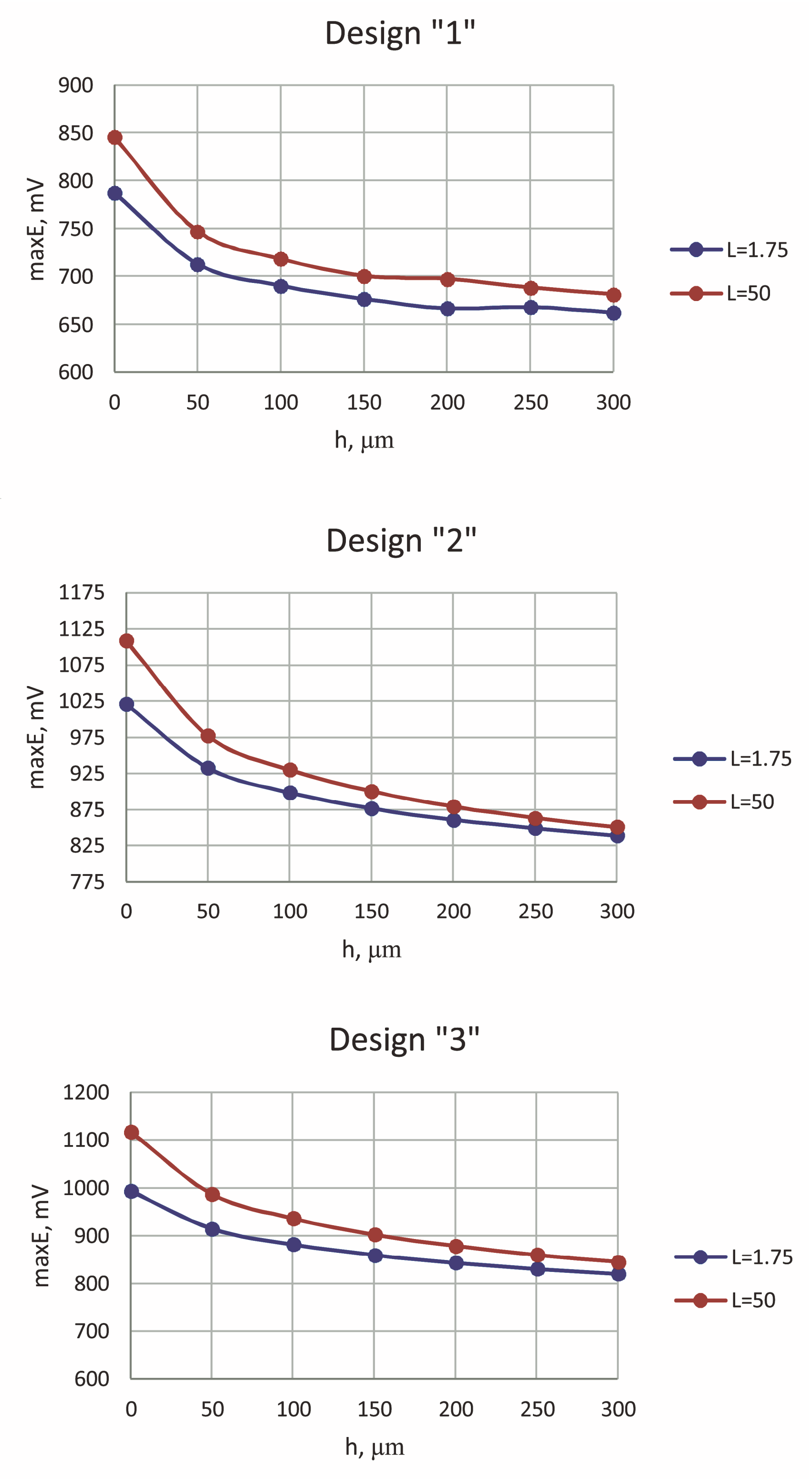

**Figure 4**. Dependence of the amplitude of the induced EMF max*E* on the gap for three designs of transducers.

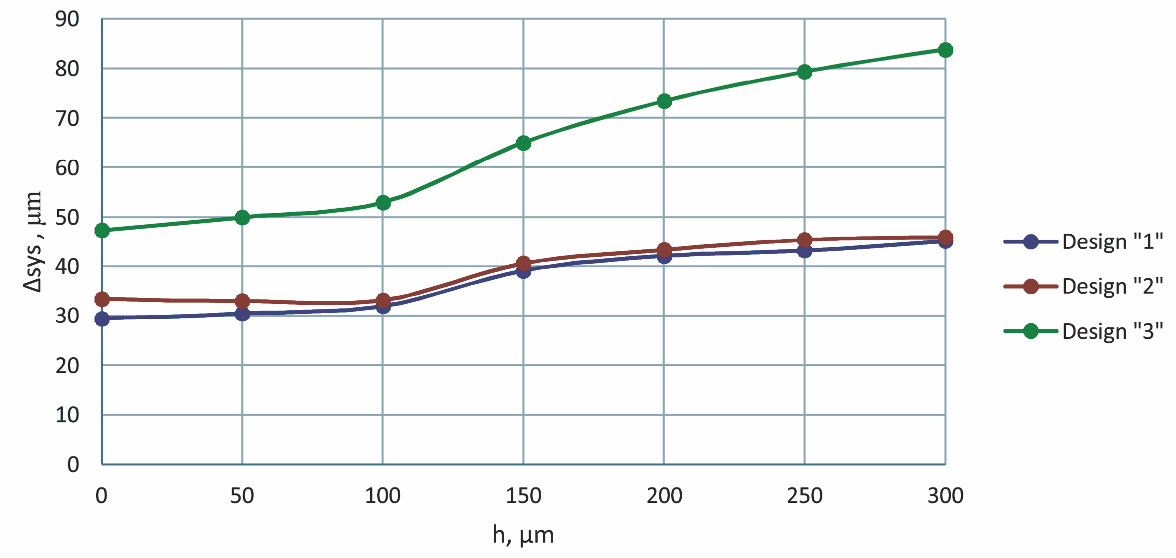

**Figure 5**. Dependence of the systematic error $\Delta_{sys}$ on $h$ for different designs of simulated transducers.

The dependence of the systematic error $\Delta_{sys}$ caused by the influence of the edge effect is shown in figure 5.

It can be seen from the presented results that the systematic error $\Delta_{sys}$ caused by the influence of the edge effect increases with an increase in the coating thickness $h$ and the overall dimensions of the transducer.

Figure 6 shows the dependence of the instrumental error $\delta_r$ on the coating thickness $h$ for three constructions of transducers.

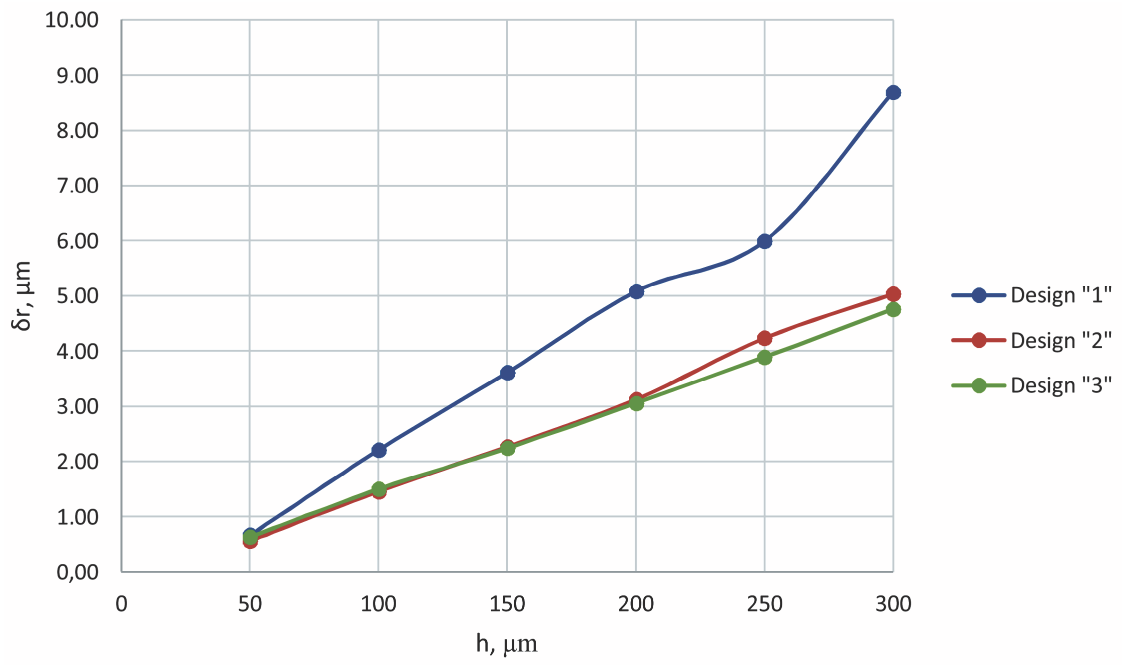

**Figure 6.** Dependence of the instrumental error $\delta_r$ on $h$ for three constructions (designs) of simulated transducers.

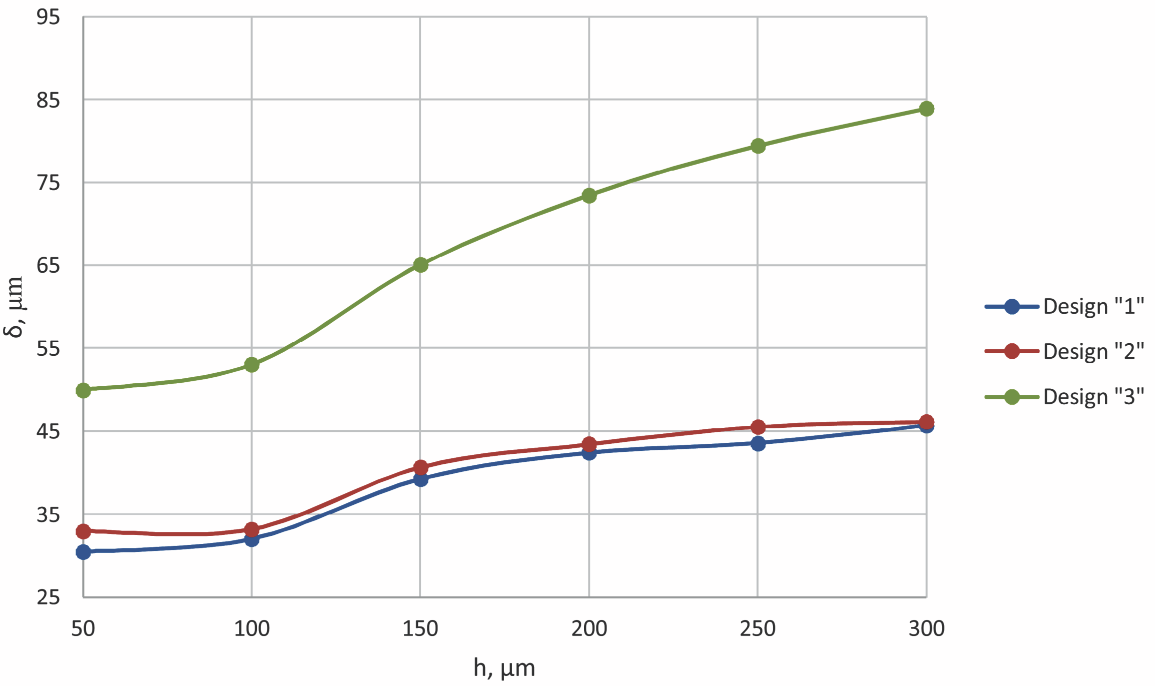

**Figure 7**. Dependence of the total measurement error δ on *h* for three constructions (designs) of simulated transducers.

It can be seen from the figure that the instrumental error $\delta_r$, in turn, decreases with an increase in the overall dimensions of the transducer, which is due to an increase in the induction on the measuring winding $W_2$ EMF $E_i$ , proportional to $\frac{\Delta\Psi}{\Delta t}$ , where Ψ is the magnetic coupling [Wb] of the measuring winding.

Figure 7 shows the dependence of the total error δ in measuring the thickness *h* of the coating for three designs of transducers.

Analyzing the presented dependence, it can be concluded that, despite the almost identical total measurement error of *h* in the range from 0 to 300 µm, provided by transducers of constructions 2 and 3, during calibration and measurements on tested objects close to real, optimal, due to smaller value $\delta_r$ is construction 2.

For experimental studies, a transducer was manufactured in accordance with construction 2, which confirmed the simulation results.

## 3. Selection of an informative parameter and suppression of the influence of interfering parameters during measurement

It is also possible to reduce the influence of interfering parameters in items 1, 2, 3, 4, 5, 11 by developing improved algorithms for exciting a magnetic field other than harmonic and processing primary measurement information using primary informative parameters based on the energy characteristics of signals.

Traditionally, in magnetic induction thickness gages, a harmonic excitation current is used $i(t) = I_0 \sin(2\pi f t)$, where $I_0$ is an amplitude, $f$ is a frequency. The amplitude of the EMF $e_2(t, h)$ induced on the secondary winding, which depends on the thickness of the coating $h$, is used as the primary informative parameter. The use of this transformation algorithm does not allow suppressing the influence of the above interfering parameters.

The use of an excitation current close to a stepped one and the use as a primary informative parameter of the area induced on the secondary winding of the EMF in the interval $\tau = N\tau_c$, $where\ \tau_c$ the period of the supply network allows to eliminate the disadvantages inherent in harmonic excitation currents.

The main task is to ensure the smoothness of the change *e*(*t*, *h*) and obtain a section *e*(*t*, *h*) = *const* where it is comparable to the ADC bit depth.

Figure 8 shows one of the options for the formation of *i*(*t*), which ensures smooth change *e*(*t*, *h*). In sections (a-b) and (c-d) $i(t)= I\cos^2(xt)$, and in section (b-c) $i(t)=At+I_0$. In this case, a pulse is induced on the secondary winding without kinks *e*(*t*, *h*) with an area *S* (τ, *h*). The pulse is digitized and calculated $N(T,h) = \sum_{i=1}^{m} n_i(t)$, where $n_i(t)$ is the single result of the analog-to-digital voltage transducer from the amplifier output, *m* is the number of conversion results in the time interval τ.

Figure 9 is a timing diagram illustrating the complete conversion cycle. At the moment *t* = 0, the microcontroller, using a high-speed built-in ADC, begins to form a control voltage, which is converted by the current source into a current *i*(*t*).

At the moment $t_1$, the current *i*(*t*) begins to change from + $I_0$ to - $I_0$ without kinks, and an EMF *e*(*t*, *h*) is induced on the secondary winding, which is fed through the amplifier to the input of a high-speed twelve-bit ADC of bitwise balancing with a conversion clock frequency of 100 kHz. Digitization of *e*(*t*, *h*) is performed relative to the midpoint of the supply voltage (reference voltage *Ref* = 1.25 V, generated by the built-in reference voltage source of the microcontroller, corresponding to $N_{average}$ ADC). The digitization of the EMF *e*(*t*, *h*) relative to the reference voltage *Ref* and the summation of the counts $n_j(t_j, h)$ is performed on the time interval $t_2 - t_1 = \tau\ (N_1(h))$.

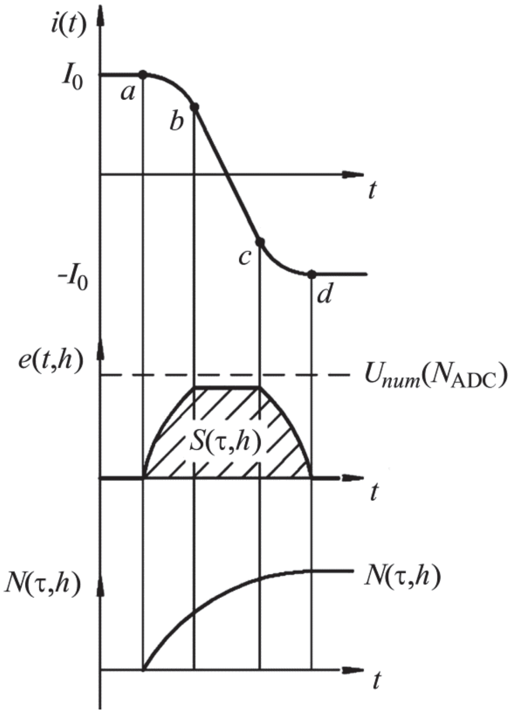

**Figure 8**. Timing diagrams illustrating the operation algorithm of a microcontroller-based transmitter using complex currents.

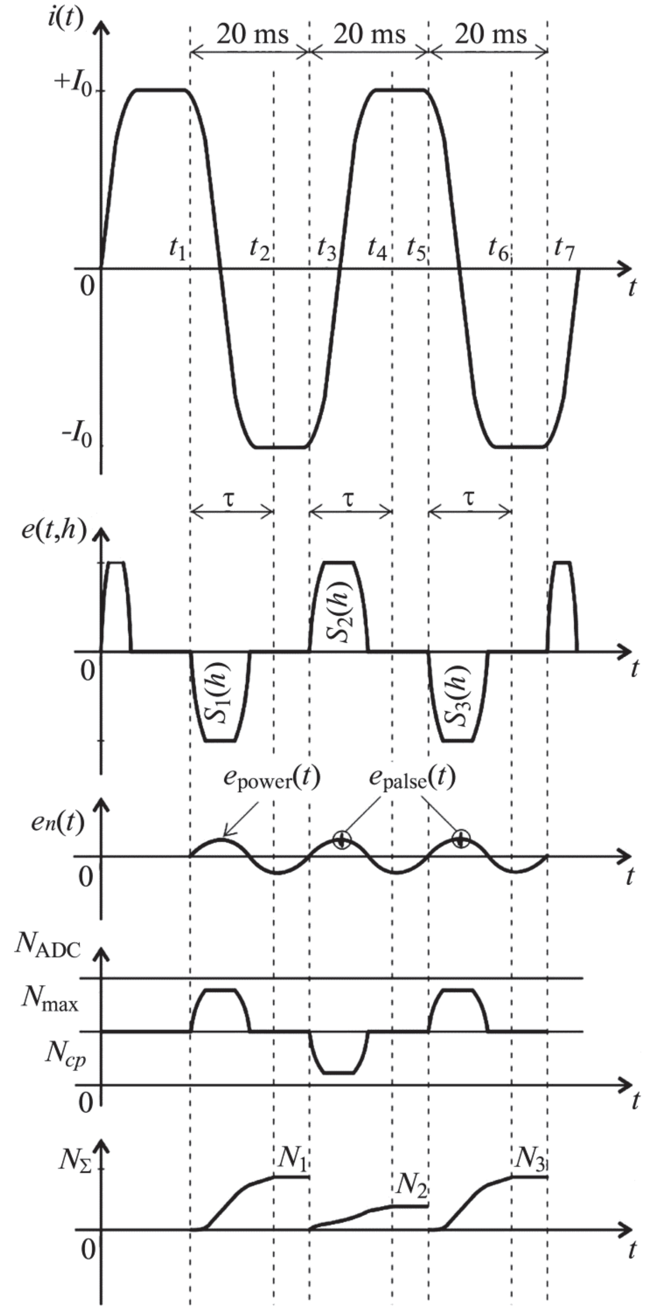

**Figure 9**. Timing diagram illustrating the complete conversion cycle.

$$N_1(T,h) = \sum_{j=1}^{m} n_j(t_j,h) \tag{5}$$

Similarly, transformations are performed on time intervals $t_4 - t_3 = \tau$ ($N_2(h)$ and $t_5 - t_4 = \tau$ ($N_3(h)$). All three conversion cycles are performed with a time shift of 20 ms, which provides equal error from network interference in each of the cycles. After that, the microcontroller calculates the code $N(h)$, which is an informative parameter

$$N(h) = [N_1(h) - N_2(h)] + [N_3(h) - N_2(h)] = N_1(h) + 2N_2(h) + N_3(h) = K\cdot\ [S_1(h) + 2S_2(h) + S_3(h)] \tag{6}$$

The code is used as the primary informative parameter:

$$\Delta N(h) = N(h) - N(h = \infty) \tag{7}$$

With this algorithm for generating current $i(t)$, a full cycle of magnetization reversal of the core is performed according to the partial hysteresis cycle. This makes it possible to suppress the influence of the residual magnetization of the core and shield material and to use hard magnetic steels with low abrasion for the manufacture of cores. The complete conversion cycle is 80 ms. The use of the informative parameter $\Delta N(h)$ allows you to eliminate the influence of line pickups and significantly reduce the effect of impulse and high-frequency pickups. Comparison of codes according to (7) makes it possible to significantly suppress the temperature and time drift of the parameters of the primary and secondary measuring transducers, caused by changes in the parameters of the environment. The conversion clocking from the microcontroller allows organizing a conversion algorithm that significantly reduces the influence of the microcontroller's own noise [6].

One more advantage of the scheme should also be highlighted. High repeatability of characteristics of ADC and DAC of microcontrollers ensures high repeatability of the transfer coefficient of the measuring transducer. In this case, the transducers can be calibrated on the bench, and when a non-volatile memory microcircuit is introduced into the primary transducer, the calibration characteristic can be written into it. When the primary transducer is connected, the thickness gauge microcontroller can read the calibration characteristic and make measurements.

## 4. Conclusion

The analysis of the influence of controlled and interfering parameters in the magnetic induction testing of the coating thickness made it possible to formulate optimization criteria for the parameters of geometrically similar primary measuring transducers used in modeling, on the basis of which, among other things, a miniature absolute primary measuring transducer was developed for rocket and aircraft engineering products, which has a minimum edge effect at a given sensitivity and a range of controlled thicknesses, as well as formulated and implemented an algorithm for measuring conversion, which makes it possible to significantly suppress most of the interfering parameters inherent in the magnetic method by using nonharmonic excitation currents and energy parameters of the induced EMF with appropriate timing of conversion cycles. The results of the study were used in the development of an electromagnetic thickness gauge of non-ferromagnetic coatings of ferromagnetic products “Constanta K6”, certified and included in the unified register of measuring instruments.

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