DOI 10.31489/2023PH1/71-79

UDK 620.179.14

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Mitigation of the effect of variations in the electrical conductivity of the material via two-frequency eddy current testing of the thickness of the electrically conductive wall under significantly varying influence parameters

The paper analyzes feasibility of the two-frequency eddy current method for measuring the thickness of an electrically conductive wall under significantly varying test and influence parameters of the test object — the lift-off between the eddy current probe and the test object surface, and the electrical conductivity of the material. An analytical solution was used to determine the dependence of the two-frequency signal of the surface eddy current probe on the influence parameters of the test object. The informative parameters used to simultaneously mitigate the effect of the two influence parameters were the amplitude of the added high-frequency voltage to determine the lift-off, the phase of the added low-frequency voltage to determine the wall thickness, and the phase of the added high-frequency voltage to suppress variations in the electrical conductivity of the material. The calculated dependences of the informative parameters on the test and influence parameters were analyzed. The use of nonlinear functions of the inverse transformation of the informative parameter into the test parameter was shown to efficiently mitigate the effect of variations in the lift-off on measurement results. A method to suppress variations in the electrical conductivity of the test object material is proposed. It implies the correction of the phase of the added low-frequency voltage by the correction value calculated from the parameters of the lift-off and wall thickness, and high-frequency phase variation caused by varying the electrical conductivity of the material.

Keywords: thickness measurement, surface eddy current probe, signal hodographs, stray parameters, suppression in eddy current testing.

Introduction

Eddy current non-destructive testing methods are widely used to test the electromagnetic and geometric parameters of multilayer electrically conductive products [1, 2].

Technical implementation of the eddy current method used to measure the wall thickness of light alloy drill pipes using a surface eddy current probe (ECP) is described in [3]. It is shown that along with the wall thickness parameter t, the main parameters of the test object that affect the ECP signal during measurement are variations in the lift-off h between the ECP and the surface of the test pipe and the electrical conductivity σ of the pipe material.

Significant variations in test and influence parameters complicate mitigation of the effect of these parameters on measurement results. The most effective solution to this problem is to use a multifrequency magnetic field [4–6]. For two-frequency eddy current testing, the excitation current frequencies are chosen so that the penetration depth of the magnetic field approximately equals half the wall thickness at high frequency f_1 and exceeds the wall thickness at low frequency f_2. In this case, the added high-frequency voltage of the eddy current probe depends on the lift-off h and material electrical conductivity σ, and the added low-frequency voltage depends on the lift-off h, material electrical conductivity σ and wall thickness t.

As shown in [7], conventional methods used to mitigate the effect of stray parameters (phase, amplitude, amplitude-phase) do not always yield the desired result, and the use of nonlinear functions of the inverse transformation of the informative parameter into the test parameter is far more efficient under the specified test conditions.

In [3], it was proposed to use nonlinear functions of the inverse transformation of the phase of the added low-frequency voltage into the test parameter to mitigate the lift-off effect, using the amplitude of the added high-frequency voltage to determine the lift-off values required for computation transformation. The study subject of this work is mitigation of the effect of variations in the electrical conductivity of the wall material on the results of measuring the electrically conductive wall thickness.

Methods and Materials

Figure 1 schematically shows the design of the surface ECP used in the study, which consists of the excitation winding w_{21}, measurement winding w_{21} and compensation winding w_{22}. The number of turns in the measurement and compensation windings is equal: $w_{21} = w_{22} = w_2$. An opposite connection of the measurement and compensation windings in the absence of the test object mutually compensates their initial electromotive force (EMF). Eddy currents generated in the electrically conductive test object located near the ECP cause a signal at the ECP output. The amplitude and phase (complex components) of the applied EMF generally depend on the amplitude and frequency of the excitation current, ECP design parameters, electromagnetic characteristics of the material and geometric parameters of the test object, and the position of the ECP relative to the test object.

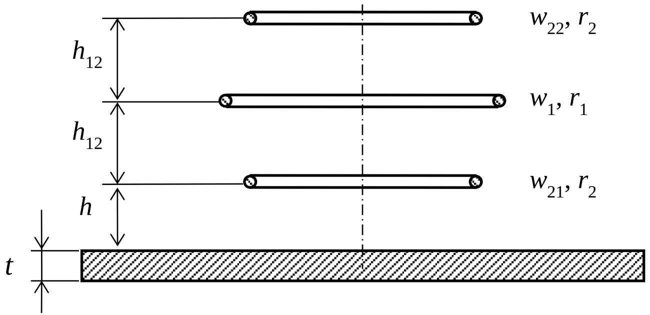

Figure 1. Surface ECP mounted over an electrically conductive plane wall

A mathematical model of the interaction between the magnetic field of the eddy current probe and the test object can be created based on well-known analytical solutions proposed in [8, 9]. To simplify the model, it was assumed that the winding cross section is infinitely small, the radii of the excitation winding r_1 and these of the measurement and compensation windings r_2 are equal to the radii of their middle turns, and the test object is of flat shape. In their mathematical structure, the results of the interaction between the ECP and the electrically conductive object having a curved surface (pipe) are similar to mathematical expressions for a flat object, which are adjusted for their numerical values [8].

A plane wall made of a non-magnetic material with the electrical conductivity σ in the range of (14…20) MSm/m with a thickness t in the range of (5…12) mm was used as a test object. The distance between the ECP measuring winding and the test object surface h varied in the range of (0…12) mm.

For the mathematical model, the ECP design used parameters were as follows: excitation winding radius $r_1 = 18$ mm; radii of the measurement and compensation windings $r_2 = 15$ mm; the distance between the planes of the turns of the measurement and compensation windings located symmetrically with respect to the excitation winding $2\,h_{12} = 22$ mm.

With regard to the above, the excitation current frequencies were chosen equal to $f_1 = 2500$ Hz and $f_2 = 125$ Hz.

Results and Discussion

According to [8], based on the assumptions, the added relative voltage of the measurement winding can be calculated by the expression:

$$\dot{U}^{*}_{21} = j\frac{1}{F}\int_{0}^{\infty}\dot{\varphi}_{to}\exp\left(-\frac{h_{12}+2h}{\sqrt{r_1\,r_2}}x\right)\times J_1\left(\sqrt{\frac{r_1}{r_2}}x\right)\times J_1\left(\sqrt{\frac{r_2}{r_1}}x\right)\mathrm{d}x\,, \qquad (1)$$

where $j = \sqrt{-1}$ is the imaginary unit; J_1 is the Bessel function of the first kind and first order; x is the integration parameter; F is the value proportional to the mutual inductance of the measurement and excitation windings calculated by the expression:

$$F = \int_{0}^{\infty}\exp\left(-\frac{h_{12}}{\sqrt{r_1\,r_2}}x\right)\times J_1\left(\sqrt{\frac{r_1}{r_2}}x\right)\times J_1\left(\sqrt{\frac{r_2}{r_1}}x\right)\mathrm{d}x\,,$$

$\dot{\varphi}_{to}$ is the function of the test object, calculated for a non-magnetic material by the expression:

$$\dot{\varphi}_{to} = \frac{-j\beta^2 \operatorname{th}\left(t^* \sqrt{x^2 + j\beta^2}\right)}{(2x^2 + j\beta^2)\operatorname{th}\left(t^* \sqrt{x^2 + j\beta^2}\right) + 2x\sqrt{x^2 + j\beta^2}},$$

where $t^* = t / r_1$ is the relative wall thickness; $\beta = r_1\sqrt{\omega\sigma\mu_0}$ is the generalized parameter; ω is angular frequency of the excitation current; σ is electrical conductivity of the material; μ_0 is the magnetic constant.

The expression for calculating the relative input voltage of the compensation winding can be obtained from (1) by formal replacement of the value h_{12} by $3h_{12}$.

The resulting value of the added relative voltage of the measurement and compensation windings can be calculated as follows:

$$\dot{U}^*_{\text{add}} = \dot{U}^*_{21} - \dot{U}^*_{22}.$$

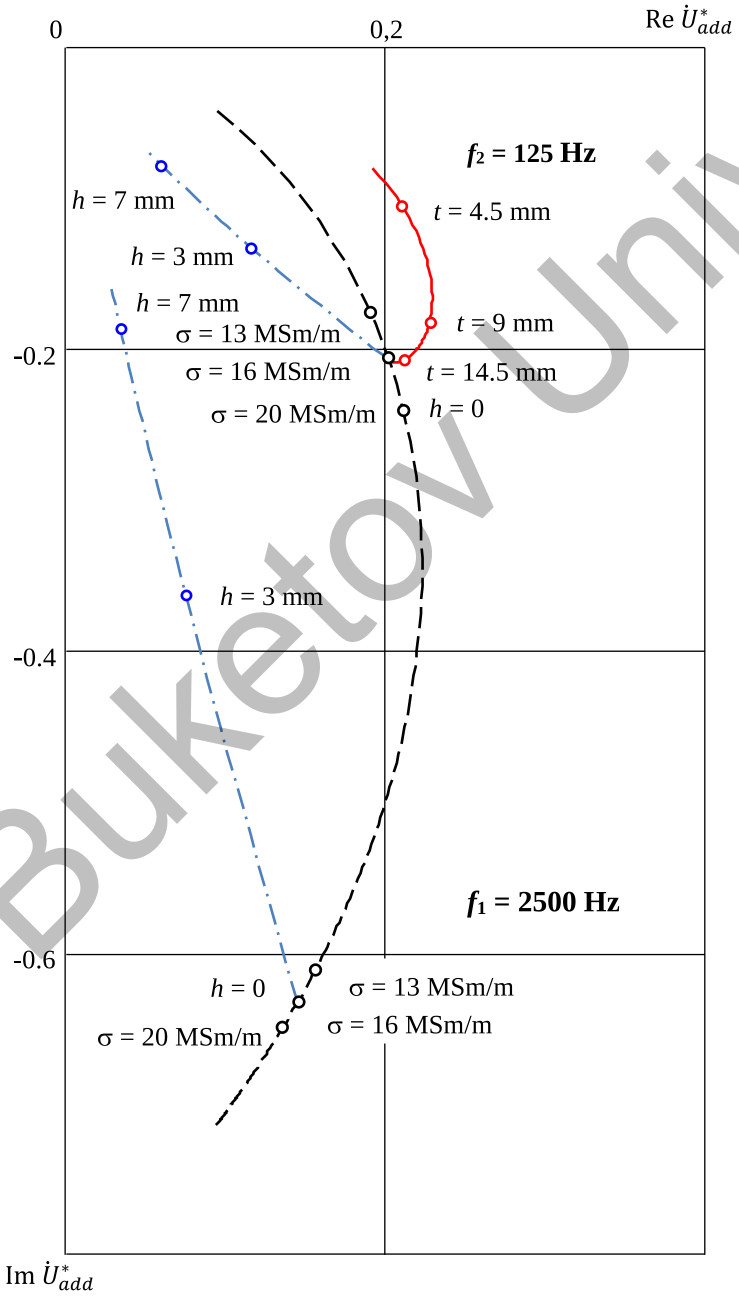

Figure 2. Hodographs of the relative added voltage of the surface ECT versus the variation in the electrical conductivity σ (— —), lift-off *h* (— · –) and thickness *t* (——)

Figure 2 shows hodographs of the added relative voltage of the surface ECP versus variations in electrical conductivity (dashed line), lift-off (dash-dotted lines), and thickness (solid line) calculated using the above analytical expressions for excitation current frequencies of 2500 Hz and 125 Hz.

The phase φ_2 of the added low-frequency voltage is typically used as an informative parameter of the added ECP voltage in two-frequency eddy current testing of the electrically conductive wall thickness *t*. The dependence pattern $\varphi_2(t)$ is monotonic. The analysis of the curves plotted in Figure 2 show that the value of the phase φ_2 depends, to some extent, on the lift-off *h*.

Figure 3 shows the dependence of the informative parameter of the added voltage φ_2 on the test parameter *t* for different values of the lift-off *h*.

The paper [3] proposes an algorithm for computation transformation of the values of the added voltage phase φ_2 and lift-off *h* into the value of the test parameter *t* using non-linear functions of the inverse transformation of the informative parameter into the test parameter. In this case, the electrical conductivity of the wall material was taken equal to a fixed value σ_0. In fact, the electrical conductivity σ of the material can vary in a wide range. Since σ significantly affects the added voltage phase φ_2, variations in the material electrical conductivity during measurement should be suppressed to minimize the measurement error of the test *t*.

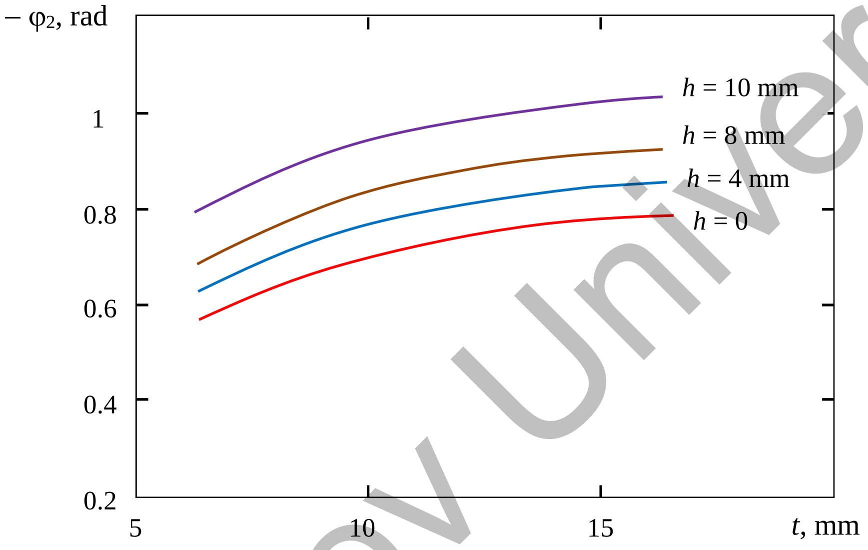

Figure 3. The informative parameter of the added voltage φ_2 versus the test parameter *t* for different lift-off values *h*

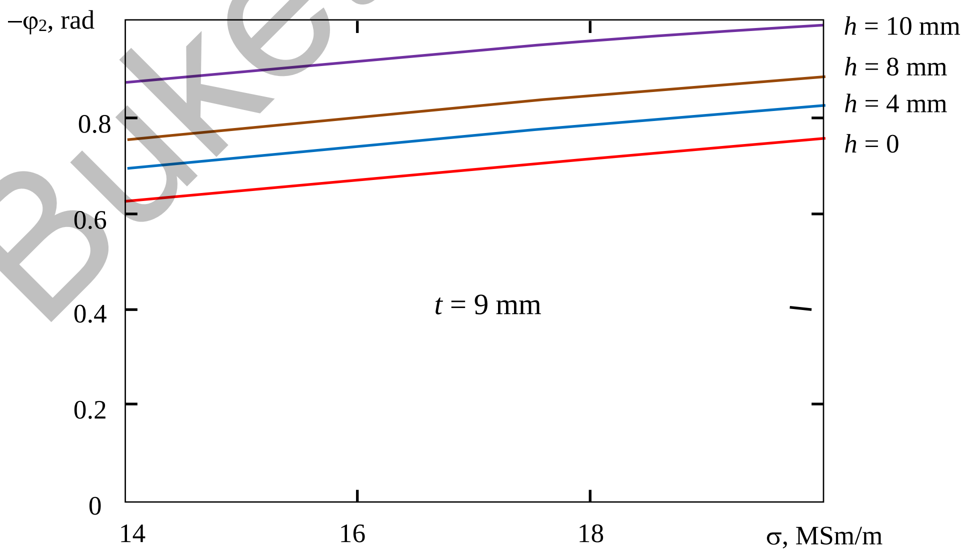

Figure 4. The added voltage phase φ_2 versus electrical conductivity σ for different lift-off values *h*

Figure 4 shows the dependence of the phase of the added low-frequency voltage φ_2 on the electrical conductivity of the material σ calculated using the above analytical expressions for different lift-off values h at fixed wall thickness t = 9 mm.

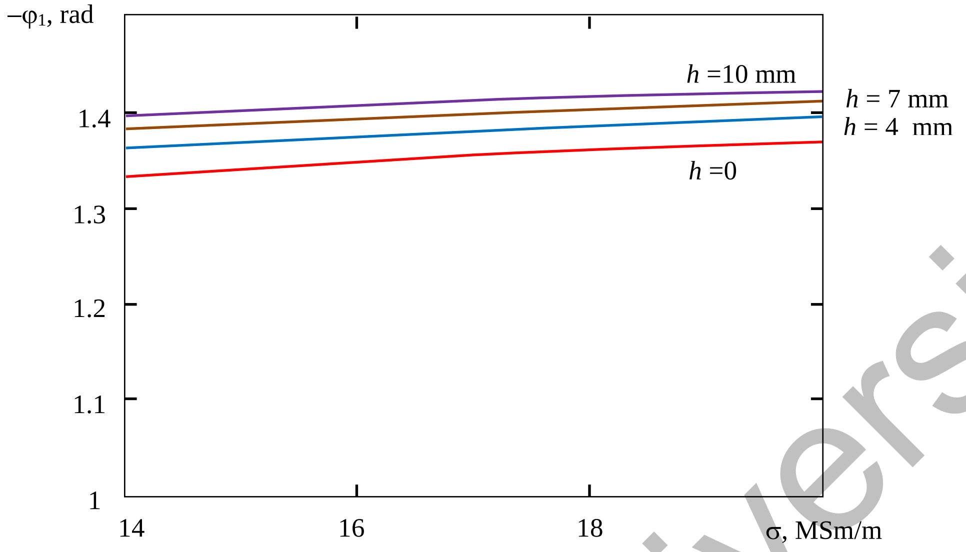

Figure 5. The added voltage phase φ_1 versus electrical conductivity σ for different lift-off values h

Figure 5 shows a similar dependence of the phase of the added high-frequency voltage φ_1 on the electrical conductivity σ for different lift-off values h.

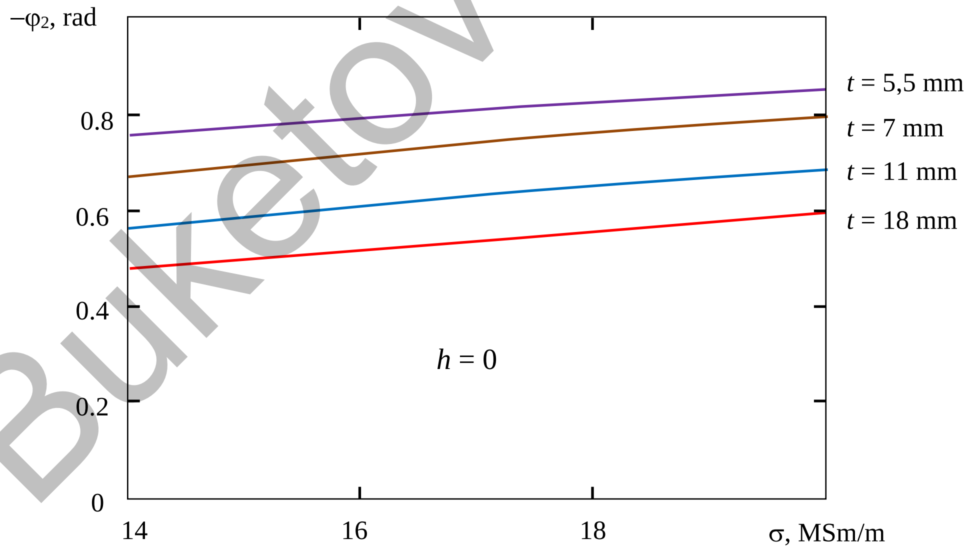

Figure 6. The added voltage phase φ_2 versus electrical conductivity σ for different thickness values t

Analysis of the dependencies presented in Figures 4 and 5 shos that both dependencies $\varphi_2(\sigma)$ and $\varphi_1(\sigma)$ are almost directly proportional. The dependences differ in a greater value of the proportionality constant in the first case, and in the dependence of the added low-frequency voltage phase φ_2 on the electrically conductive wall thickness t (Fig. 6). The added high-frequency voltage phase φ_1 virtually does not depend on the thickness t.

Based on the results of the analysis, a method was proposed for suppression of the variations in the electrical conductivity σ of the material to minimize the measurement error of the test parameter t.

The method is as follows. First, the added high-frequency voltage phase φ_{10} is determined at the measured lift-off h and the nominal electrical conductivity σ_0 using the dependence shown in Figure 5. For experimental determination of the conversion function, the value of the phase φ_{10} corresponds to the test samples.

After that, we calculate the phase difference $\Delta\varphi_1$ between the measured phase φ_1 of the added high-frequency voltage and its value φ_{10} at the nominal electrical conductivity σ_0:

$$\Delta\varphi_1 = \varphi_1 - \varphi_{10} .$$

Next, we determine the phase difference $\Delta\varphi_2$ between the measured phase value φ_2 of the added low-frequency voltage and its value φ_{20} at the nominal electrical conductivity σ_0.

The mathematical and physical modeling show that the phase difference $\Delta\varphi_2$ (due to the difference between the electrical conductivity σ of the test pipe material and its nominal value σ_0) is related to the phase difference $\Delta\varphi_1$ (due to the same reason) through the directly proportional dependence of the form

$$\Delta\varphi_2 = K\,\Delta\varphi_1 ,$$

where K is the factor.

K depends on the phases of the added voltages of low (φ_2) and high (φ_1) frequencies, with regard to the above proportional dependencies of the influence parameters for two fixed values of the electrical conductivity σ_1 and σ_2:

$$K = \frac{\varphi_2(\sigma_2, t, h) - \varphi_2(\sigma_1, t, h)}{\varphi_1(\sigma_2, t, h) - \varphi_1(\sigma_1, t, h)} .$$

K is the function of the electrically conductive wall thickness t and the lift-off h. The dependence pattern $K(t, h)$ is presented in Figure 7. Continuous lines indicate dependencies $K(t)$ for different lift-off values h.

With an acceptable degree of approximation, these dependencies can be described by polynomas of the first degree (dashed straight lines in Figure 7):

$$K(t, h) = a_0 + a_1 t + a_2 t h + a_3 h ,$$

where a_0, a_1, a_2 and a_3 are the coefficients depending on the values of low f_2 and high f_1 frequencies and the structural parameters of the eddy current probe.

The previously calculated values of the lift-off h and the thickness t are used to find the multiplier K, which is necessary to calculate $\Delta\varphi_2$. Next, we calculate the corrected value of the added low-frequency voltage phase, which corresponds to the nominal electrical conductivity σ_0:

$$\varphi_{20} = \varphi_2 - \Delta\varphi_2 .$$

After that, a new corrected phase of the added low-frequency voltage φ_{20} is used to perform recalculation the thickness t using the dependence presented in Figure 3. The recalculated thickness t is used for consistent calculations of K, $\Delta\varphi_2$, φ_{20} and the thickness t. The described calculation cycle is repeated (2... 5) times, depending on the required accuracy. The thickness t calculated in the last cycle is taken as the final test parameter t.

Test samples of different wall thickness used for experimental verification of the results and evaluation of the effectiveness of the proposed method were similar to those used in [3]. The nominal electrical conductivity was 16 MSm/m. The electrical conductivity was changed through changing the sample temperature in the range of (–10…+80) °C. The measurement of the high-frequency voltage phase showed variation in the multiplier K used to correct the values of the low-frequency voltage phase in the range from 3.2 to 5.3.

Analysis of the obtained results showed that the method proposed for mitigation of the effect of variations in electrical conductivity minimizes this effect, and the measurement error of the wall thickness *t* in the range of (5...12) mm with the lift-off changing in the range of (2...12) mm does not exceed 5 %.

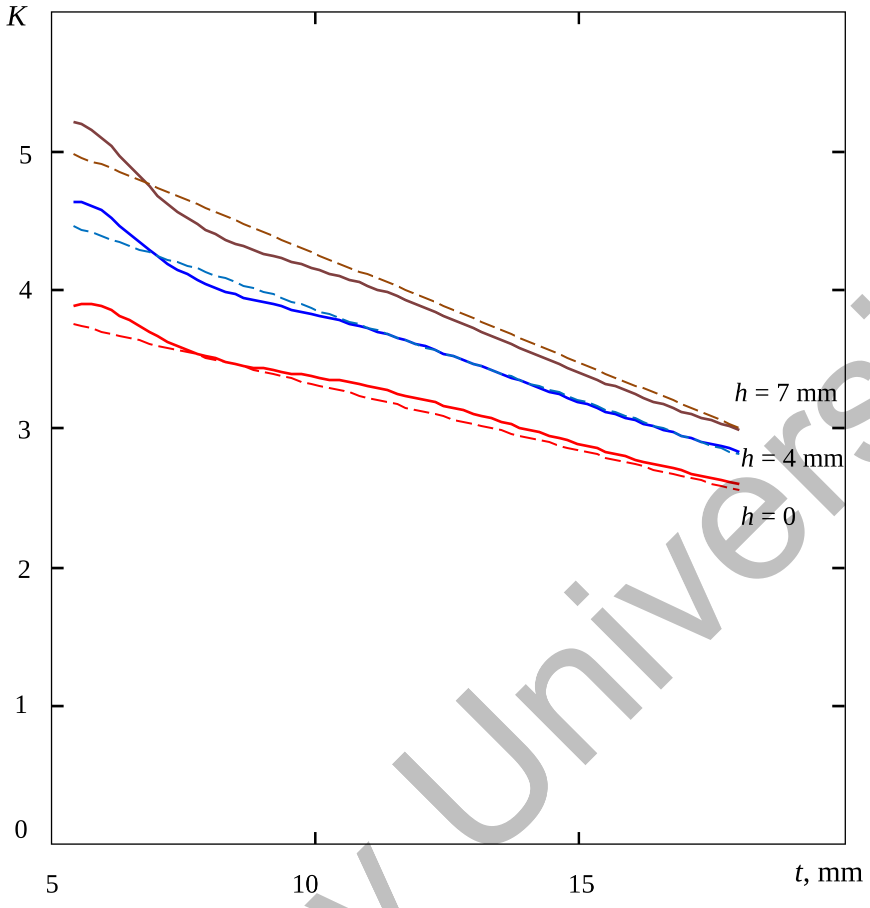

Figure 7. The factor *K* versus the wall thickness *t* and the lift-off *h*

Conclusions

The two-frequency eddy current method can be used for effective measurement of the thickness of a non-magnetic electrically conductive wall with significant variations in both test and influence parameters — the lift-off between the probe and the test object surface, and the electrical conductivity of the material. The method employs such informative parameters of the signal as the added high-frequency voltage amplitude for measuring the lift-off, added low-frequency voltage phase for measuring the wall thickness, and added high-frequency voltage phase for suppressing variations in material conductivity. To mitigate the lift-off effect, a method based on the use of nonlinear functions of the inverse transformation of the informative parameter into the test parameter has been proposed. The method proposed for suppressing variations in the electrical conductivity of the metal is based on correction of the added low-frequency voltage phase by the correction value determined by the values of the lift-off, and wall thickness, and variation in the high-frequency phase due to the changed electrical conductivity of the material. The effectiveness of the proposed methods has been evidenced by the results of mathematical and physical modeling.

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Әсер ететін параметрлердің елеулі өзгерістері жағдайында электр өткізгіш қабырғаның қалыңдығын бақылаудың екіжиілікті құйынды ток әдісін іске асыру кезінде материалдың электр өткізгіштігі өзгерістерінің әсерін анықтау

Бақылау объектісінің бақыланатын және әсер ететін параметрлері — құйынды ток түрлендіргіші мен бақылау объектісінің беті мен материалдың меншікті электр өткізгіштігі арасындағы алшақтықтың елеулі өзгерістері жағдайында электр өткізгіш қабырғаның қалыңдығын құйынды токпен бақылаудың екіжиілікті әдісінің қолданылуы зерттелді. Үстеме құйынды ток түрлендіргішінің екіжиілікті сигналының бақылау объектісінің әсер ететін параметрлеріне тәуелділігін анықтау үшін аналитикалық шешім қолданылды. Бақылау объектісінің екі әсер ететін параметрлерін бір мезгілде түзетуде ақпараттық параметрлер ретінде саңылауды анықтау үшін жоғары жиілікті қолданылатын кернеудің амплитудасын, қабырға қалыңдығын анықтау үшін төмен жиілікті қолданылатын кернеудің фазасын және материалдың меншікті электр өткізгіштігінің өзгеруінен қалпына келтіру үшін жоғары жиілікті қолданылатын кернеудің фазасын пайдалану ұсынылған. Ақпараттық параметрлердің мәндерінің бақыланатын және әсер ететін параметрлерге есептеу арқылы алынған тәуелділігі талданған. Ақпараттық параметрлердің мәндерін бақыланатын параметр мәніне кері түрлендірудің сызықтық емес функциялары саңылауының өзгеруін бақылау нәтижелеріне әсер етуден қалпына келтіру үшін пайдалану тиімділігі атап өтілген. Материалдың меншікті электр өткізгіштігінің өзгеруіне байланысты саңылау мәндерімен, қабырға қалыңдығымен және жоғары жиілікті фазаның өзгеруімен анықталатын түзету шамасына төмен жиілікті енгізілетін кернеудің фазасын түзетуге негізделген бақылау объектісінің металының меншікті электр өткізгіштігінің өзгеруінен түзету әдісі ұсынылды.

Кілт сөздер: қалыңдығын өлшеу, үстеме құйынды ток түрлендіргіші, сигнал годографтары, кедергі параметрлері, құйынды ток бақылауында түзету.

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Отстройка от влияния изменений электропроводности материала при реализации двухчастотного вихретокового метода контроля толщины электропроводящей стенки в условиях значительных изменений влияющих параметров

Исследована применимость двухчастотного метода вихретокового контроля толщины электропроводящей стенки в условиях значительных изменений как контролируемого, так и влияющих параметров объекта контроля — зазора между вихретоковым преобразователем и поверхностью объекта контроля и удельной электрической проводимости материала. Для определения зависимости двухчастотного сигнала накладного вихретокового преобразователя от влияющих параметров объекта контроля использовано аналитическое решение. Для одновременной отстройки от двух влияющих параметров объекта контроля предложено использовать в качестве информативных параметров амплитуду вносимого напряжения высокой частоты для определения зазора, фазу вносимого напряжения низкой частоты для определения толщины стенки и фазу вносимого напряжения высокой частоты для отстройки от изменения удельной электрической проводимости материала. Проанализированы полученные расчетным путем зависимости значений информативных параметров от контролируемого и влияющих параметров. Отмечена эффективность использования для отстройки от влияния на результаты контроля изменений зазора нелинейных функций обратного преобразования значений информативных параметров в значение контролируемого параметра. Предложен метод отстройки от изменения удельной электрической проводимости металла объекта контроля, основанный на коррекции фазы вносимого напряжения низкой частоты на величину поправки, определяемой значениями зазора, толщины стенки и изменением фазы высокой частоты, обусловленным изменением удельной электрической проводимости материала.

Ключевые слова: измерение толщины, накладной вихретоковый преобразователь, годографы сигнала, мешающие параметры, отстройка при вихретоковом контроле.

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