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Hindrances associated with examination of two-layer structures with use of the eddy current method

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ABSTRACT

Purpose: Determination and description of essential phenomena that occur during examination of two-layer structures with use of the eddy-current method. Development of guidelines to establish procedures that make it possible to find out optimum frequencies of eddy currents, for which measurements of the outer film covering the examined structure exhibit best performance. Estimation of errors that occur when measurements of both geometrical and electrical parameters of the upper film within the two-layer structures are carried out simultaneously.

Design/methodology/approach: During the design and scalling of the devices based on phenomenon of eddy currents implying changes of contact coil impedance components, significant influence of the electromagnetic field frequency on measurement results was observed. Additionally, some other phenomena can be observed which causes invalid interpretation of devices indications. Basing on a mathematical model of a contact coil located above a conductive non-ferromagnetic two-layer plate, the sensitivities to the measured parameters are determined. The developed mathematical model serves and the basis to calculate theoretical values of errors when all parameters of the outer film on the examined structure are measured simultaneously.

Findings: Depending on specific applications, recommendations enabling proper choice of the electromagnetic field frequency are formulated.

Practical implications: Describred phenomena and calculations are useful for the designers of the devices utilising the phenomenon of eddy currents, and also for the users of flaw detectors and conductometers. Remarks included in this paper can be useful for proper interpretation of the observed results and phenomena.

Originality/value: Determination of impact coefficients that define how parameters of the two-layer structure are vulnerable to impedance components of the measuring contact coil.

Keywords: Non-destructive testing; Eddy currents; Flaw detection; Conductometry

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PROPERTIES

1. Introduction

When the contact coil fed with alternating current is approached to the surface of a conductive material, the electromagnetic field around the coil induces eddy currents in the tested material. The currents generate their own electromagnetic field oriented, in accordance with Lenz's law, opposite to the exciting field. Eventually, the field around the coil will be reduced, leading to changes in the coil impendance. By measuring the coil impedance components of the coil it is possible to calculate the parameters of the tested conductive material. It is convenient to apply that method for examination of conductive non-ferromagnetic materials, in particular aluminium alloys, such as described in [2, 3, 4]. It is also possible to use non-metallic conductive materials, e.g. the ones that are made of carbon fibers [1] of other conductive compositions [5].

Eddy-current conductometers are suitable for measuring conductivity of materials but they are also sensitive to changes in geometrical dimensions of the examined structures. Therefore the method can be used to check dimensions or quality of welding joints [6]. Flaw detection is another important area where application of eddy currents is really useful. Any defects in materials, cracks or delaminations alter distribution of electric currents, which, in turn, is effectively detected by a measuring probe. Theoretical basis of the eddy-current methods are described in many textbooks and papers, including [13, 14, 15]. But the mathematical model for the discussed phenomena proves to be rather sophisticated. In practice, for each specific arrangement: the examined structure of any shape and the measuring probe, alteration of electric parameters can be calculated exclusively by means of the numerical methods, such as FEM (Finite Element Method) or BIM (Boundary Integral Method) [13-19]. The reverse problem that consists in determination of shapes, dimensions, conductivity or flaws in the examined material based on changes of electric parameters exhibited by the measuring probe, is still unambiguous.

It is why the assumption is made that a part of parameters and geometrical shapes is constant and subjects to no alterations and only selected parameters are measured. Changes in other parameters result in measurement errors. Another observable and important phenomenon is the influence of eddy current frequency onto sensitivity of the measurement instrument as it turns out that for some frequency ranges the sensitivity to variations of specific parameters is negligible, whilst for the same frequency ranges the measuring system is vulnerable to changes in values of other parameters. What's more, even accidental, unintentional, insignificant changes of the frequency may affect sensitivity to the measured parameters.

The next important issue consists in determination how deep eddy currents are capable to penetrate the examined structures. It is important to be aware, which area of the examined material is reflected in measurement results. The interesting suggestion how to determine penetration depth is described in [8, 9].

The studies [10, 11, 12] deal with the problem how to examine steel sheets by means of the eddy current method with use of a contact coil.

For analytic purposes it is extremely interesting to investigate materials that conduct electric current and are covered with a film of another material, also with conductive properties. Construction of a device capable to examine two-layer structures is a pretty sophisticated challenge, so it is important to use the appropriate mathematical model that makes it possible to calculate desired parameters of the examined material on the basis of alterations in impedance components of the measuring coil. Such a model should also enable selection of the most suitable frequency of eddy currents, when the desired sensitivity is high and effect of non-measured parameters as low as possible. The method described in this document refers to the two-layer model and parameters of the outer film shall be searched for as outcomes of the measurements.

2. Mathematical model

The discussed example will involve a contact coil, that is, a coil constructed in such a way that it may be approached or put in contact with a relatively flat surface of the tested element.

Fig. 1 presents a contact coil, positioned within the distance of h over the surface of the structure under test. The real structure is substituted with a half-space with its conductivity of σ_p. The half-space is covered with a foil that has the thickness of d and conductivity of σ_i. The real coil is substituted with a model coil with all its n turns encapsulated by a circle with the radius of r_0. In the following part of this paper the above generalized parameters:

$$\alpha = \frac{2h}{r_0} \tag{1}$$

$$\beta = r_0 \sqrt{\omega \mu_0 \sigma_i} \tag{2}$$

$$\rho = \frac{2d}{r_0} \tag{3}$$

$$s = \frac{\sigma_p}{\sigma_i} \tag{4}$$

where:

σ_p conductivity of the deeper layer of the two-layer structure under tests,
σ_i conductivity of the surface film,
h distance between the coil and the surface under tests,
d foil thickness,
r_0 coil radius,
ω angular frequency of the current in the coil,
n number of turns.

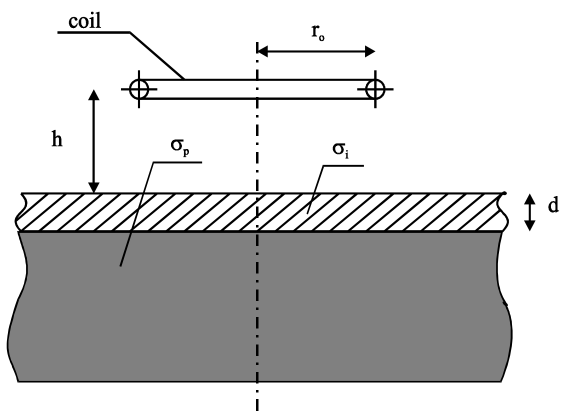

Fig. 1. A contact coil positioned over a conductive two-layer structure

Impedance change of the coil caused by presence of a two-layer conductive structure ΔZ can be calculated by the formula:

$$\Delta Z = n^2 \omega \pi \mu_0 r_0 Q(\alpha, \beta, \rho, s) \tag{5}$$

where:

$$Q(\alpha, \beta, \rho, s) = j\beta \int_0^\infty c(\alpha, \beta, \rho, s) \cdot J_1^2(\beta y) e^{-\alpha \beta y} dy \tag{6}$$

whilst the function (α,β,ρ,s) is determined by means of the equation:

$$c(\alpha,\beta,\rho,s)=\frac{(\sqrt{y^2+js}+\sqrt{y^2+j})(\sqrt{y^2+j}-y)+(\sqrt{y^2+js}-\sqrt{y^2+j})(\sqrt{y^2+j}+y)\cdot e^{-\alpha\beta\sqrt{y^2+j}}}{(\sqrt{y^2+js}-\sqrt{y^2+j})(y-\sqrt{y^2+j})\cdot e^{-\alpha\beta\sqrt{y^2+j}}-(\sqrt{y^2+js}+\sqrt{y^2+j})(y+\sqrt{y^2+j})} \tag{7}$$

Separation of the real and imaginary parts of the expression (5) makes it possible to calculate changes of the coil resistance and inductance caused by presence of the two-layered half plane:

$$r=\Delta R=R-R_0=n^2\omega\pi\mu_0 r_0\phi(\alpha,\beta,\rho) \tag{8}$$

$$l=\Delta L=L_0-L=n^2\pi\mu_0 r_0\chi(\alpha,\beta,\rho) \tag{9}$$

where:

$$\varphi(\alpha,\beta,\rho,s)=\operatorname{Re}Q(\alpha,\beta,\rho,s) \tag{10}$$

$$\chi(\alpha,\beta,\rho,s)=-\operatorname{Im}Q(\alpha,\beta,\rho,s) \tag{12}$$

R_0 and L_0 – parameters of the coil positioned within a distance from the structure under test.

Changes in components of the coil impedance, described by formulas (8) and (9) depend on values of the functions $\varphi(\alpha,\beta,\rho,s)$ and $\chi(\alpha,\beta,\rho,s)$. These functions can be referred to as generalized changes of the coil resistance and inductance caused by presence of a conductive medium, however calculation of values for the functions $\varphi(\alpha,\beta,\rho,s)$ and $\chi(\alpha,\beta,\rho,s)$ is possible exclusively by means of numerical methods. Fig. 2 presents graphs for the functions φ and χ vs. the parameter a for the values $\beta = 5$, $\rho = 0.2$ and $s = 0$, 0.5 and 1.

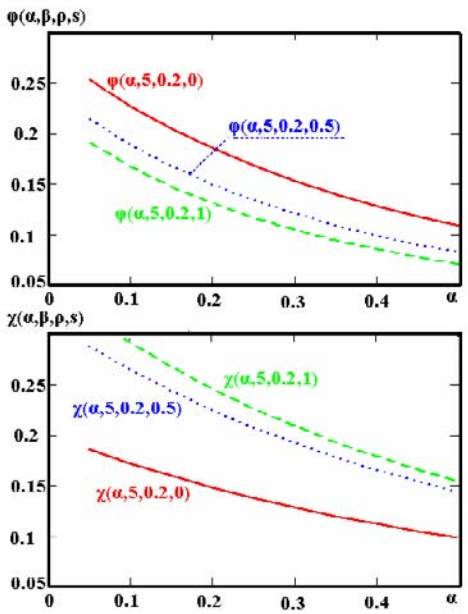

Fig. 2. Graphs for the functions φ and χ depending on the parameter a for the values of $\beta = 5$, $\rho=0.2$ and $s = 0, 0.5, 1$

Fig. 3 exhibits graphs for the functions φ and χ vs. the parameter β for $\alpha = 0.2$, $\rho = 0.2$ and $s = 0, 0.5, 1$, whilst Fig. 4 contains graphs for the same functions depending on the parameter ρ for $\alpha = 0.2$ and $s = 0, 0.5, 1$. Fig. 5 presents graphs for generalized changes in the coil impedances for several values of β parameter depending on variations of the s parameter. Sophisticated forms of the curves suggest that frequency adjustment for the field that excites eddy currents is a matter of extreme importance when multi-layer structures are to be examined. Screening properties of the surface film substantially reduces ability to penetrate deeper layers. It is also worth to mention another interesting phenomenon, namely adverse effect of the underneath layer onto examination of parameters attributable to the conductive outer film.

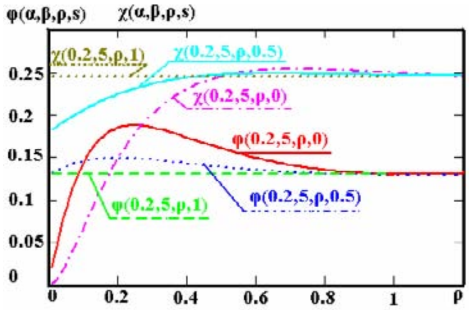

Fig. 3. Graphs for the functions φ and χ depending on the parameter ρ for the values of $\alpha = 0.2$, $\beta=5$ and $s = 0, 0.5, 1$

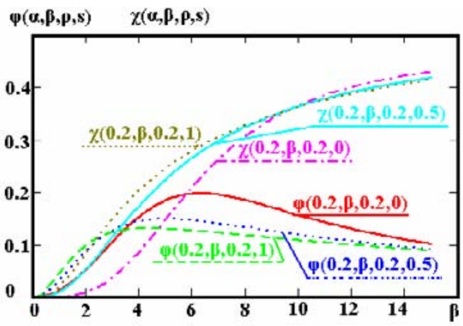

Fig 4. Graphs for the functions φ and χ depending on the parameter β for $\alpha=0.2$, $\rho=0.2$ and $s=0, 0.5, 1$

3. Measuring device sensitivity

In order to efficiently analyze effect of parameters associated with the multi-layered structure onto variations of the coil impedance components it is suitable to develop a sensitivity-based model. Coefficients that define influence of all the considered parameters onto variations of the coil impedance and inductance can be calculated by means of equations (8) and (9) with use of the total differential method. Fig. 6 is the proposed diagram for a linear model that explains impact of parameters allied to the structure under test onto impedance components of the contact coil. It is the model that makes it possible to determine coefficients that link variations of geometric dimensions d and h as well as conductivity σ_p and σ_i of subsequent layers within the examined medium with changes of resistance and inductance of the measuring coil. The impact coefficients that establish interrelations between the coil distance from the examined surface and variations of the coil resistance and inductance parameters can be expressed by means of the following formulas:

$$\frac{\Delta r}{\Delta h}=\frac{2n^2\pi\beta^2}{r_0^2\sigma_i}\frac{\partial\varphi}{\partial\alpha} \tag{13}$$

$$\frac{\Delta l}{\Delta h}=2n^2\pi\mu_0\frac{\partial\chi}{\partial\alpha} \tag{14}$$

Conductivity σ_p of the underneath layer affects changes in the coil resistance and inductance parameters in accordance to the following relationships:

$$\frac{\Delta r}{\Delta\sigma_p}=\frac{n^2\pi\beta^2}{r_0\sigma_i^2}\frac{\partial\varphi}{\partial s} \tag{15}$$

$$\frac{\Delta l}{\Delta\sigma_p}=\frac{n^2\pi\mu_0 r_0}{\sigma_i}\frac{\partial\chi}{\partial s} \tag{16}$$

Conductivity of the covering film can be transformed into changes in the coil resistance and inductance parameters in the following manner:

$$\frac{\Delta r}{\Delta\sigma_i}=\frac{n^2\pi\beta^2}{r_0\sigma_i^2}\left(\frac{\beta}{2}\frac{\partial\varphi}{\partial\beta}-\frac{\sigma_p}{\sigma_i}\frac{\partial\varphi}{\partial s}\right) \tag{17}$$

$$\frac{\Delta l}{\Delta\sigma_i}=\frac{n^2\pi\mu_0 r_0}{\sigma_i}\left(\frac{\beta}{2}\frac{\partial\chi}{\partial\beta}-\frac{\sigma_p}{\sigma_i}\frac{\partial\chi}{\partial s}\right) \tag{18}$$

The coefficients to establish how thickness of the covering film with its conductivity of σ_i affects alterations of the coil impedance components are defined by the expressions:

$$\frac{\Delta l}{\Delta d}=2n^2\pi\mu_0\frac{\partial\chi}{\partial\rho} \tag{19}$$

$$\frac{\Delta r}{\Delta d}=\frac{2n^2\pi\beta^2}{r_0^2\sigma_i}\frac{\partial\varphi}{\partial\rho} \tag{20}$$

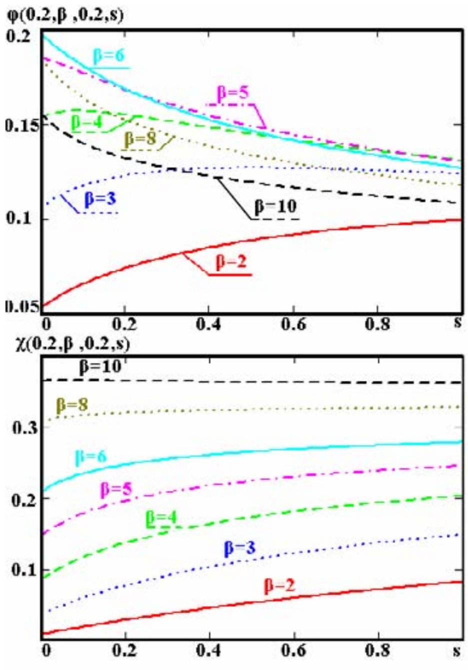

Fig. 5. Graphs for the functions φ and χ depending on the parameter s for $\alpha=0.2$, $\rho=0.2$ and $\beta=2, 3, 4, 5, 6, 8$ and 10

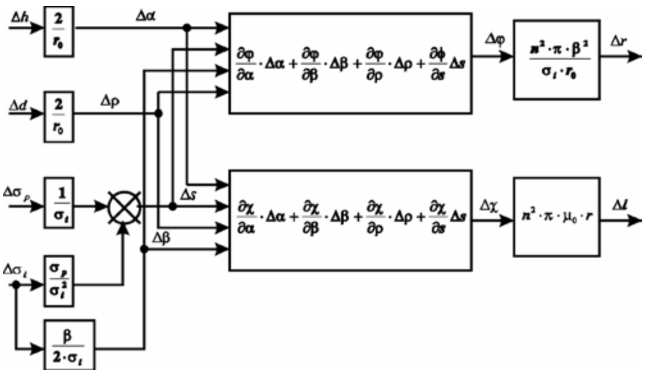

Fig. 6. The diagram that illustrates the proposed sensitivity-based calculation model

The impact coefficients defined in the above manner can be calculated by means of numerical methods. They are highly suitable to establish such a value of excitation frequency for eddy currents that is the most appropriate for the specific application.

4. Optimum conditions for conductance measurements

Attention should be paid to the fact that pulsation (angular frequency) ω of the field that excites eddy currents occurs in the foregoing formulas solely in the expression (2) that defines the parameter of β. Therefore it seems reasonable to determine such value of the generalized parameter β that enable the expressions (15) - (20) to reach their maxima. Hence, for every specific application, sensitivity of the measuring instrument shall be the most advantageous if the frequency of eddy currents is calculated in the above manner.

Figs. 7 and 8 below exhibit results of numerical calculations in the form of graphs for functions (15) and (16). These functions represent impact coefficients that link variations of conductivity σ_p of the deeper (underneath) layer within the examined structure and variations of impedance components for the measuring coil. Fig. 7 refers to impact coefficients as a function of the β parameter and constant value of the *a* parameter, i.e. $\alpha=0.2$. Upper curves are plotted for the case when $s=0.5$, which means that the surface film conducts the electric current twice better than the layer underneath. On the contrary, the curves in the lower graphs correspond to the value of $s=2$, which equivalents to the relative conductivity of the two media when $\sigma_p=2\sigma_i$. Vertical lines on the graphs connect maximum values of the functions for impact coefficients with the X-axis thus indicate the optimum values of the β parameter that correspond to the determined frequencies of eddy currents. The graphs in Fig.7 are plotted for various thickness values of the outer film, i.e. $\rho=0.01, 0.05, 0.1$ and 0.2.

Fig. 8 exhibits graphs for identical sensitivity coefficients, where the graphs are plotted for the constant thickness of the outer film $\rho=0.2$ but various values of the parameters $s=0, 0.01, 0.05, 0.1, 0.5$ *and* 1. For $s=0$ it was merely possible to calculate the limit value as screening properties of the outer film effectively prevent from measurements of the underneath layer. The higher conductivity of the outer film is exhibited the less sensitivity of conductivity measurements for the underneath layer can be achieved. In such a case it becomes important to be able to assess how trustworthy the measurement results can be. The assessment can be provided by comparison of calculated values for the expressions (15) and (17) as well as (16) and (18). Increase in conductivity for the outer film is associated with application of lower frequency with the aim to achieve optimum sensitivity for measurements of the layers beneath. Similarly, thicker outer films impose application of lower frequencies during measurements. Each time it is necessary to determine the optimum frequency by seeking for maximum values of functions (15) and (16). It should be noted that impact of the conductivity σ_p onto alterations of the coil impedance is the least when the frequency is quite low as for such frequencies variations of the resistance are insignificant or even approach zero. It is the phenomenon that can be used for implementation of the compensation method to eliminate effect of the surface unevenness, deviations in the thickness of the outer film, etc.

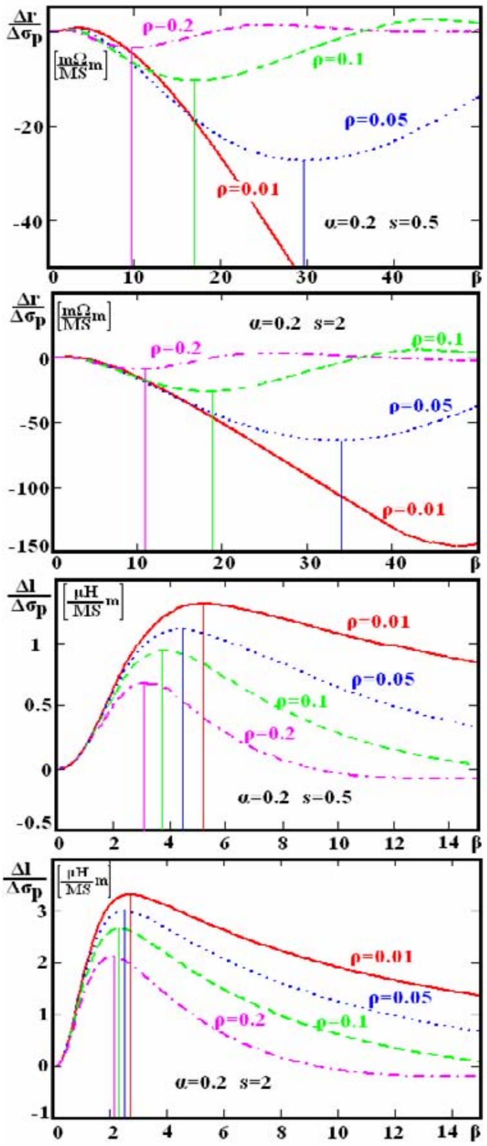

Fig. 7. The impact coefficients that collate conductivity values of the underneath layer within the examined structure and variations of impedance components for the measuring coil as the function of β for some selected values of the ρ parameter

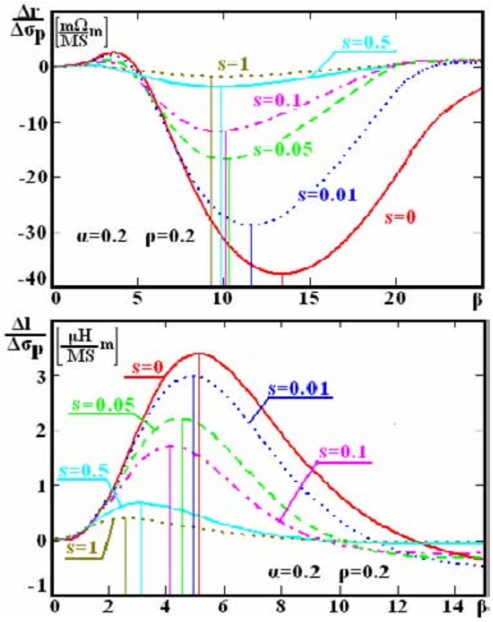

Fig. 8. The impact coefficients that collate conductivity values of the underneath layer within the examined structure and variations of impedance components for the measuring coil as the function of β for some selected values of the s parameter

Figs. 9 and 10 exhibit graphs for the functions (17) and (18). These functions represent impact coefficients and link up alterations in the conductivity of the outer film covering the examined structure and changes in impedance components of the measuring coil. The graph in Fig. 9 discloses impact coefficients as a function of the β parameter when the a and s parameters are constant and equal to $\alpha=0.2$ and $s=0.5$. These graphs are plotted for several thickness values of the outer film, i.e. $\rho=0.01$, 0.05, 0.1 *and* 0.2. In turn, Fig. 10 is developed for the constant values of $\alpha=0.2$ and $\rho=0.5$ and for a set of values $s=0$, 0.01, 0.1, 0.5 and 1.

5. Errors in conductance measurements of two-layer structures

In practice the problem how to asses quality of the coating film is a frequent question. It can be done if the thickness and conductivity of that outer film are measured.

The measuring instrument is used for simultaneous measurements of the coil resistance and inductance. After every single measurement, the equation system (8) and (9) makes it possible to calculate any two geometric or electric parameters of the system that comprises the coil and the measured structure, where measured alterations of the both components of the coil inductance serve as the basis for calculations. In case of a multi-layered structure it is pretty difficult to calculate parameter of a single layer due to shielding effect of the second one. Therefore, the method of total differential enables calculation of the maximum error for simultaneous determination of the thickness *d* of the outer film and conductivity σ_i of the material the film is made of. Let us assume that the errors for resistance measurement Δr and coil inductance Δl are known and, for simplification, these errors are independent on the frequency of the electromagnetic field that is used to induce the eddy currents.

The error for thickness measurements *d* of the outer film is:

$$\Delta d = \frac{r_0\sigma_i}{2n^2\pi\mu_0\beta^2 M}\left(\left|\left(\frac{\mu_0 r_0\beta}{2}\frac{\partial\chi}{\partial\beta}-\frac{\sigma_p\mu_0 r_0}{\sigma_i}\frac{\partial\chi}{\partial s}\right)\Delta r\right|+\left|\left(\frac{\beta^3}{2r_0\sigma_i}\frac{\partial\phi}{\partial\beta}-\frac{\beta^2\sigma_p}{r_0\sigma_i^2}\frac{\partial\phi}{\partial s}\right)\Delta l\right|\right) \quad (21)$$

where:

$$M = \frac{\partial\phi}{\partial\rho}\left(\frac{\beta}{2}\frac{\partial\chi}{\beta}-\frac{\sigma_p}{\sigma_i}\frac{\partial\chi}{\partial s}\right)-\frac{\partial\chi}{\partial\rho}\left(\frac{\beta}{2}\frac{\partial\phi}{\partial\beta}-\frac{\sigma_p}{\sigma_i}\frac{\partial\phi}{\partial s}\right) \quad (22)$$

The error for simultaneous determination of the conductance σ_i equals to:

$$\Delta\sigma_i = \frac{r_0\sigma_i^{\,2}}{n^2\pi\mu_0\beta^2 M}\left(\left|\frac{\beta^2}{r_0^2\sigma_i}\frac{\partial\phi}{\partial\rho}\Delta l\right|+\left|\mu_0\frac{\partial\chi}{\partial\rho}\Delta l\right|\right) \quad (23)$$

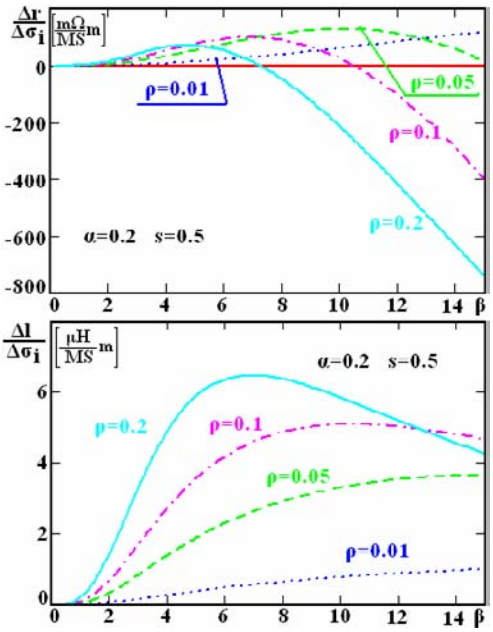

Fig. 9. The impact coefficients that collate conductivity values of the external film on the examined structure and variations of impedance components for the measuring coil as the function of β for selected values of the ρ parameter

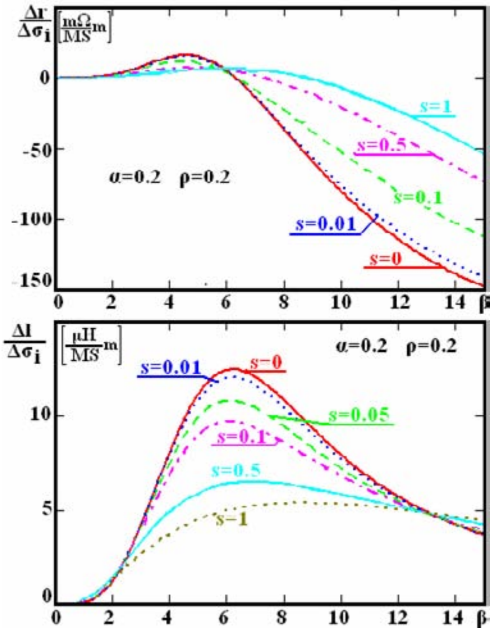

Fig. 10. The impact coefficients that collate conductivity values of the deep layer within the examined structure and variations of impedance components for the measuring coil as the function of β for selected values of the *s* parameter

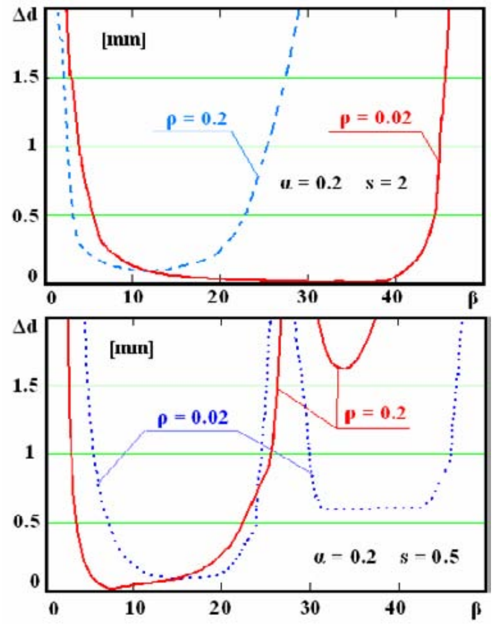

Fig. 11. Graphs for maximum values of measurement errors for the outer film *d* as a function of the generalized parameter β for two different values of the ρ parameter

Values defined by the formulas (21) and (23) can be calculated by means of numerical methods. Figs. 11 - 14 present graphs for maximum errors (deviations) for measurements of the outermost film thickness d and its conductivity σ_i. Graphs in Fig. 11 have been plotted with regard to the generalized parameter β and variable thickness value of d that correspond to the parameter $\rho = 0.02$ and $\rho = 0.2$. The diagrams on the top of the figure refer to the structure where conductivity of the outermost film is worse that the reciprocal parameter of the underneath substrate, i.e. $s = 2$. On the upper drawing $s = 0.5$, which means that the outermost film conducts the electric current twice better than the underneath layer. Fig. 12 discloses graphs for the same measurement error as a function of the β parameter for the selected values of the parameter $s = 2, 0.5, 0.1$ and 0 (the function limit is calculated for s approaching zero) whereas the thickness of the outermost film remains unaltered. Calculations are made for the coil with equivalent radius $r_0 = 1\ cm$ and equivalent distance to the examined surface [1] $h = 1\ mm$. It should be noted here that frequency of eddy currents is reflected in the foregoing equations solely as a generalized parameter β. Therefore the formulas (21) and (23) along with the presented graphs are well suited to select the most appropriate frequency of eddy currents in order to achieve minimum measurement errors.

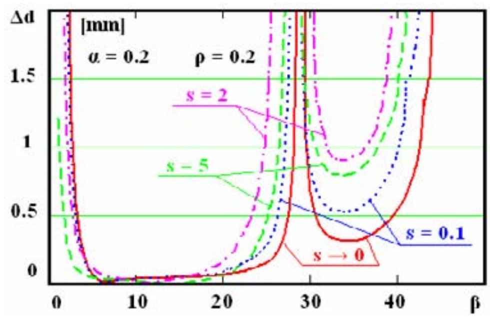

Fig. 12. Graphs for maximum values of measurement errors for the film thickness d as a function of the β parameter and for two different values of the s parameter

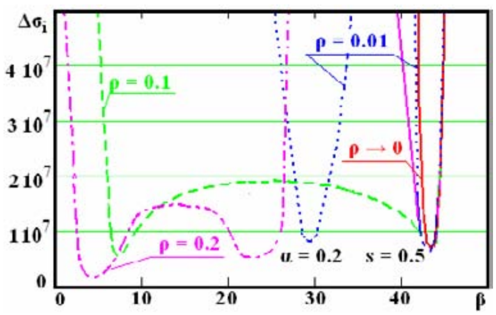

Fig. 13. Graphs for maximum values of measurement errors for the conductivity σ_i as a function the β parameter and for four different values of the ρ parameter

Fig. 13 presents the graph of the error associated with determination of the outer film conductivity as a function of the β parameter and for constant value of the s parameter. Respectively, Fig. 14 exhibits also errors associated with determination of the outer film conductivity, but for different values of the s parameter and constant values of conductivity σ_p and σ_i.

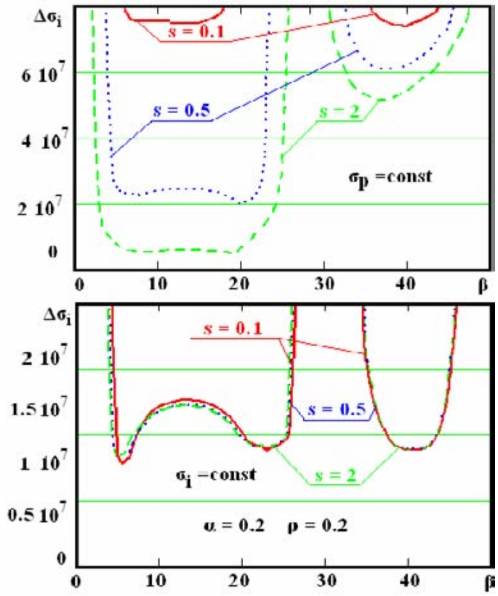

Fig. 14. Graphs for maximum values of measurement errors for the conductivity σ_i as a function of the β parameter and for two different values of the s parameter

6. Conclusions

Sensitivity is defined as the impact of the surface film conductivity onto variations of the coil inductance and its reaches its maximum for a certain frequency that depends on the thickness of that film. Location of that maximum to no extent depends on interrelationships between conductivity values of the two layers within the examined structure. However, thicker values of the outer film are associated with optimum measurement frequencies. For such an optimum frequency the sensitivity, defined as the impact of the measured conductivity σ_i onto variations of the coil resistance, equals to zero. It is the fact that can be applied to compensate the effect of undesired parameters onto measurement results. The impact coefficient of the conductivity σ_i onto resistance variations reaches its maximum for very low frequency values. It is then positive but assumes pretty low value. Frequencies for optimum measurements are lower when thickness values for the outer film are higher. The second maximum (not shown on the drawings) occurs for high frequencies. In such a case the sensitivity is high and adopts negative values. It is the range of frequencies that makes it possible to carry out very accurate measurements when surface of the examined structures are very smooth.

Errors associated with simultaneous determination of both the thickness and conductivity of the outer film strongly depend on the eddy current frequency, thus it is the reason, why the presented model is extremely suitable to determine the optimum value of that frequency.

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