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Selection of the frequency of eddy currents in non-destructive testing of non-ferromagnetic plates

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Properties

ABSTRACT

Purpose: To determine the optimal frequency of the electromagnetic field exciting eddy currents during the search for surface defects in non-ferromagnetic materials or at the time of conductivity measurements by means of eddy currents methods.
Design/methodology/approach: On the grounds of a mathematical model of a contact coil located above a conductive non-ferromagnetic plate, the sensitivities to the measured parameters were designated. Furthermore, a new definition of eddy currents penetration depth was proposed.
Findings: Recommendations facilitating proper selection of the electromagnetic field frequency were formulated, depending on specific applications.
Practical implications: The discussed phenomena and calculations are useful not only to constructors of the devices utilising the phenomenon of eddy currents, but also to users of flaw detectors and conductometers.
Originality/value: A modified definition of the actual penetration depth of eddy currents is proposed in the paper, which differs from the classical approach based on the 1/e level. The new definition may be very convenient and useful for operators utilising eddy current devices. The described sensitivity model facilitates setting up the devices for a specific task involved in a given process technology.
Keywords: Non-destructive testing; Eddy currents; Flaw detection; Conductometry

1. Introduction

The contact coil, fed with alternating current, is put against the surface of a conductive plate. Eddy currents are induced in the tested material. The magnetic field associated with eddy currents acts on the exciting field and evokes changes in the impedance components of the coil. The measurements of the changed components provide information on the plate conductivity and thickness, as well as on the distance from the tested surface. This phenomenon is used in conductometers, thickness gauges and flaw detectors operating on the grounds of the eddy currents phenomenon [1-3]. Any defect in the tested material evokes disturbances in the flow induced by eddy currents. The measuring device will detect such a condition as an apparent decrease in the tested material conductivity and as an apparent increase in the distance between the coil and the material surface. Such a flaw detector may be scaled in the range of the assumed artificial defects.

2. Mathematical model

The problem of determining the changes in the impedance of the contact coil evoked by a conductive element, the thickness of which d is smaller than the penetration depth of eddy currents shall be solved by assuming that the dimensions of the measured element are clearly bigger than the dimensions of the contact coil. The coil has n turns concentrated in a circle with the radius r_o, placed at the distance h from the tested element surface. The coil is fed with sinusoidal alternating current. The position of the coil in relation to the measured element is shown in Fig.1. [4-6]. Let us calculate the change in the coil impedance evoked by the presence of the conductive material [4]. For this purpose, the following generalized parameters are useful:

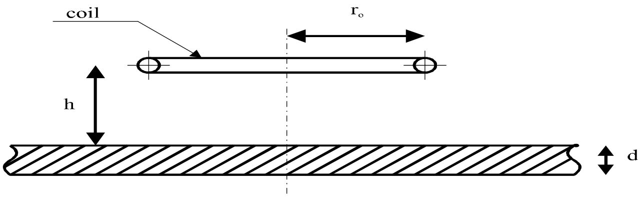

Fig. 1. The contact coil above the tested element

$$\alpha = \frac{2h}{r_0} \quad (1) \qquad \beta = r_0\sqrt{\omega\mu_0\sigma} \quad (2) \qquad \rho = \frac{2d}{r_0} \quad (3)$$

where: σ - conductivity of the material, h - distance between the coil and the tested surface, d- plate thickness, r_o -coil radius, ω- current angular frequency in the coil, n- number of turns.
ΔZ - denotes the impedance change of the coil.

$$\Delta Z = n^2\omega\pi\mu_0 r_0 Q(\alpha,\beta,\rho) \qquad (4)$$

where:

$$Q(\alpha,\beta,\rho) = \int_0^\infty J_1^2\ (y)e^{-\alpha y}\frac{\beta^2\left(1-e^{-\rho\sqrt{y^2+j\beta^2}}\right)}{\left(\sqrt{y^2+j\beta^2}-y\right)^2 e^{-\rho\sqrt{y^2+j\beta^2}}-\left(\sqrt{y^2+j\beta^2}+y\right)^2}dy$$

By separating the real part of the equation from the imaginary one, it is possible to derive a dependence that describes the change in the coil impedance components evoked by the presence of the conductive material:

$$r = R - R_0 = n^2\omega\pi\mu_0 r_0\varphi(\alpha,\beta,\rho) \qquad (5)$$

$$\omega l = \omega(L - L_0) = -n^2\omega\pi\mu_0 r_0\chi(\alpha,\beta,\rho) \qquad (6)$$

where:

$$\varphi(\alpha,\beta,\rho) = \mathrm{Re}Q(\alpha,\beta,\rho) \quad (7) \qquad \chi(\alpha,\beta,\rho) = \mathrm{Im}Q(\alpha,\beta,\rho) \quad (8)$$

where: R_o and L_o are the parameters of the distance between the coil and the tested element.

Using the described model [5] it is possible to calculate the sensitivities defined as the coefficients of the impact of conductivity σ , distance between the coil and the plate h on the coil impedance components: r and l.

$$\Delta rh = \frac{\Delta r}{\Delta h} = \frac{n^2\beta^2\pi}{\sigma r_0^2}\frac{\partial\varphi}{\partial\alpha} \quad (9) \qquad \Delta r\sigma = \frac{\Delta r}{\Delta\sigma} = \frac{n^2\beta^3\pi}{4\sigma^2 r_0}\frac{\partial\varphi}{\partial\beta} \quad (10)$$

$$\Delta lh = \frac{\Delta l}{\Delta h} = -n^2\mu_0\pi\frac{\partial\chi}{\partial\alpha} \quad (11) \qquad \Delta l\sigma = \frac{\Delta l}{\Delta\sigma} = -n^2\mu_0\pi r_0\frac{\beta}{4\sigma}\frac{\partial\chi}{\partial\beta} \quad (12)$$

In the next step, numerical calculations were made on the grounds of equations (9), (10), (11) and (12). To facilitate the comparison between the calculations results, it is convenient to express them in the form of relative sensitivity values:

$$\partial Rh = \frac{\Delta R}{R}:\frac{\Delta h}{h}, \qquad \partial R\sigma = \frac{\Delta R}{R}:\frac{\Delta\sigma}{\sigma}, \qquad \partial Lh = \frac{\Delta L}{L}:\frac{\Delta h}{h}, \qquad \partial L\sigma = \frac{\Delta L}{L}:\frac{\Delta\sigma}{\sigma}.$$

In Fig.2 the results of the numerical calculations are shown in the form of graphs. The assumed coil diameter is 2 cm, n=300 turns, ρ= 0.2 and α = 0.4. Some characteristic values of the generalized parameter β are compiled in Fig.2. For $\beta = \beta_m$ the function φ described by equation (7) has its maximum due to an independent variable β.

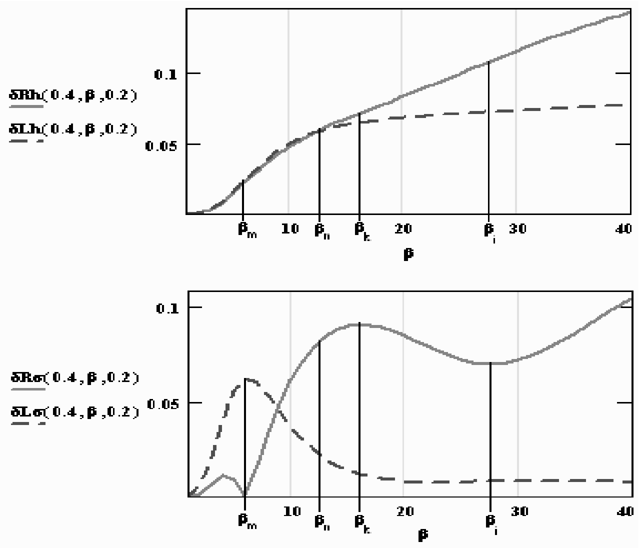

Fig. 2. The coefficient of the impact of coil conductivity and distance from the tested surface on the coil impedance components as a function of the generalized parameter β

For the frequency corresponding to β_m the impact of conductivity on the changes in the coil inductance is the biggest, whereas conductivity exerts no impact on resistance. Changes in distance h affect both impedance components. An increase in frequency up to the value corresponding to β_m leads to an increase in the sensitivity of the two measured parameters to the coil resistance; at the same time, the impact of conductivity on the inductance decreases. The range from β_m to β_k is very interesting in view of the majority of applications. A more detailed designation of the optimal frequency of the exciting field should be carried out in consideration of the problem of compensating the discontinuity of the tested structure.

3. Conductometer and flaw detector

One of the most important problems that should be solved in the design and construction of the devices utilising the eddy currents principle is the decision concerning the method of compensating the influence of the unevenness of the tested structure and material defects on the measurements results. Such a surface emerges, for example, after the treatment described in [7]. Depending on the chosen compensation mechanism, a given device may be a conductometer or a flaw detector. The compensation in a conductometer enables the measurement of the conductivity of coarse or cracked materials, even though the said devices were scaled by means of polished standard samples. On the other hand, as far as eddy currents flaw detectors are concerned, this mechanism should be inversed and should amplify the impact of small cracks on the readings. The oldest compensation method was discussed in [8]. Nowadays, in view of considerable computational power (DSP), more sophisticated methods may be employed. However, in each case, the method must be adjusted to the frequency of the exciting field and to the coil impedance components. In some solutions, the effectiveness of the compensation is so important that it compels the use of a specific frequency of the exiting field. In Fig.3 functions φ and χ described by equations (7) and (8) were plotted in view of the dependence on parameter β . If the measuring device is set up for direct measurements of the coil resistance and inductance, for example, in the case of the equivalence bridge, it is convenient to select the frequency corresponding to $\beta = \beta_m$. The measurements of the changes in resistance lead to the designation of apparent increase in distance *h*, and, subsequently, to the calculation of the correction, which is considered in the designation of conductivity on the grounds of the measurements of inductance. Modern devices measure the impedance components by the technical method with a sufficiently small error; thus, two parameters that are functions of resistance and inductance are measured directly.

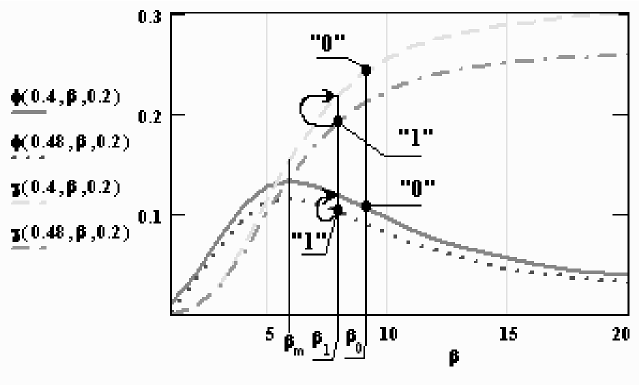

Fig. 3. Graphic interpretation of the compensation process for surface defects in the course of conductivity measurements

In such a case it is recommended to select the frequency corresponding to the range of the generalized parameters from β_m to β_i. The compensation process is presented in a graphic way in Fig.3. If there were no defects in the material, and its surface was smooth, the observed changes in the impedance components would correspond to the values of functions φ and χ (for α=0.4) designated as "0". In such a case, the measured conductivity could be derived from equation (2) on the grounds of $\beta = \beta_o$. In reality, in view of the non-ideal nature of the tested material, the measured impedance components correspond to the values of functions φ and χ designated as "1". It should be noted that the curves relate to φ and χ (for α=0.48), so the parameter $\beta = \beta_1$ decreases. The compensation process assumes that the distance between the coil and the tested surface does not change; hence, the parameter α does not change either. Accordingly, the calculations should be continued with the applicable curves, designated as arrows in Fig.3. Finally, following certain assumptions, it is possible to achieve effective elimination of the impact of surface defects.

4. Impact of the frequency of eddy currents on the penetration depth

In the course of selecting the frequency of eddy currents, limited penetration depth of the tested element should be taken into account. The classic concept of eddy currents penetration depth, e.g. as discussed in [9-11], may be calculated by the methods proposed in [12-15]. The penetration depth of eddy currents may also be determined as a minimal conductive plate thickness *d* influencing, in consideration of the accuracy of measurements, the change in the impedance components to the same degree as any semi-space with identical conductivity. Due to placing the coil onto the conductive semi-space, its impedence components are changed by values: *r* and *l*. The penetration depth of eddy currents is regarded as equal to *d* designated in the following way: after placing an identical coil at the identical distance, not onto the semi-space, but, this time, onto the plate with thickness *d*, the coil impedance components changed by values *r* and *l* designated with the accuracy of the error in the measurement of the impedance components of a given measuring device. Let us denote the error in designating the resistance change as δr, and the coil inductance as δl. The changes in the coil impedance components are caused by the proximity of the conductive material. In such a case, for each pair of parameters α and β, each of the equations expressed below may be solved in view of the unknown ρ.

$$\frac{2 \cdot \delta r}{n^2 \omega \pi \mu_0 r_0} = \left| \varphi(\alpha,\beta,\rho) - \lim_{\rho \to \infty} \varphi(\alpha,\beta,\rho) \right| \qquad \Rightarrow \rho_r \tag{13}$$

$$\frac{2 \cdot \delta l}{n^2 \pi \mu_0 r_0} = \left| \chi(\alpha,\beta,\rho) - \lim_{\rho \to \infty} \chi(\alpha,\beta,\rho) \right| \qquad \Rightarrow \rho_l \tag{14}$$

Let us assume that the maximal value from all the calculated values of ρ_r and ρ_l shall be the generalized penetration depth of eddy currents: $\rho_p = MAX(\rho_r, \rho_l)$ (15)

The real infiltration depth of eddy currents may be derived if the dimensions of the contact coil are known $d_p = (\rho_p\, r_0):2$. (16)

The knowledge of the real penetration depth of eddy currents, dependent on frequency, is very useful during the tests. It may also be calculated by means of a digital device in the course of measurements. To explicate the observed nature of penetration depth, equation (13) is transformed to the following form:

$$\delta r = a(\alpha,\beta,\rho) = \frac{n^2 \omega \pi \mu_0 r_0}{2} \cdot \left[\varphi(\alpha,\beta,\rho) - \lim_{\rho \to \infty} \varphi(\alpha,\beta,\rho) \right] \tag{17}$$

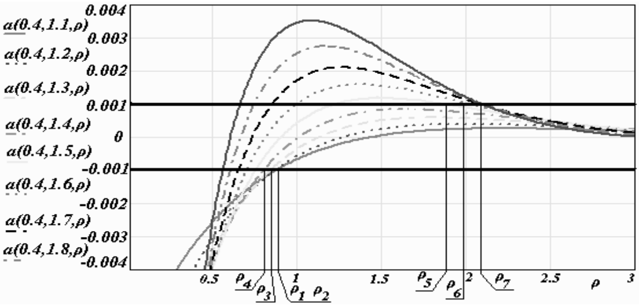

Fig. 4. Explication of the phenomenon of the abrupt change in the penetration depth of eddy currents

In Fig.4 the plotted values $a(\alpha,\beta,\rho)$ were calculated for the generalized parameter $\beta = 1.1 - 1.8$. As far as the tests on copper are concerned, for the coil with replacement radius equal to 1 cm, the corresponding frequencies are on the level of dozens of Hz. However, a similar example may also be found for higher frequencies. Analysing Fig.4, with the indicated dead zone of the measuring device, it may be stated that for the generalized parameter $\beta = 1.1$ and $\beta = 1.2$ the values of the generalized penetration depth are close and equal to ρ_1 and ρ_2. If the frequency of the exciting field is increased to the value of the generalized parameter $\beta = 1.3$, the penetration depth of eddy currents shall decrease to the value corresponding to ρ_3. Likewise, if the frequency of the exciting field is increased to the value of the generalized parameter $\beta = 1.4$, the penetration depth of eddy currents shall decrease to the value corresponding to ρ_4. Another increase in frequency corresponding to the value of the generalized parameter $\beta = 1.5$ leads to improved sensitivity of the measuring method at higher depths and, accordingly, the penetration depth of eddy currents is ρ_5 and this value is bigger than ρ_4. Every successive insignificant increase of frequency evokes a significant increase in the penetration depth of eddy currents to the values of the generalized parameter ρ_6 and ρ_7, successively.

5. Conclusions

The proposed mathematical model of the phenomenon of the impact of eddy currents on the contact coil impedance facilitates the designation of the optimal frequency of the changes in the field exciting the eddy currents. The observations concerning the penetration depth of eddy currents are of particular importance, as this parameter may be calculated by means of numerical methods on the grounds of the model: contact coil placed above semi-space. It turns out that the presence of a defect in the tested material, even if located below the designated boundary, is detected by the measuring device. Such a defect apparently increases the infiltration depth of eddy currents. Thus, the measuring device has a penetration zone bigger than the calculated infiltration depth. The proposed definition of the infiltration depth of eddy currents put forward in the paper is more convenient for flaw detectors: contact coil placed above a conductive non-magnetic plate.

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