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THE PHASE METHOD FOR MEASUREMENT OF COMPONENTS OF IMPEDANCE EDDY-CURRENT SENSORS IN DEVICES FOR NON-DESTRUCTIVE TESTING

Annotation. Offered and discussed a method of obtaining information regarding the tested value in devices for non-destructive testing which use the eddy-current sensors. The method is based on the definition of the components of impedance of such sensor using the phase response of the measuring circuit containing the sensor.

Introduction. A number of non-destructive testing methods (NDT) of substances, materials and products are based on the use of non-contact eddy-current sensors of parametric type [1, 2].

The impedances Z of such sensors depends on the controlled magnitude $\boldsymbol{x}$ and frequency f of the current flowing through the sensor:

$$Z(x,f) = Re[Z(x,f)] + j\cdot Im[Z(x,f)] \equiv Z_{Re} + j\cdot Z_{Im}, \quad j^2 = -1$$

The information regarding $\boldsymbol{x}$ may be obtained indirectly through Z_{Re}, Z_{Im}, by converting values Z_{Re}, Z_{Im} into the value of voltage, current or frequency. This information may be also obtained from derivative values of Z_{Re} and Z_{Im} such as module $M(Z) = [Z_{Re}^2 + Z_{Im}^2)]^{1/2}$, arctg $[Z_{Im}/Z_{Re}]$, as well as from schematic functions of measuring circuit, which includes the sensor.

Background and statement of the problem. Overview of the hardware implementations of these methods has shown that under certain technical conditions of NDT is preferable to the use of schematic functions.

Selection the type of schematic function is based on the structure of the measuring circuit, which include the sensor as component. If circuit is the four-pole, then as schematic function is advantageous to select the function of the transfer on voltage

$$K(s) = U_2(s)/U_1(s),$$

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where: $s = \sigma + j\omega$ – Laplace transformation parameter, U_1, U_2 – voltage at the input and output pair of poles of the measuring circuit, respectively.

The projection of the transfer function $K(s)$ on the frequency axis corresponds the complex coefficient of voltage transmission

$$K(j\omega) = K(s)\big|_{s=j\omega} = K(\omega)\ \exp\ [\ j\Phi(\omega)\ ],$$

where: $K(\omega)$ - amplitude-frequency characteristic (AFC) measuring circuit, and $\Phi(\omega)$ - its phase-frequency characteristic (PFC).

Data about the components of impedance Z_{Re}, Z_{Im}, and then – about controlled value $\boldsymbol{x}$ can be obtained based on some parameters of AFC and PFC. Thus, for the measuring circuits of the second order, its FRF has an extremum and its PRF – a corresponding point of an inflection. For example, if the FRF have a maximum, that ordinarily use such parameters:

– frequency ω_M, at which the FRF has been achived the peak K_M;

– frequency ω_A and ω_B, at which the FRF intersects the level $\sqrt{2} \cdot K_M$ "at left" and "at right" on frequency axis ($\omega_A < \omega_M < \omega_B$);

– value $\boldsymbol{Q}$ which defined from this frequencies: $Q = \omega_M / (\omega_B - \omega_A) \equiv \omega_M / \Delta\omega$.

All these parameters can be determined from the corresponding PFC. This is provides a number of significant advantages in comparison with the determination ω_M and $\boldsymbol{Q}$ from AFC [3]. Based on this in [3], it was proposed to use the PFC to determine all three frequencies ω_A, ω_M, ω_B, associated with the values of K_M and $\sqrt{2} \cdot K_M$ AFC. Herewith to obtain information of the controlled value $\boldsymbol{x}$ it was proposed to use such parameters as ω_M and $\boldsymbol{Q}$.

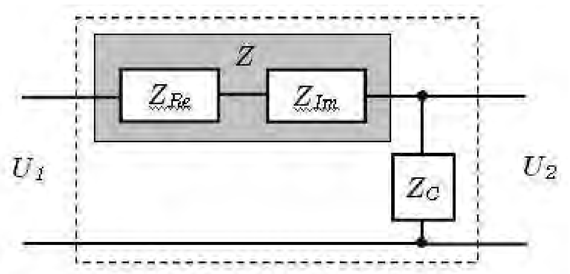
Naturally has emerge a question about the possibility of develope such method of obtaining information about x which will be able to use only PFC of measuring circuit. This would enable to implement intermediate conversions of information signals in the time domain. In practice this means that such signals can be presented in the form of time interval, frequency and duty factor.

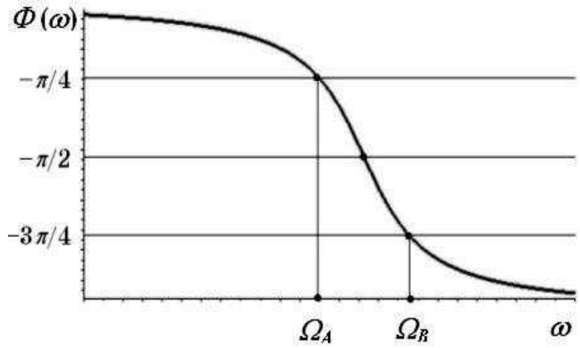
In the context of this question it was set the goal to develop a method for getting information about controlled value $\boldsymbol{x}$ with using only PFC of the measuring circuit. For this the method should provide the measurement of magnitudes components of impedance of the sensor Z_{Re}, Z_{Im}.

Main section. Consider the measuring circuit of 2nd order implemented as Г-like four-pole, which includes the eddy-current sensor which has impedance

$$Z = Z_{Re} + jZ_{Im} = R + j\omega L \qquad (1)$$

and an auxiliary capacitor whith impedance $Z_C = -j/(\omega C)$, где $\omega = 2\pi f$ (Fig.1a).





а) б)

Figure 1 – The measuring circuit: a) chain structure;
b) PFC fragment in the vicinity of the inflection point

The transfer function on voltage for this circuit $K(s) = U_2(s)/U_1(s) = Z_C(s)/(Z_R(s) + Z_I(s))$. It has two complex conjugate poles in the left half surface $(\sigma, j\omega)$ of the complex variable s, so that AFC $K(\omega)$ has a maximum in the frequency domain, and PFC $\Phi(\omega)$ - the corresponding point of inflection at the level $-\pi/2$ (Fig. 2b).

PFC $\Phi(\omega)$ of the measuring circuit represented as:

$$\Phi(\omega) = arctg \frac{\mathrm{R}}{\left(\omega L - \dfrac{1}{\omega C}\right)}, \quad 0 < \Phi(\omega) < -2\pi \qquad (2)$$

Rewrite (1) otherwise:

$$tg\Phi(\omega) = \frac{R}{\left(\omega L - \dfrac{1}{\omega C}\right)} \qquad (3)$$

Substituting in (3) $\omega = \Omega_A$ and $\omega = \Omega_B$, we obtain a system of 2 equations:

$$tg\Phi(\Omega_A) = \frac{\mathrm{R}}{\left(\Omega_A\ L - \dfrac{1}{\Omega_A\ C}\right)}, \quad tg\Phi(\Omega_B) = \frac{\mathrm{R}}{\left(\Omega_B\ L - \dfrac{1}{\Omega_B\ C}\right)} \qquad (4)$$

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If at frequencies Ω_A и Ω_B magnitude of PFC $\Phi(\Omega_A) = -\pi/4$ and $\Phi(\Omega_B) = -3\pi/4$, as its shown in Fig. 2, that

$$tg\Phi(\Omega_A) = -1, \quad tg\Phi(\Omega_B) = 1$$

and solution of system (4) concerning R and L elementary simple:

$$L=\frac{1}{\Omega_A\Omega_B C} = \frac{1}{(2\pi f)^2 F_A F_B C}\ ;\ R = \frac{\Omega_B - \Omega_A}{\Omega_A\Omega_B C} = \frac{F_B - F_A}{(2\pi f)^2 F_A F_B C}), \quad (5)$$

where $F_A=1/2\pi\Omega_A$ and $F_B=1/2\pi\Omega_B$.

If Ω_A and Ω_B chosen so that the angle $\Phi(\Omega_A) \neq -\pi/4$ и $\Phi(\Omega_B) \neq -3\pi/4$, the formula (6) become only more complicated computationally. Let's show it.

Assume Ω_A and Ω_B is such that $\Phi(\Omega_A) = -\pi/2+\varphi$, $\Phi(\Omega_B) = -\pi/2-\varphi$, where $0 \le \varphi \le \pi/2$. In this case $\Phi(\Omega_A)$ and $\Phi(\Omega_B)$ located "symmetrically" concerning level $-\pi/2$ and (6) takes the form:

$$L = \frac{1}{\Omega_A\Omega_B C}\ ,\ R = \frac{\Omega_B - \Omega_A}{\Omega_A\Omega_B C\cdot tg(\varphi)} \qquad (5')$$

And finally, assume that Ω_A and Ω_B such that $\Phi(\Omega_A) = -\pi/2+\varphi$, $\Phi(\Omega_B) = -\pi/2-\psi$, where $0 \le \varphi \le \pi/2$, $0 \le \psi \le \pi/2$. In this case $\Phi(\Omega_A)$ and $\Phi(\Omega_B)$ located "asymmetrically" concerning level $-\pi/2$ and (6) takes such form:

$$L = \frac{\Omega_A\, tg(\varphi) + \Omega_B\, tg(\psi)}{\Omega_A\Omega_B C\,[\Omega_B\, tg(\varphi) + \Omega_A\, tg(\psi)]}\ ,\ R = \frac{(\Omega_B)^2 - (\Omega_A)^2}{\Omega_A\Omega_B C\,[\Omega_B\, tg(\varphi) + \Omega_A\, tg(\psi)]} \qquad (5'')$$

From formulas (5) - (5″) follows that in order to obtain the numerical values of the parameters R and L of the sensor, sufficiently gauge only two frequencies: $F_A=1/2\pi\Omega_A$ and $F_B=1/2\pi\Omega_B$ using PFC of measuring circuit.

Then, if exist a certain continuous and mutually unambiguous dependence $R = R(\boldsymbol{x})$ and (or) $L=L(\boldsymbol{x})$, then the transformation functions required for the implementation of the NDT, may be represented in the form $\boldsymbol{x} = U_R(F_a, F_b)$ or $\boldsymbol{x} = U_L(F_a, F_b)$.

This will be true, since the auxiliary capacitor of measuring circuit (see component Z_C on fig.1a) does not interact with the testing object and respectively capacitance C is independent of $\boldsymbol{x}$. Lets consider two cases.

1. It is necessary to obtain information on *deviations* $\Delta \boldsymbol{x}$ from the specified standards $\boldsymbol{x}_0$. Because in formulas (5) - (5) - (5″) value of $1/C$ is a constant, we must only provide sufficient thermal stability of capacity C.

2. It is necessary to obtain information concerning the *absolute values* of $\boldsymbol{x}$. In this case the capacity C also must be independent on temperature but moreover, the numerical value of C must be measured in advance with the required accuracy.

Now consider the question of the uncertainty of the numerical value of the reactive component of the impedance $ZI_m=\omega L$, because the value of L is determined by two frequencies $\omega = \Omega_A$ and $\omega = \Omega_B$. This question is of fundamental importance if it comes to *measuring* the magnitude Z_{Im} at the some specified frequency. However, the proposed here Phase method is not intended to solve problems that relate to the field of impedance measurements as such.

Therefore, since the frequency ω is independent parameter, therefore for the tasks of NDT the value ωL carries no additional information of tested value $\boldsymbol{x}$ in comparison with value of L.

The formulas (5) - (5″) were obtained on the basis of the simplest model of an eddy-current sensor when its impedance may be presented as $Z = Z_{Re} + jZ_{Im} = R + j\omega L$. They are shown here only to explain the essence of the proposed method.

The model of real eddy-current sensor necessarily includes its own winding capacitance C_o. Its calculation which depends on form-factor of the winding and the dielectric constant of the body of winding, is a very difficult task, even if the winding implemented as solenoid [4]

Therefore we will simply use C_o in the next model of the sensor as is, without representation C_o in the form some formula. In this case, based on theoretical studies presented in [4], we assume that the value of C_o does not depend on the frequency.

Then calculation of the impedance gives:

$$Z = \frac{R}{1+ [(R^2+(\omega L)^2)-2(L/C_o)]\,(\omega C_o)^2} +$$

$$+ j\omega \frac{L- [(\omega L)^2+R^2]C_o}{1+ [(R^2+(\omega L)^2)-2(L/C_o)]\,(\omega C_o)^2},$$

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so that, if interpret this expression like (1), we can write $Z \to Z(\omega) = R(\omega) + j\omega L(\omega)$, namely:

$$R(\omega) = R+2R\omega^2 LC_o, \quad L(\omega) = L+[(\omega L)^2-R^2]\omega C_o.$$

To simplify subsequent formula of PFC $\Phi(\omega)$ we fulfill series expansion of Z in the neighborhood of $C_o = 0$. Without loss of generality, we can consider only the first two terms of the expansion. We have:

$$\Phi(\omega) = arctg\left(\frac{R(1+2\omega^2 LC_o)}{[(\omega L)^2-R^2]\omega C_o+(\omega L - \frac{1}{\omega C})}\right).$$

However, to obtain the solution of equations

$$tg\,[\Phi(\Omega_A,R,L)] = -1, \qquad (6)$$
$$tg\,[\Phi(\Omega_B,R,L)] = 1$$

in an analytical form as functions of R and L, just as was done for the formulas (5) - (5″), not possible as a matter of principle. Furthermore, at attempting of numerical solution of this system is encountered problem associated with a discontinuity of function $tg\,[\Phi(\omega,R,L)]$ at $\Phi(\omega,R,L) = \pi/2$.

The latter problem can be solved as follows. Suppose that the frequency Ω_A determined experimentally at which $\Phi(\Omega_A) = -\pi/4$, and the frequency Ω_B at which $\Phi(\Omega_B) = -3\pi/4$. Then, instead of (6), we get the set of equations

$$\Phi(\Omega_A,R,L) = -\pi/4, \qquad (7)$$
$$\Phi(\Omega_B,R,L) = -3\pi/4.$$

Numerical solution of the set concerning R and L is free of the above problem, since the function $\Phi(\omega,R,L)$ in the neighborhood of the interval $(-\pi/4, -3\pi/4)$ is smooth and have not point of break fig. 2b).

Finally, lets consider the most common model of the eddy-current sensor. It may be represented as:

$$Z(\boldsymbol{x},\omega) = R(\boldsymbol{x},\omega) + j\omega L(\boldsymbol{x},\omega), \qquad (8)$$

where formulas for $R(\boldsymbol{x},\omega)$ and $L(\boldsymbol{x},\omega)$ can be obtained by using the results given in some studies [1,2 and other].

Conclusions. The solutions of the set of equations (7) for the components $R(\boldsymbol{x},\omega)$ and $L(\boldsymbol{x},\omega)$ is based on a generalized model of the eddy-current sensor (8) is basic method for obtaining information about the tested value $\boldsymbol{x}$. The formulas (5) - (5″) are also possible to use, if it is allowable by the technical conditions of the NRC. For the implementation of this method necessary that PFC $\Phi(\omega)$ can be described in analytical form (as formulas). $\Phi(\omega)$ may also be described as an approximation function obtained by semi-empirical way.

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