Research Interacted Eddy-Current Transformer Located on Ferromagnetic Material with “Crack Type” Defects

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Abstract. The work contains the results of theoretical and experimental research of interaction between a laying-in eddy-current transformer and tested ferromagnetic material with defects of through-the-thickness crack type at variation of the main disturbing factor – variable air-gap fluctuation between the sensor and tested surface. Developed a graphic-analytical simplified model and received equations for engineering calculation of introduced inductances of such eddy-current transformer depending on crack width and air-gap fluctuation size. Received equations for estimation sensitivities of eddy-current transformer to depends on crack width growth and to change of air-gap.

1. Eddy-current transformer over ferromagnetic material with crack

In modern defectoscopy of ferromagnetic parts and units when dealing the problems of technical diagnostics, there widely are used electromagnetic methods of non-destructive testing, in particular, the method of eddy currents. For solving the problems of eddy current diagnostics widely applied there are two the most acceptable types of eddy current transformers (ECT):

- a laying-in ECT with U-type core, traditionally used for testing anysotropy products;
- a laying-in ECT with rod-type core which is used for registration of local defects.

However, theoretical description of physical processes arising from control of multivendor environment by transformers with nonuniform field causes some difficulties. A classical approach to solve this problem is based on solution of Maxwell and Helmholtz equations in differential form and is complicated and rather onerous. Thus, for creation of engineering methods there can be used simplifications, assumptions, equivalent methods etc.

The objective of the research is creation of simplified mathematical model which is able to describe interaction between a laying-in eddy-current transformer (ECT) with U-type core and ferromagnetic material with a defect of through-the-thickness crack type with variation of the main disturbing factor – the gap δ between ECT poles and the tested surface.

A U-type core lying-in parametrical ECT consists of a coil with a ferrite U-type core on which coiled high-frequency winding with quantity of turns W [1, 2]. Fig.1 illustrates the principle of operation of U-type core ECT located over the tested ferromagnetic specimen with a crack width *T*. Magnetic flux *F* from ECT induces eddy-currents *i*, in the tested specimen, intensity of which is determined by electric conductivity of the specimen and by the parameters of the crack.

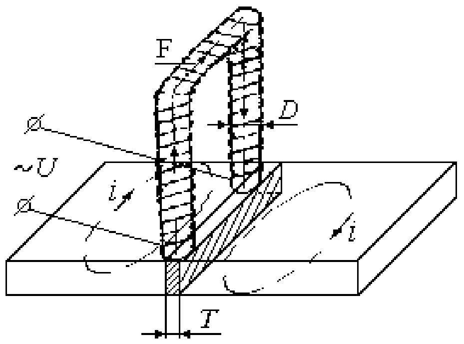

Fig.1. U-type core ECT located over a ferromagnetic specimen with a crack

2. Introduced ECT inductance from the air gap between transformer poles and the tested surface

When opening of the crack T or gap δ changes, interlinkage of magnetic field and magnetic resistance of circuit ECT-specimen change too. Let's determine dependence of current strength I in the winding on the gap δ and crack opening T.

$$I = \frac{U}{Z_0 + Z_{add}} = \frac{U}{Z}, \tag{1}$$

where U - is voltage of the current feeding ECT;

Z_0 - resistance of ECT winding in air;

Z_{add} - additional resistance, introduced to ECT by the specimen ($Z_{add}=f(T,\delta)$);

Z - full resistance of ECT winding.

Under harsh conditions of part production technological process dictated by present-day competitive surroundings, magnetic permeability μ and electric conductivity σ of the material remains practically the same for all specimens. Therefore, we ignore the influence of μ and σ on Z_{add} when solving the problem put by.

Impedance of ECT winding consists of active resistance R and inductive resistance X_L:

$$Z = \sqrt{R^2 + X_L^2} = \sqrt{R^2 + (2\pi f L)^2}, \tag{2}$$

where f - is current frequency;

L - inductance of ECT winding, which equaling:

$$L = L_0 + L_{add} = \frac{W \cdot F}{I}, \tag{3}$$

where L_0 - is inductance of ECT winding in air;

L_{add} – additional inductance introduced by ECT specimen ($L_{add}=f(T,\delta)$).

With small enough values T and δ and substantial values of magnetic permeability of ECT core and the tested specimen, we may ignore dispersion flux and assume that the entire magnetic flux is closed through the specimen:

$$F = \frac{I \cdot W}{R_m}, \tag{4}$$

where R_m – is magnetic resistance of the circuit ECT-specimen, $R_m=R_{st}+R_{air}$ (R_{st} - magnetic resistance of the core and ferromagnetic steel the part is made of; R_{air} - magnetic resistance of the air gap).

Magnetic resistance of the air gap:

$$R_{air} = \frac{2\delta}{\mu_0 S}, \tag{5}$$

where μ_0 - is magnetic constant (μ_0=4·π·10^{-7} H/m);

S – cross-section area of the core in the air gap zone.

All this considered , the magnetic current :

$$F = \frac{I \cdot W}{R_{st} + 2\delta/(\mu_0 S)}. \tag{6}$$

Then, according to equations (3) and (6) inductive impedance of ECT winding:

$$X_L = \omega L = \frac{\omega \cdot W^2}{R_{st} + 2\delta/(\mu_0 S)}. \tag{7}$$

Full impedance of ECT winding:

$$Z = \sqrt{R^2 + \omega^2 \cdot \left[\frac{W^2}{R_{st} + 2\delta/(\mu_0 S)}\right]^2}. \tag{8}$$

Analyzing equation (8), it can be concluded that with air gap increase impedance Z is reducing.

Ignoring the value R_{st} in (8) since magnetic resistance of the air gap by far exceeds magnetic resistance of the core we will receive simplified equations for determining inductive resistance and inductance:

$$X_L = \frac{\omega \cdot W^2}{2\delta/(4\pi \cdot 10^{-7} S)} = \frac{2\pi\omega W^2 S}{\delta} \cdot 10^{-7}; \tag{9}$$

$$L = f(\delta) = \frac{\frac{W^2 \mu_0 S}{2}}{\delta} = \frac{K}{\delta}, \tag{10}$$

where K – is a function of constructive parameters of ECT.

It should be noted that with substantial gaps the part of magnetic flux is closed not through the specimen but through air. This should be taken into account when developing eddy-current defectoscopes.

Let's determine sensitivity of ECT when connected to the arm of bridge circuit in the capacity of variable resistance. The bridge is supplied with variable current voltage of frequency f. By sensitivity of ECT to air gap change K_δ we will assume relative gap change. The gap change is normalized to air gap increase [3]:

$$K_\delta = \frac{\Delta Z / Z}{\Delta\delta}, \tag{11}$$

where $\Delta\delta$ - is air gap increase causing undesirable change of ECT winding full resistance Z by the value ΔZ.

With $R \ll X_L$, we will receive $Z = \omega L$. The change air gap derivative of full resistance with ω=const and taking into account equation (9):

$$\frac{dZ}{d\delta} = \frac{\omega \cdot dL}{d\delta} = -\frac{\omega W^2 \mu_0 S}{2\delta^2}, \tag{12}$$

or in finite increment:

$$\frac{\Delta Z}{\Delta\delta}=-\frac{\omega W^2\mu_0 S}{2\delta^2}. \tag{13}$$

Out of (10), (11) and (13) we will receive an equation for determining sensitivity of ECT to air gap change:

$$K_\delta=\frac{\Delta Z/\Delta\delta}{Z}=\frac{\omega W^2\mu_0 S}{2\delta^2\omega L}=\frac{W^2\mu_0 S2\delta}{2\delta^2 W^2\mu_0 S}=\frac{1}{\delta} \tag{14}$$

Thus, with air gap increase the sensitivity of ECT is decreasing hyperbolically. With small work air gaps sensitivity K_δ is very big. For example, with δ=0.1 mm and $\Delta\delta$=0.01 mm sensitivity $K_\delta=1/10^{-4}=10000$ 1/m and relative resistance change $\Delta Z/Z=K_\delta\Delta\delta=10000\cdot10^{-5}=0.1$; that is with gap change by 0.01 mm, ECT resistance is changing by 10% which is commensurable with useful signal from the crack.

3. Introduced ECT inductance from the opening of crack

For determine dependence of introduced inductance of ECT L_{intr} from the opening of crack, let's conceive a crack located under the poles of ECT core in the form of a rectangle and two segments adjacent to it (fig2.).

Let's designate the relation of crack opening width T to the diameter of core D through the value α: $T/D=\alpha$. As is shown on fig.2:

$$\sin\gamma=\frac{T/2}{D/2}=\frac{T}{D}.$$

For small values of angle γ $\sin\gamma\approx\gamma$, so $\gamma\approx\alpha$.

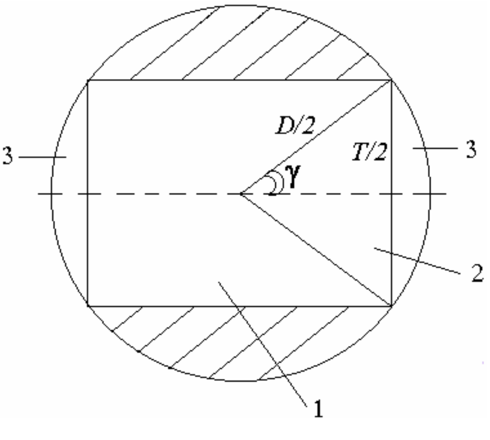

Fig.2. The crack located under the ECT core pole and divided into the following elements: 1- rectangle; 2-triangle; 3-segments

Crack area S_{cr} equals the sum of rectangle S_{rec} and two segments S_{seg} areas:

$$S_{cr}=S_{rec}+2S_{seg}.$$

With small $\alpha\,(\alpha\le 0{,}3)$ rectangle area:

$$S_{rec} = \frac{D}{2}\cos\gamma \cdot 2 \cdot T = D \cdot T \cdot \sqrt{1-\sin^2\gamma} \cong D \cdot T \cdot \sqrt{1-\gamma^2} =$$

$$= D \cdot T \cdot \sqrt{1-\alpha^2} \cong D \cdot T \cdot (1-\frac{1}{2}\alpha^2) = \mathrm{D}^2\alpha(1-\frac{1}{2}\alpha^2)$$

Segment area:

$$S_{seg} = \frac{\pi R^2}{360} \cdot 2\gamma - S_{tr},$$

where S_{tr} – is the area of triangle.

$$S_{seg} = \frac{\pi\left(\frac{D}{2}\right)^2}{360} \cdot 2 \cdot \frac{360}{2\pi} \cdot \alpha - S_{tr}.$$

Triangle area:

$$S_{tr} = \frac{1}{2} \cdot \frac{D}{2} \cdot \cos\gamma \cdot T = \frac{D^2}{4} \cdot \alpha \cdot \sqrt{1-\alpha^2} = \frac{D^2}{4} \cdot \alpha \cdot (1-\frac{1}{2}\alpha^2).$$

So, segment area equals:

$$S_{seg} = \frac{D^2}{4} \cdot \alpha - \frac{D^2}{4} \cdot \alpha \cdot (1-\frac{1}{2}\alpha^2) = \frac{D^2}{8} \cdot \alpha^3.$$

Total crack area under ECT pole equals:

$$S_{cr} = D^2\alpha + 2\frac{D^2}{8}\alpha^3 - \frac{1}{2}D^2\alpha^3 = D^2\left[\alpha - \frac{1}{4}\alpha^3\right] = D^2\left[\frac{T}{D} - \frac{1}{4}\left(\frac{T}{D}\right)^3\right] \quad (15)$$

Let's find angle γ for maximum crack opening $T/D=\alpha=0.3$, that is $\sin\gamma=0.3$; $\gamma=17°\approx0.3$ rad. Thus, total crack area with $\alpha=0.3$ equals:

$$S_{cr} = D^2(0.3 - \frac{1}{4} \cdot 0.027) = 0.293 \cdot D^2.$$

Analysis of this ratio shows that with 2% error we can presume that within the limits of $0 \le \alpha \le 0.3$ crack area S_{cr} changes linearly depending on the parameter α:

$$S_{cr} \cong \alpha D^2.$$

So, with $\alpha \le 0.3$ active area of pole cross-section over the crack S^a (not shaded on fig.2) will be connected with linearly with crack opening T:

$$S^a = S_0 - S_{cr} = \frac{\pi D^2}{4} - \alpha D^2 = \frac{\pi D^2}{4}\left[1 - \frac{4}{\pi}\alpha\right],$$

where S_0 – is a total area of ECT pole.

The size of dispersion flux is proportional to crack area $S_{cr} \approx \alpha D^2$, hence with increase of crack opening T it will increase linearly. ECT inductance

$$L = \frac{2\pi W^2 S}{\delta} \cdot 10^{-7} = K_1 \cdot S = K_1 \cdot S_0(1 - \frac{4}{\pi}\alpha) \quad (16)$$

will decrease linearly with increase of T (and α consequently). So, dependence of ECT introduced inductance value on crack opening T change is described with linear function under condition that $T/D \leq 0.3$:

$$L_{\mathrm{int}\,r} = f(T) \approx \left[1 - \frac{4}{\pi} \cdot \frac{T}{D}\right]. \tag{17}$$

Let's determine ECT sensitivity K_{cr} to crack opening. Sensitivity is a relative change of resistance divided by increment of crack opening area value:

$$K_{cr} = \frac{\Delta Z_{cr} / Z_{cr}}{\Delta T} = \frac{\Delta Z_{cr} / Z_{cr}}{D \cdot \Delta \alpha}. \tag{18}$$

Inductance L_{cr} of ECT winding, poles of which are located along the crack, can be found by simplified equation:

$$L_{cr} = \frac{W^2}{2\delta / (\mu_0 S)} = \frac{W^2 S \mu_0}{2\delta} = \frac{W^2 \mu_0}{2\delta} S_0 (1 - \frac{4}{\pi}\alpha). \tag{19}$$

Total resistance:

$$Z_{cr} = \sqrt{R^2 + \omega^2 \left[\frac{W^2}{2\delta / (\mu_0 S)}\right]^2}. \tag{20}$$

With $R << X_L$, we will receive $Z_{cr} = \omega L_{cr}$. Crack opening change derivative for total resistance:

$$\frac{dZ_{cr}}{d\alpha} = \omega \frac{dL_{cr}}{d\alpha}. \tag{21}$$

$$\frac{dZ_{cr}}{d\alpha} = \frac{2\pi\omega W^2}{\delta} S_0 \frac{d(1 - \frac{4}{\pi}\alpha)}{d\alpha} = -\frac{8\omega W^2 S_0}{\delta}. \tag{22}$$

Having divided equation (22) by

$$Z_{cr} = \omega L_{cr} = \frac{2\pi\omega W^2 S_0}{\delta},$$

we receive:

$$K_{cr} = \frac{\Delta Z}{Z D \Delta \alpha} = \left| - \frac{\frac{2\pi\omega W^2 S_0}{\delta}}{\frac{\omega W^2 \mu_0 S_0 (1 - \alpha)}{2\delta}} \right| = \frac{1}{D(1 - \alpha)} = D(1 - \alpha)^{-1} \approx D(1 + \alpha) \tag{23}$$

Thus, with crack openings α≤0.3 ECT sensitivity changes approximately linearly with increase α.

When comparing equation (14) for determining ECT sensitivity to gap variation δ (K_δ=1/δ) with equation (23) for determining ECT sensitivity to crack opening T changes, it is evident that gap variation between ECT and the tested surface is a grave hindrance factor. Therefore, to increase precision of eddy-current testing we developed a resonance method of suppression from gap interfering variation [4].

Experimental research conducted on frequencies 1 kHz та 10 kHz with the help of digital measuring immitance device E7-14, with 85% precision confirmed validity of equations (10), (17) [5].

The results of the research have been for developing a device for defectoscopy of high-loaded hydro-pump parts of fluid power drive ГСТ-90.

4. Experimental research of eddy-current transformer

The research technique included the following:
- manufacturing of lying-in ECT samples with rod-type core and U- type core;
- imitating extended cracks with the opening width T , standardized to D diameter of ECT core pole on the samples made of ferromagnetic steel;
- imitating the gap δ between laying-in ECT and the tested surface, standardized to diameter D of ECT core;
- determining dependencies of introduced inductances $L'_{вн}$ from correlation T/D and δ/D;
- substantiation of ECT design.

The choice in favour of ECT with U-type core against ECT with rod-type core for examining of “fusion” in plunger is substantiated by the comparative research results on digital gauge E7-8 (gauge L,C,R) when supplying ECT sinusoidal current with frequency f=1 kHz, as well as on a digital gauge E7-14 (imitance gauge) when supplying current f=1 kHz and f=10 kHz to ECT, averaged results of the research being presented according to 10 measurements.

ECT with U-type and rod-type cores were made in such a way so that they have same inductance beyond the tested surface (in the air) L_0=1.19 millihenry. The cracks had a rectangular shape with opening width T/D that could change within T/D=0.014÷0.3. Besides, the gap δ between laying-in ECT and the tested surface was also changed within δ/D=0.014÷0.3.

The mesurement results of standardized introduced inductances $L'_{\text{int}\,r}$ ($L'_{\text{int}\,r} = \dfrac{L_{\text{int}\,r}}{L_0}$, where L_0=1.19 millihenry own inductance) in the function T/D and δ/D on the samples made of ferromagnetic steel when supplying ECT with current of f=1 kHz and f=10 kHz frequency are shown on fig.3.

The data of dependence is approximated with the help of the least-square method (LSM) – the dependence $L'_{\text{int}\,r} = f(T/D)$ is best described by linear functions:

$$L'_{\text{int}\,r} = a_1 \frac{T}{D} + b_1, \tag{24}$$

the best curve describing the dependence $L'_{\text{int}\,r} = f(\delta/D)$ is hyperbola:

$$L'_{\text{int}\,r} = \frac{a_2}{\delta / D} + b_2, \tag{25}$$

where a, b - are coefficients determined by LSM (shown in table 1, table 2).

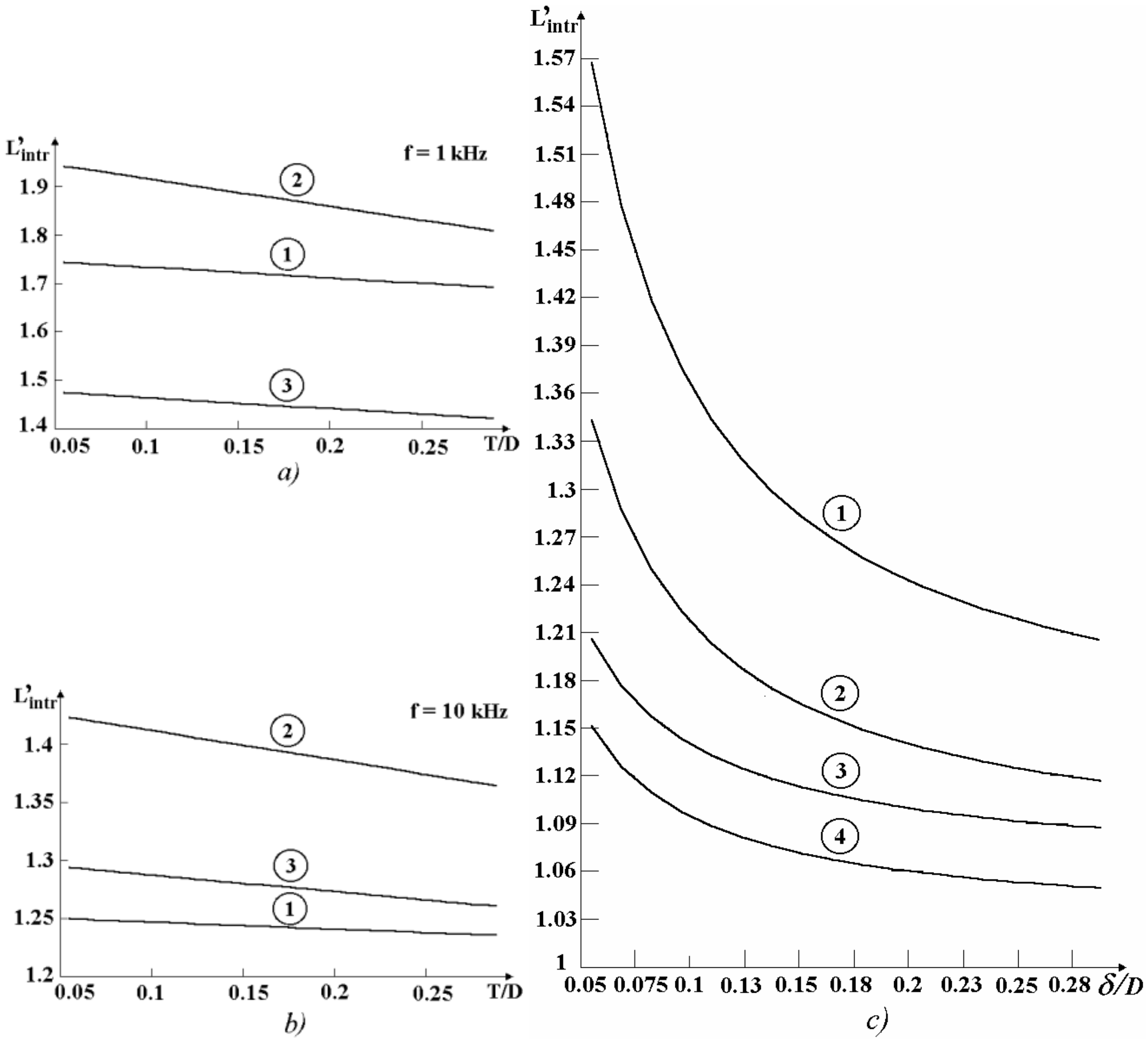

Fig.3. Dependences of introduced inductance relative values $L'_{\text{int}\,r}$

a) $L'_{\text{int}\,r} = f(T/D)$ with a rod-type core (curve 3) and with U-type core, when one of the poles is located over the crack(curve 1), and when both poles are locate over the crack (curve 2) on the samples made of ferromagnetic steel with the frequencies: f=1 kHz and *b)* f=10 kHz correspondingly;

c) $L'_{\text{int}\,r} = f(\delta/D)$ for ECT with U-type core with frequency 1 kHz (curve 1); for ECT with a rod-type core with frequency 1 kHz (curve 2); for ECT with U-type core with frequency 10 kHz (curve 3); for ECT with a rod-type core with frequency 10 kHz (curve 4).

Table 1. Values of coefficient *a*, *b* and pair correlation coefficient *K*

Eddy-current transformer over crack with opening width T	Linear function ($L'_{\text{int}\,r} = a_1 \frac{T}{D} + b_1$)					
	f=1 kHz			*f=10 kHz*		
	A_1	b_1	K	a_1	b_1	K
Rod-type core	-0.227	1.487	0.989	-0.142	1.301	-0.982
U-type core, when one of the poles is located over the crack	-0.223	1.756	0.997	-0.061	1.253	0.999
U-type core, when both poles are locate over the crack	-0.573	1.974	0.996	-0.251	1.437	0.97

Table 2. Values of coefficient *a*, *b* and pair correlation coefficient *K*

Eddy-current transformer over the tested surface with certain air-gap δ	Hyperbolic dependence ($L'_{\text{int}\,r} = \frac{a_2}{\delta / D} + b_2$)					
	f=1 kHz			*f=10 kHz*		
	a_2	b_2	K	a_2	b_2	K
Rod-type core	0.015	1.063	0.956	0.0069	1.026	0.963
U-type core	0.025	1.12	0.967	0.008	1.06	0.986

As is shown on fig.3*a,b* on the samples made of ferromagnetic steel, sensitivity (curve slope) of ECT with U-type core, when its both poles ate located above the crack, by two times exceeds sesitivity of ECT with a rod-type core. Even if a crack occures under only one of the working poles of ECT with U-type core, its sensitivity is not worse than that of ECT with a rod-type core. ECT with a rod-type core unlike ECT with U-type core has only one working end. This accounts for its lesser sensitivity. That is the sensitivity of ECT with U-type core is sufficient for registering cracks even by one of the poles. So the most reliable way to detect a defect can be ensured if it is placed under both ECT poles. Thus, for testing anysotropy products opt a laying-in ECT with U-type core, which has the best sensitivity to anisotropy for example a “fusion-crack” defect.

Analyzing functional dependencies on fig.3*c*, one can come to conclusion that either ECT with frequency 10 kHz has lesser sensitivity to gap δ influence than with frequency 1 kHz.

With bigger probability of 95% our experimental points get to the “corridor” of values for the sought quantity. Thus model parameter values correspond to true coefficient values a_1 i b_1. Analogous results are received also for other experimental dependences.

Under dynamic eddy-current testing parts since it is impossible to variable air-gap fluctuation δ in the process of scanning it is necessary to use the proposed ours method of dejaming from its influence. On the basis of this method and on the basis of this researches was developed an eddy-current defectoscope for the testing ferromagnetic parts and microprocessor system for non-destructive diagnostic cylindrical ferromagnetic parts [3, 4].

Conclusions

Thus, as a result of the conducted research there has been created graphic-analytical simplified model of ECT with U-type rod located over the ferromagnetic specimen with a crack. The analysis of the model brought the following conclusion:

1. Dependence of eddy-current transformer introduced inductance value on the change of the ratio between crack width (T) and core pole diameter (D) on condition that $T/D \le 0.3$ is approximated by linear functions on condition that

$$L_{\text{int}\,r} \approx \left[1 - \frac{4}{\pi} \cdot \frac{T}{D}\right].$$

2. Dependence of eddy-current transformer introduced inductance value on the change of air-gap size (δ) between the transformer and tested surface (main disturbing factor) is approximated by hyperbolic functions

$$L_{\text{int}\,r} \approx \frac{K}{\delta}.$$

where K – construction parameter function of eddy-current transformer.

3. For estimation of eddy-current transformer sensitivity the have been received the following equations:

- eddy-current transformer sensitivity depends on crack width growth T linearly over the range $T/D \le 0.3$

$$K_{cr} \approx D \cdot \left[1 + \frac{T}{D}\right];$$

- eddy-current transformer sensitivity to change of air-gap is inversively of δ

$$K_{\delta} \approx \frac{1}{\delta}.$$

4. When comparing equation for sensitivity depends on crack width growth T with equation for sensitivity change of air-gap δ, it is obvious that air-gap variation between the sensor and the tested surface is a grave disturbing factor. Therefore to increase eddy-current non-destructive test precision we proposed to use resonance method of suppression from disturbing influence of air-gap variation.

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