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AUTOMATION NON-DISTRUCTIVE TESTING SYSTEM FOR METAL CRIPPLING (METAL CRACKS) IN THE PROCESS OF MANUFACTURING CYLINDRICAL PARTS

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ABSTRACT

The work contains the results of theoretical and experimental research of eddy-current control for high –loaded hydro-pump parts and creation herewith of automated testing system. The subject of the research is the process of eddy-current control of metal crippling (metal cracks) and faulty fusion when manufacturing parts for reversible alternating capacity pump of fluid power drive ГСТ-90. The objective of the research is improvement of the parts through removal, in the result of control, of uncritical defects or rejection of the parts if they exceed defectiveness threshold; control expresiveness increase; increase in labour productivity through development and research of combined methods for automation systems. Methods of research are grapho-analytical and experimental. Theoretical research has been carried out on the basis of the electromagnetic induction theory, the theory of electronic system operation and mathematical statistics. Experimental research has been carried out with application of modern measuring apparatus and equipment with computerized data processing. There have been received formulas for defining transformer sensibility to crack width change and to nuisance gap changes between the eddy-current transformer and the tested surface. There has been argumented the choice of operation frequency for eddy-current transformer on the criterion of necessary electromagnetic field penitration depth. There has been proposed the method of reduction of the main hindrance factor under dynamic sddy-current control i.e. resonance method of crack change influence supression. There have been proposed circuit designs and fulfilled technical realization of eddy-current defectoscope models and automation non-destructive testing system for metal crippling (metal cracks) on the basis of a single-chip microcontroller of the assamblage MCS51.

Keywords: Automation testing system, Eddy-current method, Eddy-current transformer, Electro-magnetic field, Single-chip microcontroller

1. The research of eddy-current transformers for non-destructive testing of high-loaded hydro-pump parts

Axialpiston machines manufactured at machine-building plant “Hydrosila” (Kirovohrad, Ukraine) are exported to many world countries and are used in making tractors, combine harvesters, road machines, handling and mining equipment. One of the main units of an axialpiston machine is a reversible alternating capacity pump of a fluid power drive ГСТ-90. Therefore, while making the pumps it is necessary to carry out an all-round non-destructive test for defects in the most loaded and responsible ferromagnetic parts like plunger, distributor and separator. The named parts are of cylindrical form and complicated configuration with many grooves and openings, all parts having axial symmetry. As a consequence of manufacturing technology, the most common defect for the plunger is a “fusion” type weld defect and for the distributor and the separator is integrity violation of a “crack” type. The plunger is made of two cylindrical blanks by friction welding. The quality of welding deteriorates as there occur oscillations of welded part speed rotation, contact duration, axial vibrations, environment factor influence etc. For plunger defectoscopy the customer plant requires that a pared-down defectoscope should be developed. As per technical specifications it is required that hand scanning of plunger surface should be removed and the test should be simplified to 2-3 manipulations during which one could determine the weld quality.

On the grounds of comparative analysis of physical methods of non-destructive testing we opted for an eddy-current method of defectoscopy which is the optimum one for creation of automation testing system for hydro-pumps parts.

The object of the research is substantination of a primary laying-in eddy-current transformer (ECT) design that could be more sensitive to anisotropy of the tested sample caused by a “fusion” type weld defect. Hence, in our opinion, for the testing of a plunger it is appropriate to examine ECT with a U-type ferrite core. When testing distributors and separators for cracks it is necessary to scan the whole working surface of parts. It is desirable that ECT should be as light-weighted as possible and be smaller in shape to ensure locality of the test. When choosing ECT that can ensure the necessary sensitivity, test locality and dejamming from hindrance factors (gap or slope position to the tested surface), the whole range of properties typical of ECT of different types should be taken into account. It should be noted, however, that there is no ECT with universal properties.

Previous research showed that for solving the problems put by there are two the most acceptable types of ECT [1]:

- 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.

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 sinusoidal current of 1 kHz frequency to ECT, as well as on a digital gauge E7-14 (imitance gauge) when supplying current of 1 kHz and 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 mGn. 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 $L'_{вн}$ ($L'_{вн} = \frac{L_{вн}}{L_0}$, where L_0=1.19 mGn 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 kGz and f=10 kHz frequency are shown on fig.1.

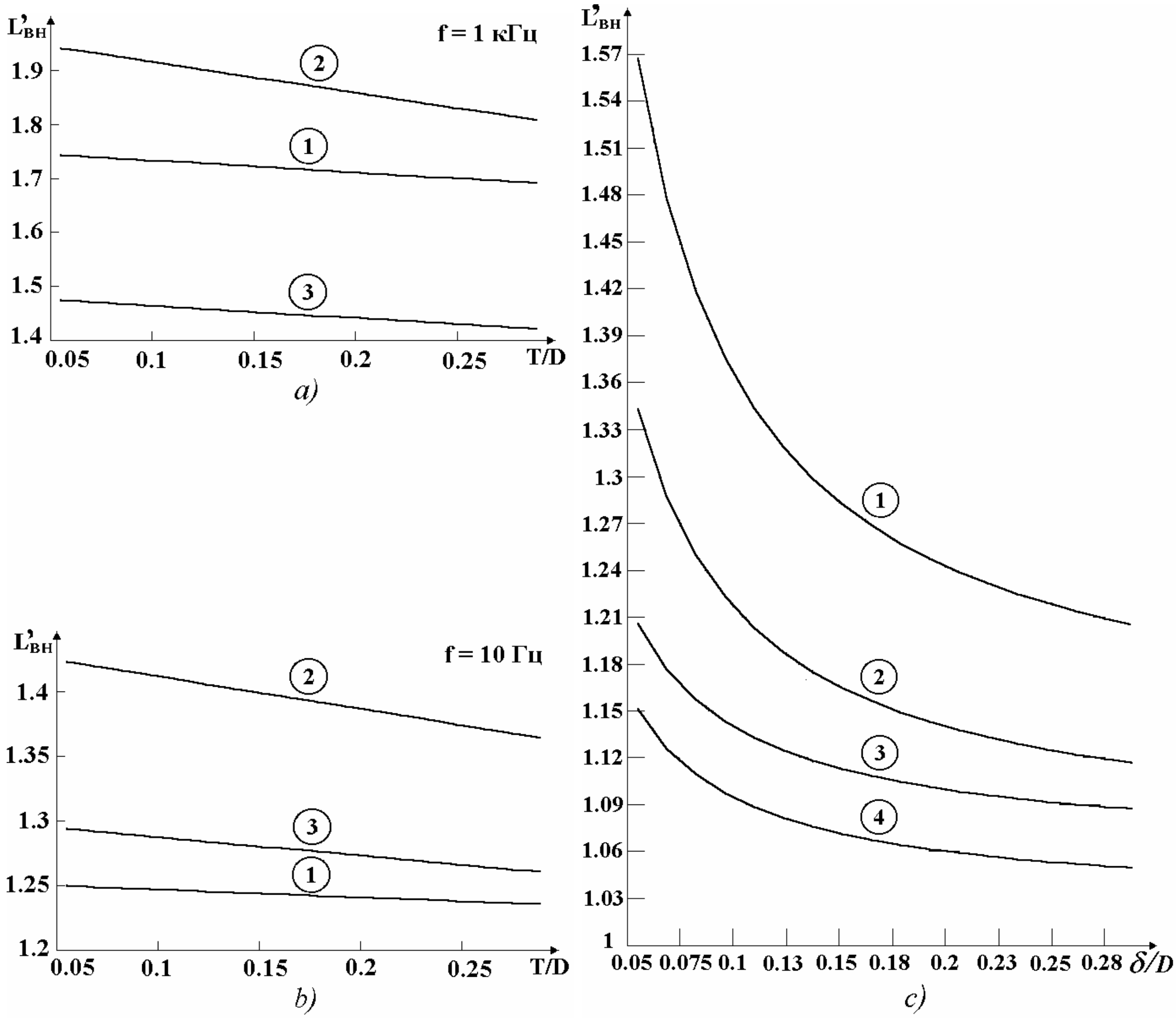

Fig. 1: Dependences of introduced inductance relative values $L'_{вн}$.

a) $L'_{вн} = f(T/D)$ 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) $L'_{вн} = f(\delta/D)$ 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).

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

$$L'_{вн} = a_1 \frac{T}{D} + b_1 , \qquad (1)$$

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

$$L'_{вн} = \frac{a_2}{\delta / D} + b_2, \quad (2)$$

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

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

Eddy-current transformer over crack with opening width T	***Linear function*** ($L'_{вн} = a_1 \frac{T}{D} + b_1$)					
	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*** ($L'_{вн} = \frac{a_2}{\delta / D} + b_2$)					
	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.2*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 detecting "fusion" in a plunger we opt for a laying-in ECT with U-type core, which has the best sensitivity to anisotropy of a "fusion-crack" defect, ECT with U-type core being built in a measuring needle in that way so both poles are located along the tested welding place.

Analyzing functional dependencies on fig.2c, one can come to conclusion that either ECT with frequency 10 kHz has lesser sensitivity to gap δ influence than with frequency 1 kHz.

The least-squares method, as an algebraic instrument for making polynomial models, allows to define point estimates for coefficients *a, b* on experimental data. However, coefficients of polynomial models, estimated after the variety $L_{вн}$ deviation results, became variates themselves. Their distribution interval with known "risk" α "overlaps" true coefficients *a* and *b* in the model. Hence the conclusion: the model setup may be considered as finished and the model itself may be used for making engineering solutions only after algebraic calculations for coefficients estimates a_1, b_1 and discrepancies Δu is supplemented with statistical analysis of both coefficients and the model as a whole.

For a linear function (1), (fig.2*a*,*b*) the confidence interval η_p with probability *P* for $\hat{L}_{вн}$ in the point with relation T/D is determined by the equation [2]:

$$P(\hat{L}_{вн} - t(\alpha/2, f_e)S(\hat{L}_{вн}) < \eta_p \le \hat{L}_{вн} + t(\alpha/2, f_e)S(\hat{L}_{вн})) = 1-\alpha .$$

Experimental values T/D – *n* are equal to 18 (n=18), and the range of discretion - *f* is equal to 17 (f_e=17). With the help of table [3] we find for α=0.05 and f_e=17 the value t=2.11; and determine the dispersion value $S(\hat{L}_{вн})$. Then for the results represented on fig.2*a*:

$$P(\hat{L}_{вн} - 2.11\cdot 0.01 < \eta_p \le \hat{L}_{вн} + 2.11\cdot 0.01) = 0.95 .$$

That is with probability of 95% the true value $L_{вн}$ in each point T/D is in the interval $[\hat{L}_{вн} - 0.02; \hat{L}_{вн} + 0.02]$. With bigger probability of 98% 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.

2. Development of automation eddy-current testing system for crippling in high- loaded hydro-pump parts

At the heart of the given automation system there lies an eddy-current defectoscope to detect metal crippling in the form of surface and subsurface defects in hydro-pump parts.

The device should be noncontact and its readings should be independent of a variable air-gap fluctuation between the sensor and the tested surface. This will enable to improve control without prior cleaning the parts from grease, dust and other non-conductor substances.

It should be provided for that there not be erroneous work of the defectoscope when the sensor is placed over a sharp edge of the tested part.

When designing defect signalling it should be taken into consideration that the test is carried out astir and the use of pointer indicators may be inconvenient because of their high time lag.

Besides, the device should be simple in manufacturing and debugging, should have small sizes for easy handling and operation.

Under dynamic test of distributor and separator since it is impossible to variable air-gap fluctuation in the process of scanning it is necessary to use the proposed method of tuning out from its influence [3]. On the basis of this method we made an eddy-current defectoscope for the testing of ferromagnetic parts.

Block diagram of eddy-current defectoscope is shown on fig.2 [4]. The device consists of amplitude and phase processing channels, search system and indication unit. The search system comprises generator sinusoid signals with a frequency regulator unit and two identical LC oscillatory circuits: measuring and calibrating. Outcoming signals of amplitude and phase channels are given to inputs of a coincidence unit to outputs of which an indication unit is connected. ECT (sensor) is a part of a measuring LC circuit.

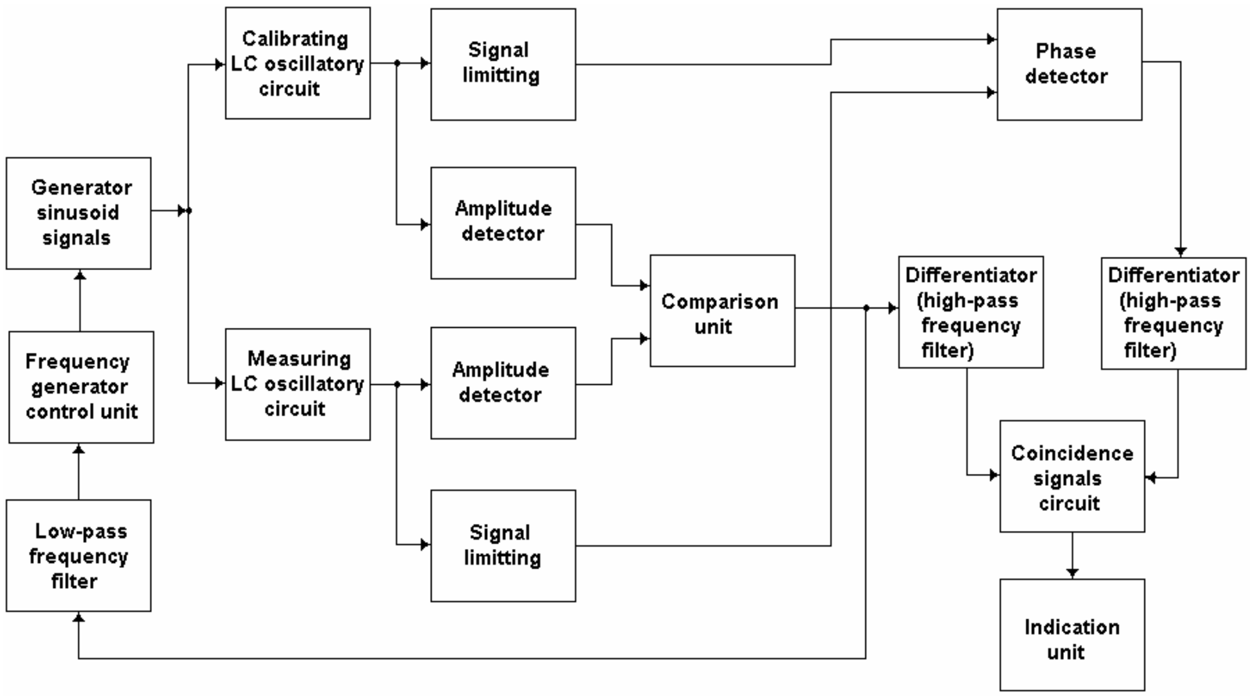

Fig. 2: Block diagram of eddy-current defectoscope.

To test welds in plungers, taking into account anisotropy, we selected ECT with U- type core as a sensing device; to test distributor and separator and to register crack defects we chose ECT with rod-type core. If a crack is detected the sensor stress vector absolute magnitude is increasing and right phase displacement is taking place. In case the sensor is placed on sharp edges of a unit, amplitude of a sensor signal is also increasing, but with left phase displacement. Thus, a two-channel device (phase and amplitude channels) allows to tuning out from such interfering factor as surface edge influence on detecting crack defects. Change of air-gap size between the sensor and the tested surface causes change of sensor signal amplitude. However, on a certain frequency, when sensor placed on the tested surface, change of sensor voltage equals zero. So when selecting generator frequency, one can achieve independence of sensor signal amplitude from the air-gap size. Such generator frequency setting can be done automatically. With this purpose, a calibrating LC circuit is used. It is done similarly to a measuring one. A calibrating LC circuit is located outside the tested surface (in the body of the device) and is assigned to regulate generator frequency. The method of comparison of signals from measuring and calibrating LC circuits is used for this. A comparison circuit outcoming signal work as a feedback through low-pass filter on a frequency generator control unit. If, when installing the sensor on the tested surface, there is a difference in signal amplitudes of measuring and calibrating LC circuits, the comparison device create a “difference” signal and work through low-pass frequency filter on a frequency generator control unit. As a consequence, the frequency changes towards decrease of the detected deference of signals. So the feedback ensures independence of signal amplitude from the size of a air-gap. Parameter changes in the tested surface are automatically kept track on (change electroconductivity, change magnetic condudtivity). Disturbing factors (air-gap, change electroconductivity, change magnetic condudtivity) are changing relatively slow when the sensor is moving along the tested surface. Therefore, the feedback signal is located in the zone of low-pass frequency filter work and thus working on a frequency generator control unit. If a defect is found, a sensor output signal is

represented the form of a short impulse. It is not let pass through by the low-pass frequency filter and is not working on a frequency control unit. Such signal through comparison unit, differentiator (high-pass frequency filter) and the coincidence unit goes to the indication device. The phase channel is used to switch off false malfunction if the sensor is installed on a edge of a part, the sensor signal amplitude increasing as if in the case when the sensor found a defect, but phase change being of opposite sign. When fast increase a signal in amplitude coincides with fast increase a signal in the phase, the coincidence unit emits a signal for the indication unit.
We have developed a scanning device with a microprocessor control designed for automation of the testing process of hydro-pump separator and distributor responsible parts [5]. The block diagram of the device is given on fig.3.

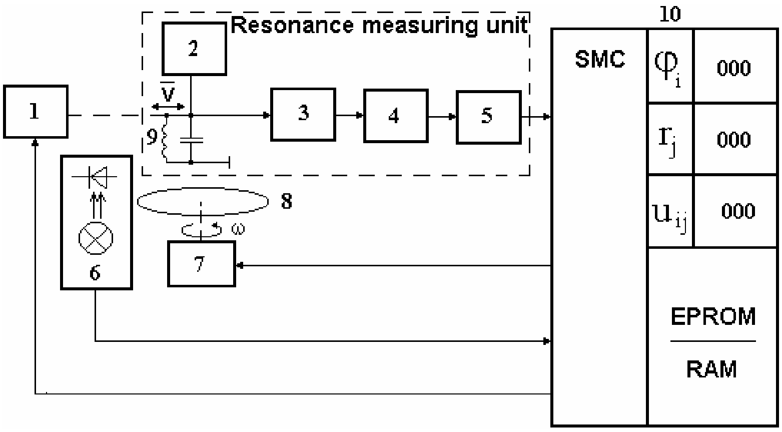

Fig. 3: Block diagram of the scanning device.

The part is installed on dialectric disk 8, which rotates owing to the first stepping motor with reductor 7. ECT 9, under the influence of other stepping motor with reductor 1 with a step equal to the diameter of ECT core, is moving forward from the periphery to the center of the part. The speed of ECT movement is syncronized with part rotation. The rotation meter has optoelectronic couple 6. The resonance measuring unit of the defectoscope contains generator 2, amplitude detector 3, amplifier 4.
The signal from ECT has a complicated character as per assigned configuration of the part. Under existing conditions defects are detected through signal processing in control microcomputer 10 (SMC). Statistically averaged information received from the scanning of some non-defectless parts (standards) with allowable variations is recorded on a erasable programmable read-only memory (EPROM).
When scanning the part on each step (on each scanning point), values of ECT signals are constantly compared to analogical signal values recorderd to EPROM, border effects, edge influence and other relief features being eliminated automatically. EPROM has a recording of standard signals for a few types of parts. Before the test part, the operator sets the scanning device working mode which corresponds to the configuration of a certain part. As per the results of the defectogram a conclusion can be formulated about operational capability of the given part to exploatation or, in case of negative information, the part is additionally tested for mechanical exertion and with application of another non-destructive testing methods.
When passing a defective zone, signal deviation ΔU_{ij} from a legitimate value shows up; the value U_{ij}, the angular $\varphi_i=\omega t$ and the radial $r_j=N_i d$ coordinates (t_i - scanning time, N_i - number of ECT steps, d - ECT core diameter) is recorded on the random-access memory (RAM). The value ΔU_{ij} in defined measure characterizes the size of the defect.
Analog-digital transformer (ADT) 5 has a period of descritization which corresponding to ECT movement to the distance:

$$\Delta l_i = \frac{\pi r_j \Delta\varphi_i}{180^0}.$$

Sufficient precision for achieving the objective is realized with Δl_i=d.
To reduce the testing time a defectoscope threshold behavior work is provided for. It is assigned to record presence of the so-called dangerous (critical) defects. The defect is considered critical when the size of the defect causes destruction of the part during exploitation. In this mode the scanning process lasts as long as the first dangerous defect is detected, further control being stopped, the scanning device being returned to starting position and the part being immediately defectived. This is accompanied with a warning signaling.
Block diagram of automation eddy-current testing system is shown on fig.4 [6].

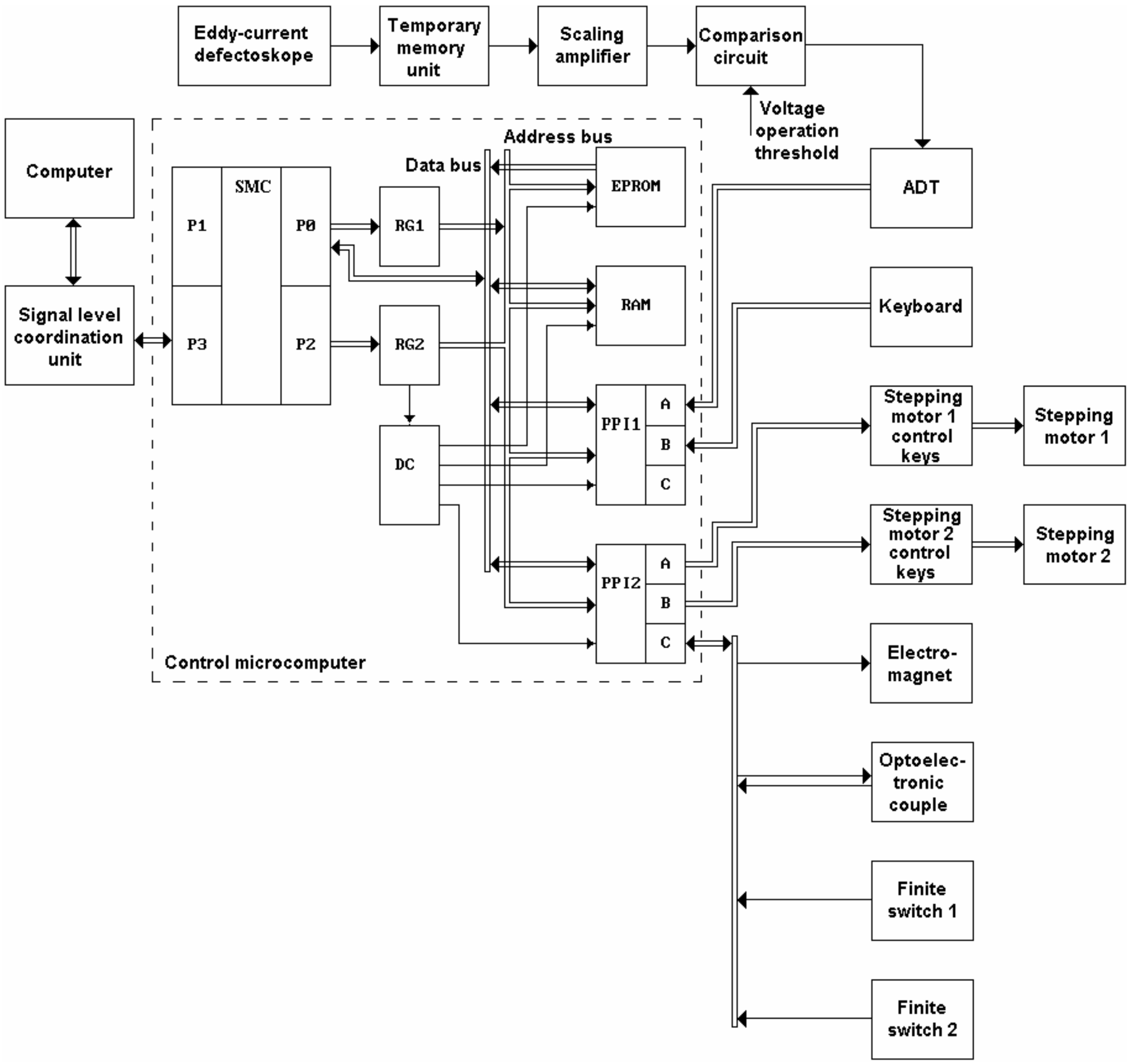

Fig. 4: Block diagram of automation eddy-current testing system.

The automation eddy-current testing system consists of the following blocks:

- eddy-current defctoscope;
- temporary storage device for the information which incame from the defectoscope;
- scaling information signal amplifier;

- comparison circuit assigned to fixation information about presence of dangerous (critical) defects;
- control microcomputer which made on the basis of a single-chip microcontroller (SMC); eight-bit buffer latch-registers (RG1, RG2); eight-bit address decorder (DC); erasable programmable read-only memory (EPROM); random access memory (RAM); programmable parallel input-output interfaces (PPI1, PPI2);
- analog-digital transformer (ADT);
- stepping motor 1 which rotates the part;
- stepping motor 2 which moves ECT forward from the periphery to the center of the part;
- stepping motor 1 and stepping motor 2 control keys;
- electromagnet assigned to move ECT up and down in relation to the tested surface;
- optoelectronic couple which starts reading out the process of scanning and also assigned to count rotations;
- keyboard assigned to control automation process;
- switchers assigned to switch off stepping motor 2 in case ECT oversteps the verge of control zone;
- serial connection interface serving also to coordinate signal levels between a single-chip microcontroller and prsonal computer.

Analog signal from eddy-current defctoscope is given to analog-digital transformer input through temporary storage device, amplifier and comparison circuit. The comparison circuit is assigned to provide a threshhold behaviour of work the automation eddy-current testing system when the presence of critical defects is recorded. Digital information through one of the channels of port A of an input-output programmable parallel interface PPI1 is received on the control microelectronic computer, assambled on the basis of a single-chip microcontroller (SMC). A keyboard is connected to port B of an input-output programmable parallel interface PPI1. Horizontal motion stepping motor control keys, an electromagnet for regulating up and down movement of ECT, optoelectronic couple to determine the start of scanning process readout and finite switches for a horizontal motion stepping motor are connected to ports A, B, C of an input-output programmable parallel interface PPI2.

3. Conclusions

Experimental research of laying-in ECTs with U-type and rod-type cores brought the following results:

1. Experimental dependences of introduced normalized inductances $L'_{вн}$ on the ratio of crack width *T* to core diameter *D* $L'_{вн} = f(T/D)$ for ECT with U-type and rod-type cores with frequency 1 kHz and 10 kHz are close to linear ones.
2. Dependences of introduced standardized inductances $L'_{вн}$ on the ratio of the gap size δ to core diameter *D* $L'_{вн} = f(\delta/D)$ for ECT with U-type and rod-type cores with frequency 1 kHz and 10 kHz are hyperbolic.
3. Experimental curves are approximated by the least-squares method; there have been defined coefficients of functional dependences of introduced normalized inductances.
4. As the result of the research there has been chosen operation frequency of 10 kHz.
5. There has been developed an eddy-current defectoscope - the main measuring device of the automation system.
6. There has been created an automation eddy-current testing system for metal crippling in high-loaded hydro-pump parts.

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