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ROBOTIC SYSTEM OF NON-DESTRUCTIVE EDDY-CURRENT TESTING OF COMPLEX GEOMETRY PRODUCTS

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An analysis was carried out for relevant state of development of automated and automatic systems of eddy-current non-destructive testing of complex geometry products. The necessity is shown in development of adaptive robotic systems, in which an operator is not directly engaged in testing process. The substantiation is given for the need of implementation of new efficient methodology of eddy-current signals processing. It uses a theory of discrete Hilbert transform in combination with the methods of theory of signals statistical manipulation. A structural scheme was proposed for a robotic automatic control complex consisting of industrial robot-manipulator, coordinate table with several degrees of freedom and device for tested object fixing, automatic station with a set of eddy-current converters of different types, block of machine vision probes, PC and electron block for control and processing of eddy-current signals. 12 Ref., 7 Figures.

Keywords: *automatic non-destructive eddy-current testing, adaptive robotic complex, machine vision probe, amplitude and phase characteristic of eddy-current signal*

Problem relevance. Operations of product quality control, which are based on application of non-destructive testing methods (NDT) [1, 2], take a relevant place in a structure of advanced productions at their different stages. Improvement of competitiveness and reliability of products to the most extent depend on rate of implementation of new structural materials and components, progressive technological processes, the latest achievements in fundamental and applied sciences. Under such conditions the developers of new products in their work should base on innovative methods and means of quality control, oriented on perspective materials with improved characteristics and parameters. Such means should accumulate the latest achievements from different branches of knowledges, i.e. physics, mathematics, engineering, electronics, computer engineering etc. This to the full refers to eddy-current testing (ECT), which is extremely informative and at the same time sufficiently complex from point of view of getting useful information and outlining diagnostic characteristics, particularly when this is a product of complex geometry.

Regardless implementation of modern design solutions, achievements of computer and information-measurement technologies, the considerable part of testing means is directed on «manual» scanning of tested object (TO) surface. Presence of human factor results in increase of subjectivity of testing, decrease the probability for correct diagnostic decision making. Therefore, practice shows that the manual method does not guarantee high testing quality even with available sophisticated testing procedures. Presence of a human-operator in technological testing chain significantly increase probability of acquiring wrong decisions that does not allow realizing high potential capabilities of NDT means in full scope.

Thus, increase of productivity and reliability of results of ECT of complex geometry products requires development of automatic testing systems, which obviously will use new approaches to testing procedure as well as mathematical support of flaw detector. Basic conditions for this are the next ECT peculiarities, namely need in absence of mechanical contact between TO and eddy-current probe (ECP); application of small size ECP designs; stability of ECP characteristics in operating temperature range as well as in time. One of the most perspective directions for realizing automatic ECT is development of robotic non-destructive testing systems.

Analysis of available solutions and problem statement. One of the main disturbances, which can significantly affects the results of automatic ECT is change of vision gap between the converter and TO. In the case of robotic testing such a gap is determined by:

- roughness of TO surface;
- accuracy of movement of eddy-current probe (ECP) on set trajectory;

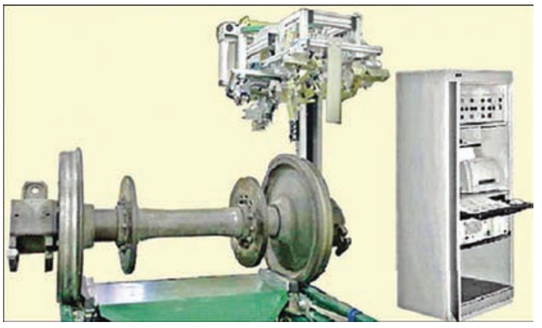

Figure 1. Automated module of ECT system for wheel pairs of railway cars PELENG-AUTOMAT

Figure 2. Mechanized system of ECT of pipes

● accuracy of approximation of computer geometry model of TO;

● accuracy of machine vision means (laser-triangulation video sensor) that is used at stage of adaptation to specific TO specimen [3].

Previous calculations show that uncontrolled change of a gap value in process of robotic eddy-current testing of large TO can reach ±0.5 mm. This disturbance can be significantly reduced in application of ECP with special spring-mounted fixture that provides tightness of ECP with TO surface, but increases testing time. Application of ECP with regular fixture, compensation of disturbance due to change of the gap value shall be performed by special mathematic module of robotic ECT system.

Mechanized and semi-automatic systems, that during some time fulfilled the industrial needs, preceeded the development of automatic NDT systems. Not very complex linear manipulators providing sufficient positioning accuracy [4] were used in such systems. For example, NDT of wheel pairs of cars used the automatic complex «PELENG-AUTOMAT» («ALTEC» Company, Russia). It consists of ECT module for the whole wheel surface and brake disk (Figure 1). Figure 2 shows mechanized ECT system for average diameter pipes (from 1.75 to 38´´) based on ChainXY-scanner from «Olympus» Company. Application of such a system is limited by testing of simple shape parts (plates, pipes etc.).

Testing systems with anthropomorphic robot-manipulators that have six and more degrees of freedom [5–7] are more flexible and productive. Such systems are used in the places which require high productivity or performance of testing of complex geometry products.

Robotic NDT systems can be conventionally divided on two classes, namely adaptive and non-adaptive. The non-adaptive systems are used for NDT of parts and products with not complex geometry. The main criterion of quality functioning of such systems is their productivity. These systems are mainly designed for testing of small parts with insignificant surface roughness. As an example of systems of such type Figure 3, *a* shows ECT robotic system «EloScan-system» for non-destructive testing. It is mainly designed for checking the symmetric rotation components in aircraft construction. Accuracy of TO posi-

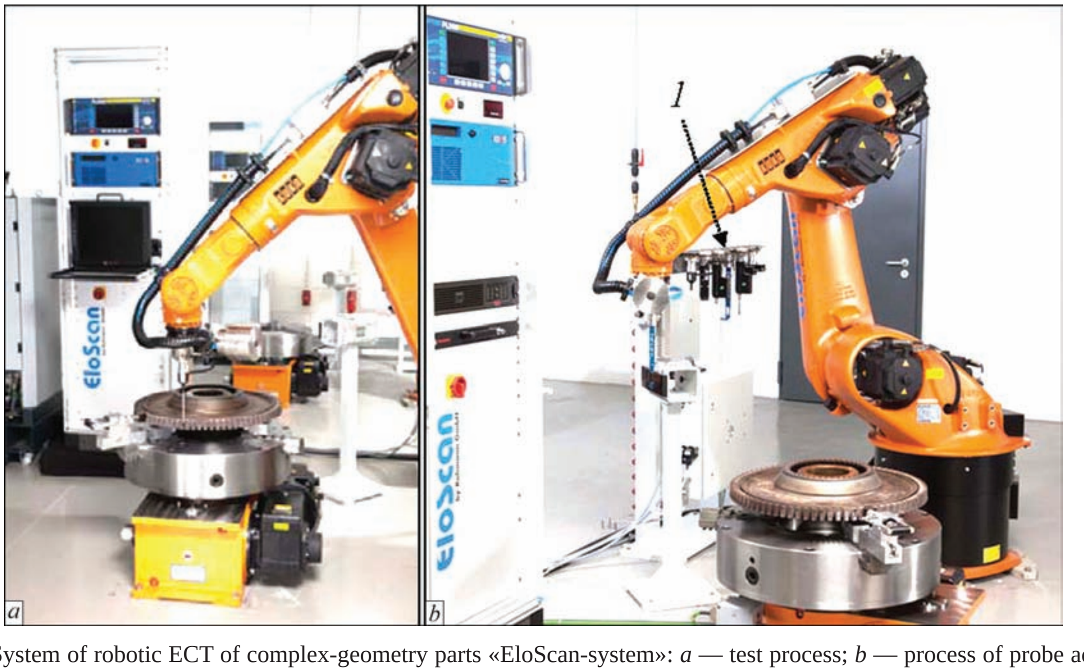

Figure 3. System of robotic ECT of complex-geometry parts «EloScan-system»: *a* — test process; *b* — process of probe adjustment (*1* — station for probe servicing)

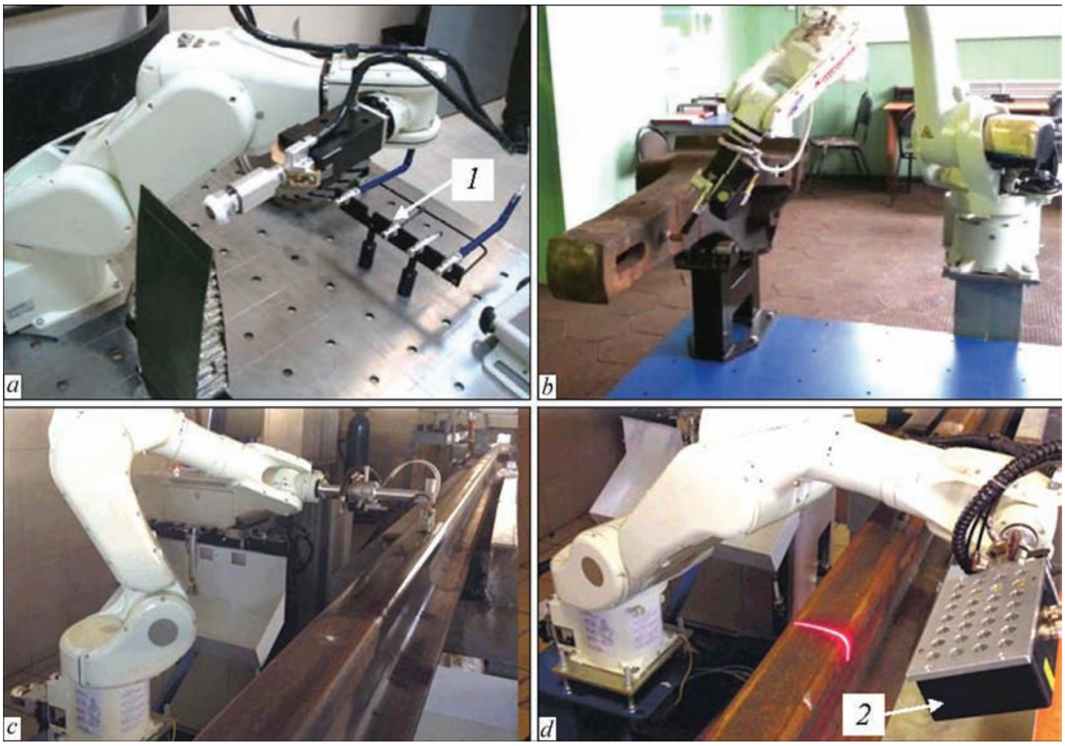

Figure 4. NTD system of «Roboskop VTM-3000» type for ECT: *a* — elements of plane wing; *b* — railway towing device; *c* — railway track; *d* — rail geometry (*1* — station for probe servicing; *2* — laser-TV video sensor)

tioning is provided by high manufacturing accuracy of the part being tested as well as application of special product manipulator of «lathe chuck» type. The system has a service station for probes (Figure 3, *b*) that allows quick replacement and effective readjustment of the probes during ECT for testing of the products with different geometry depending on task and type of test zone surface.

Adaptive robotic systems are used in the cases when it is necessary to carry out NDT of large parts and products with complex geometry. The main criterion of functional quality of such systems is a high level of possibility of defect detection at a determined level of testing productivity. This system can include laser-TV video sensor, productive work of which is provided by scattered reflection of laser light from surfaces being tested. The representatives of systems of this class are the robotic non-destructive ECT complexes of «Roboskop VTM-3000» type («WorldNDT» Company, Russia) [8] that are presented in Figure 4.

These systems consist of two anthropomorphic robots, laser-TV video sensor and station of eddy-current probes servicing. The laser-TV video sensor can be used in a complex with ECT for initial measurement of TO size or adapting to real size of specific TO as well as independently as a tool for determination and testing of product geometry parameters (Figure 4, *d*).

Application of that or another type of video sensor depends on required measurement accuracy as well as TO geometry. Testing of large products with flat surfaces can be carried out using video sensor with larger triangulation angle. A video sensor with smaller triangulation angle has significantly small dimensions, therefore it is reasonable to use if TO geometry includes narrow zones and noticeable deepening.

Efficient functioning of robotic ECT system is related with correct selection of eddy-current converters (ECC) with a specific set of probes, necessary for operational product testing [9]. ECC designs for each type of TO are determined by their designation, conditions of usage, frequency range of actuation current and other factors. Size of ECC coils is limited from the bottom by several millimeters in diameter and ECC mass by tens of grams (without taking into account fixing assemblies and displacement of ECC and interface elements).

Special attention shall be given to ECT devices. Current market is full of devices of different designation, including eddy-current flaw detectors that have high technical characteristics. Under conditions of manual scanning reliability of ECT results to a significant extent depends on preparation, experience and emotional state of flaw detector operator. However, their application in robotic NDT systems is limited by several factors. First of all, known eddy-current flaw detectors from the very beginning are oriented on operator, who makes decisions on visual signal in form of hodograph (Figure 5). Generally, such a hodograph is transferred to peripheral devices that creates certain inconveniencies for application of such signals in the automated systems. Obviously, that application of hodographs is very limited in robotic ECT systems.

Secondly, such devices for developer of NDT robotic systems are like «blackboxes». Process of selection of testing mode, calibration, algorithm of

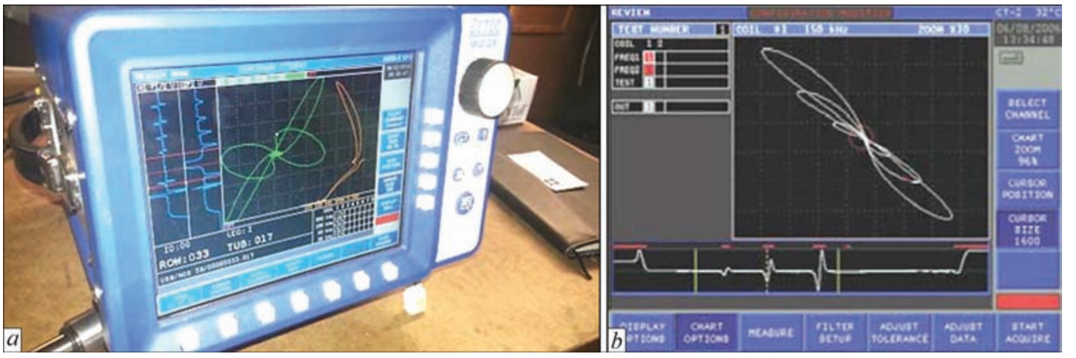

Figure 5. Graphic presentation of results of non-destructive ECT with manual scanning systems: *a* — portable system; *b* — stationary computer system

processing of experimental data is in whole «hidden» from the user that complicates integration of such devices in automation testing systems.

Thirdly, processing of ECC signals is based on analysis of signals' amplitude characteristics. Application of phase methods has auxiliary nature and can be directed, for example, on increase of testing selectivity [9]. At the same time, analysis of phase characteristics of ECC signals, including their statistical processing and determination of circle chart statistics [10] allows outlining additional diagnostics features that creates basics for expansion of functional possibilities of ECT, increase resolution ability of eddy-current flaw detection, implementation of new characteristics in ECT practice.

Thus, task of this work was formulated in the following way based on the results of carried analysis, i.e. it is necessary to substantiate general structure of robotic ECT system of products with complex geometry and propose procedure for ECC signals processing for such a system with the possibility of formation of diagnostic features from amplitude as well as phase characteristics of the signals with wide application of statistical methods of their manipulation.

Proposed technical solution. Based on carried analysis of known technical solutions it can be stated that typical robotic NDT complex shall include robot-manipulator, coordinate table with several degrees of freedom, automated station with a set of converters of different types, TO fixation device, machine vision devices, PC, block of electron control and signal processing.

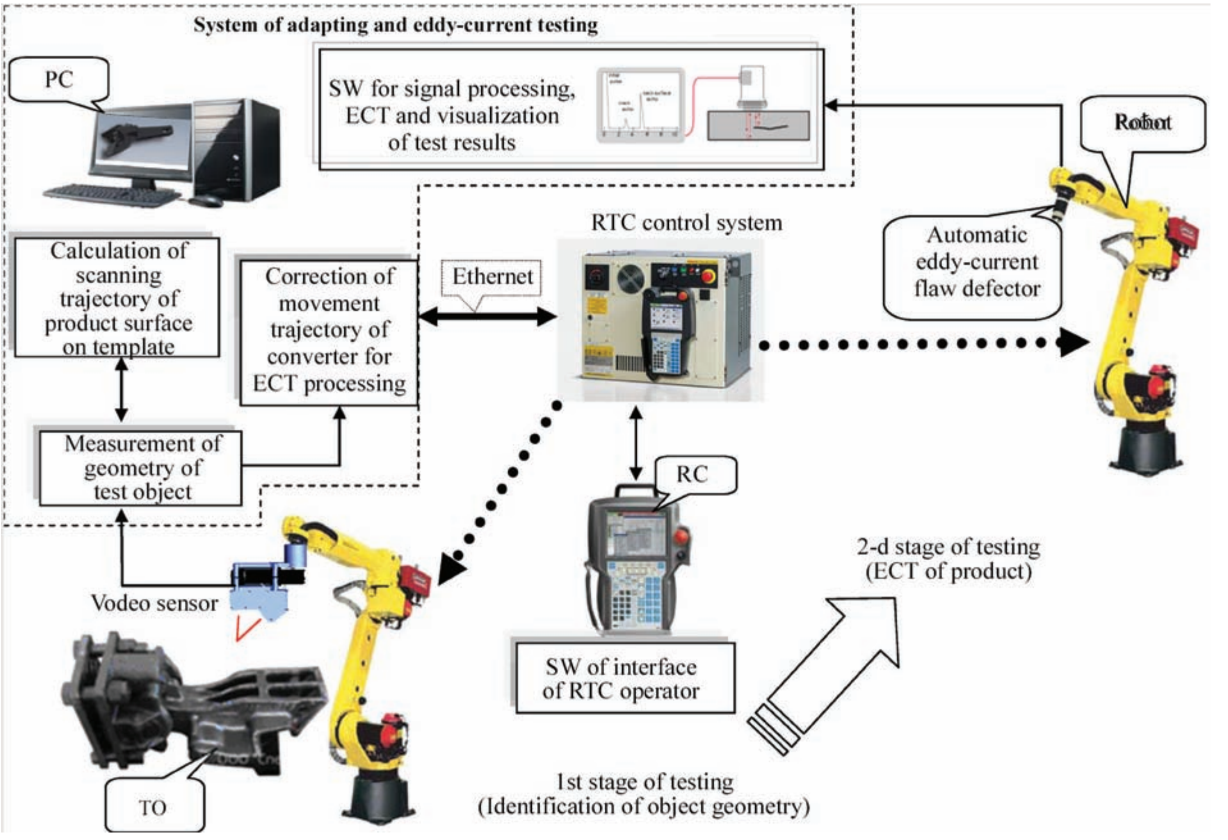

Figure 6. Structural scheme of robotic adaptive system of non-destructive ECT: RC — remote control; SW — software; RTC — robotic technical complex

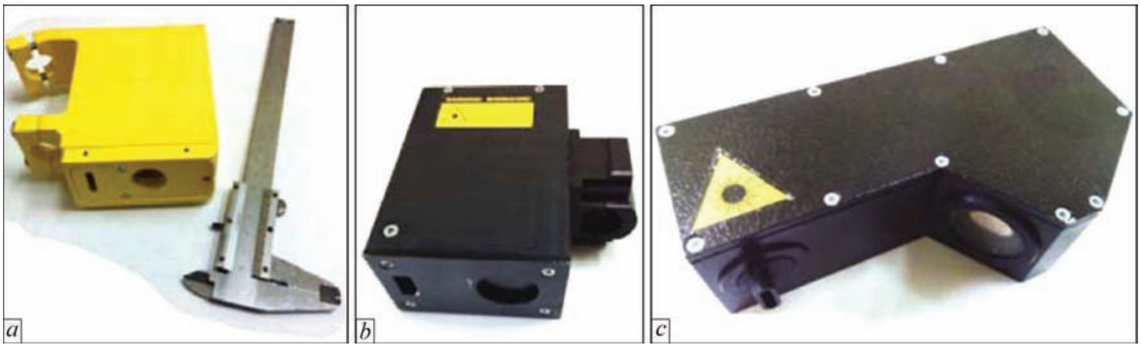

Figure 7. Laser-TV video sensors for robotic NDT systems with triangulation angles: *a* — 15; *b* — 20; c — 40°

The following structure of robotic adaptive ECT system, shown in Figure 6 (scheme does not show ECT service station and module for TO positioning), was proposed on the ground of mentioned above.

The robotic system of non-destructive ECT provides two-stage testing mode. Identification of TO geometry model is carried out at the first stage using laser-TV video sensor, i.e. machine vision probe. Such video sensors are an important element for adapting the robotic systems of non-destructive ECT to different TO. Currently, there are no versatile machine vision probes, therefore, such adapting devices are developed for specific tasks. E.O. Paton Electric Welding Institute has developed a range of models of laser-TV video sensors that can be used for identification of TO geometry in automatic systems. Figure 7 shows a range of such video sensors that differ by dimensions as well as value of triangulation angle.

System adaptability is realized at the expense of:

● algorithm of scanning of TO surface and registration of measurement results, which were gotten using laser-triangulation video sensor;

● algorithm of specification of key parameters of TO geometry model;

● algorithm of calculation of ECC scanning trajectory for product surface on set model;

● algorithm of calculation of amendments for robot control system at all scanning trajectory.

The second phase of testing is particularly directed on performance of ECT of a product. Such a testing is carried out in automatic mode. Operations on calibration, change of ECC type and re-adjustment of ECC operating mode are carried out without operator. Mathware of the PC generates corrections in a system of control of robotic technological complex (RTC) during regulation of robot trajectory. These corrections proceed in real time mode on Ethernet interface channel and result in correction of scanning trajectory that provides maximum sensitivity of ECC and prevents appearance of its collision with TO surface. This stage also includes start of work of mathematical module used for ECC signal processing and visualization. A decision on level of defectiveness of the controlled area of the product is formed based on the results of analysis of determined diagnostic characteristics.

Robotic NDT system stipulates for operator the possibility to perform some actions which are related with operations on installation and removal of TO from product manipulator. A remote control (RC) and special software which realize interactive communication in operator- RTC system are designed for this.

Typical peculiarity of mathematical and program software of the ECT robotic system is realization of paradigm of adaptability and versatility of technological process of testing. It can be reached due to possibility of ECC change for adapting to TO geometry and testing tasks as well as the following special function characteristics:

● determination of the coordinates of TO prepared for testing in 3D coordinate system;

● scanning of TO surface by set program;

● calculation of amplitude characteristic of ECC signal;

● calculation of phase and frequency characteristic of ECC signal;

● statistical processing of characteristics of ECC signals and other data;

● calculation and analysis of spectra of ECC signals;

● software control of parameters of signals for ECC actuation and modes of operation of system measurement channel;

● formation of diagnostic solutions as for determination of TO defectiveness and interactive communication with technologist-inspector based on the results of analysis of ECC signal etc.

Thus, the proposed structure of robotic system of non-destructive ECT allows realizing a paradigm of adaptive non-destructive testing of complex geometry products.

Realization of concept of complete ECT automation requires more general approach to ECT signals processing and formation of fields of informative features related with TO in coordinate system.

Mostly, ECC actuation is carried out using harmonic currents of the following type:

$$i_0(t) = I_0 \cos\left(2\pi f_0 t \pm \varphi_0\right), \quad t \in (-\infty, \infty), \tag{1}$$

where t is the present time; $I_0 > 0$ is the amplitude of actuation signal; $\varphi_0 \in [0, 2\pi)$ is the initial phase; $f_0 >$ > 0 is the frequency.

An output signal exists in a form of sine voltage that is observed at the background of additive noises $n(t)$. Localizing of the TO inhomogeneities in space during ECC scanning of TO surface in the robotic ECT systems results in time and space local changes (disturbances) of signals' parameters. Therefore, in general case the arguments of ECC signals are not only time t, but also vector of $\bar{p}_r$ parameters of «ECC–TO» system and space Cartesian coordinates $r = \{x, y, z\}$ of points of TO surface:

$$u\left(t, \bar{p}_r, r\right) = U\left(t, \bar{p}_r, r\right) \times$$
$$\times \cos\left(2\pi f_0 t - \varphi\left(t, \bar{p}_r, r\right)\right) + n(t), \; t \in T_{\text{a}}, \quad (2)$$

where T_{a} is the full time for analysis of the whole TO.

The first informative component of the signal (2) belongs to class of sine signals with locally concentrated disturbances of informative parameters. Space coordinates are limited by collection of values $\{x_{\max} \ldots x_{\max}, y_{\min} \ldots y_{\max}, z_{\min} \ldots z_{\max}\}$ that are determined by technical characteristics of robot-manipulator. Range of values of vector components of $\bar{p}_r$ parameters is also limited and determined by physical parameters and characteristics of TO material and geometry characteristics of «ECC–TO» system.

Noise component $n(t)$ of the signal (2) is generated due to action of number of factors, i.e. noises of electron components of the system, electromagnetic guidance and mechanical vibrations etc. Usually, $n(t)$ substantiation as realization of Gaussian random process with zero mathematical expectation and σ^2 dispersion is not contradictory.

Signal (2) is non-stationary at all analysis interval. However, the conditions of testing process realizing allow the following simplification. Process of measurement of ECC signal parameters in digital systems takes place discretely in time in a finite collection of space points $r_g = \{x_g, y_g, z_g, g \in [1, G]\}$. Every separate measurement is carried out in T_g, $T < T_g <<$ $<< T_{\text{a}}$ time interval. Such a condition appears due to relatively small scanning rate or even the possibility of measurement after ECC stop in the next point g. Therefore, in specific time interval T_g, the signal $u(t, \bar{p}_g, r_g), \; t \in T_g$ can be assumed as locally stationary, parameters of which, amplitude and initial phase remain constant during T_g. Such the assumption allows significant simplification of ECC signal analysis.

ECC signal processing in modern ECT systems is carried out in digital form that provides discrete time sampling with $T_{\text{a}} << 1/f$ step. Signal discrete analogue is presented as

$$u\left[j, \bar{p}_g, r_g\right] = U\left[j, \bar{p}_g, r_g\right] \times$$
$$\times \cos\left[2\pi f_0 j - \varphi\left[j, \bar{p}_g, r_g\right]\right] + n[j], \quad (3)$$
$$g \in [1, G], \; j \in \left[1, \; T_{\text{à}} / T_{\text{a}}\right].$$

There is a discrete Hilbert transform for model (3). This is a base model for processing of signals in ECT robotic systems.

From point of view of general algorithm processing of ECC signals in robotic testing systems can be conditionally divided on three stages, namely primary (formation and processing of analogue signal), secondary (processing of digital signal and its discrete characteristics) and ternary (visualization of testing results and their statistical processing).

The first step is carried out under traditional scheme [9], which provides formation of ECC actuation signals (1) and control of their parameters, software amplification of ECC signals (2), equalization (if necessary) of unbalance signals, analogue-digital transform of the signals.

The second stage of processing of eddy-current signal is designed for sampling of useful information in relation to defectiveness of controlled surface and formation of diagnostic features.

The general concept of ECC signal processing is based on combination of Hilbert discrete transform [10, 11] and statistical methods for processing of signal characteristics [12]. Application of algorithm of «moving average» with double window is the most efficient for getting evaluations of signal parameters that are continuous in real time.

The first window $W_1[j_k]$ with aperture k provides formation of present sample from sequence (3). Discrete Hilbert-image is calculated for the sample

$$u_{\text{H}}\left[j_k, \bar{p}_g, r_g\right] = \mathbf{H}\left\{u\left[j_k, \bar{p}_g, r_g\right]\right\}, \quad j_k = \overline{j, j+k}, \quad (4)$$

where $\mathbf{H}\{\cdot\}$ is the operator of Hilbert discrete transform.

Sequences (3) are associated to their complex significant analytical version $u\left[j_k, \bar{p}_g, r_g\right] + i u_{\text{H}}\left[j_k, \bar{p}_g, r_g\right]$, where $i = \sqrt{-1}$ for which the following characteristics can be determined:

- discrete amplitude characteristic

$$A\left[j_k, \bar{p}_g, r_g\right] = \sqrt{u^2\left[j_k, \bar{p}_g, r_g\right] + u_{\text{H}}^2\left[j_k, \bar{p}_g, r_g\right]}; \quad (5)$$

- discrete phase characteristic

$$\Phi\left[j_k, \bar{p}_g, r_g\right] = \text{arctg}\frac{u_{\text{í}}\left[j_k, \bar{p}_g, r_g\right]}{u\left[j_k, \bar{p}_g, r_g\right]} +$$
$$+ -\left\{2 - \text{sign}\; u_{\text{í}}\left[j_k, \bar{p}_g, r_g\right]\left(1 + \text{sign}\; u\left[j_k, \bar{p}_g, r_g\right]\right)\right\} + \quad (6)$$
$$+ 2\pi\left[u\left[j_k, \bar{p}_g, r_g\right], u_{\text{í}}\left[j_k, \bar{p}_g, r_g\right]\right],$$

where sign is the sign function; **L** is the operator of development of phase characteristic out of the interval [0, 2π);

- discrete frequency characteristic

$$f[j]=\frac{\Phi\left[j_k,\bar{p}_g,r_g\right]-\Phi\left[j_k-1,\bar{p}_g,r_g\right]}{2\pi T_{\hat{o}}}; \quad (7)$$

- difference of discrete phase characteristics of two sequences, for example $u_1\left[j_k,\bar{p}_g,r_g\right]$ (determined for measuring signal) *i* and $u_2[\bar{i}_k]$ (determined for reference signal)

$$\Delta\varphi\left[j_k,\bar{p}_g,r_g\right]=\Phi_1\left[j_k,\bar{p}_g,r_g\right]-\Phi_2\left[j_k\right]. \quad (8)$$

The second window $W_2[j_m]$ with aperture $m << k$ provides sampling of present values of discrete characteristics of signals, in particular, sequence (7) helps to determine new for ECT circular statistical characteristics [11]: circular sampling average, dispersion, length of resulting vector, median, mode etc.

The stage of ternary processing provides documenting and backup of testing results, defects classification, statistical processing of test results of single-series products or their fragments, construction and visualizing of the fields of diagnostic features in connected with TO coordinate system etc.

Discussion of received results. Combination of commercial robot-manipulators with ECT devices in scope of single diagnostic NDT complexes has the following advantages for flaw detection:

- complete automation of ECT process and improvement of its productivity;
- possibility for stabilizing of a gap between TO surface and ECC;
- enhancement of objectivity and probability of testing due to removal of human factor at all stages of testing from ECC signal forming to diagnostic decision making;
- possibility of presentation of testing results on 3D models and obtaining respective flaw patterns (documenting of testing results);
- possibility the binding the testing results to points on product surface in one space coordinate system;
- high accuracy and repeating of ECC positioning;
- possibility of retesting (or testing of different single-type products) in points with constant space coordinates that is necessary, for example, for realizing multiparameter ECT);
- possibility of adapting and fast readjustment of a complex for different types of ECC, TO geometry and testing tasks.

Expansion of possibilities of digital processing of ECC signal based on combination of discrete Hilbert transform and statistical methods of evaluation of signal characteristics allows increasing sensitivity and probability of testing using new for ECT circular statistics which are determined through phase characteristics of ECC signals.

Thus, robotics of ECT processes allows increasing productivity of non-destructive testing as well as improving its quality characteristics.

Conclusions

1. Combination of possibilities of modern robot-manipulators, methods of digital processing of signals and statistical methods of processing of measurement results allows developing current robotic ECT system with improvement of technical characteristics and novel possibilities that guarantee automatic non-destructive testing of complex geometry products.

2. Proposed was the effective procedure of ECC signal processing. It is based on application of Hilbert discrete transform in combination with statistical methods of processing of signals' characteristics.

3. A structure of robotic system for automatic non-destructive testing was proposed. It allows reaching new indices of productivity and reliability of NTD results of complex-geometry products.

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