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RELIABILITY OF PIEZOELECTRIC SCANNERS IN PROBE MICROSCOPY

The paper considers the issues related to the reliability of systems made up of multifunctional piezoelectric modules which depends on an automated system of control of piezoelectric scanners as a whole (and of individual piezoelectric modules), as well as on the reliability of piezoelectric modules themselves wherein electrical energy converts into mechanical energy.

Keywords: *scanning probe microscopy, multifunctional piezoelectric module, reliability of piezoelectric scanner, probability of failure-free operation, relative inaccuracy.*

A scanner (piezoengine) is the main element of scanning probe microscopes (SPM) which enables a device's operation in atomic resolution modes. The scanner is made up of polycrystalline piezoelectric materials, which, on the one hand, provide high rigidity of the design and, on the other hand, provide the ability to shift at very small distances, up to a few picometres.

Besides, the state-of-the-art of SPM is such that it has led to the necessity of transition from purely qualitative measurements of surface structures to quantitative, metrologically verified measurements, which requires the profound study of behavior of piezoelectric materials used for manufacturing of scanners, development of precision measurement methods and metrological certification and correction of piezoelectric scanners. At the same time, procedures of lithograph require scanners with orthogonality in a plane at the level better the tenth of a percent. If it is still accepted to correct non-orthogonality in a plane by methods of program correction, non-orthogonality in a plane of the *Z* axis, which can reach tens of degrees in uncorrected ceramics, is inadmissible as it leads to that the low lateral frequency of a scanner becomes essential for feedback loop operation, which considerably reduces work quality of a device.

It is these circumstances that have led to the necessity to profoundly study the properties of a scanner and to develop a technology of their correction at the physical level.

Practically in all SPMs, the piezoelectric scanner is used as a very sensitive positioning device to move a probe in relation to a sample, or a sample in relation to a probe. The scanner provides two independent movements: scanning along the surface of a sample (in the *XY* plane) and moving in the direction perpendicular to the surface (along the *Z* axis) [1].

The scanner of a probe microscope shifts the probe in relation to a sample like a raster image, as is shown in Fig.1

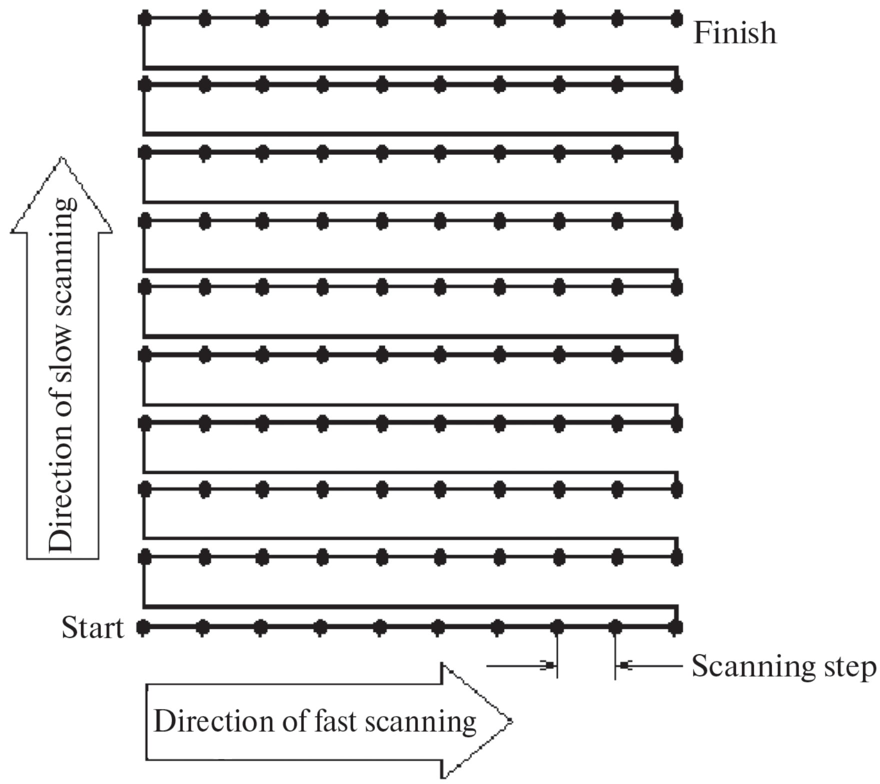

Fig. 1. Motion of scanning probe microscope (SPM) in a plane (X, Y).
Points indicate places of information collection

The scanner moves along the first line of scanning and back. Then it is shifted a step up in a perpendicular direction onto the following line of scanning, moves along it and back, then it is shifted onto the third line, and so on. The way differs from a traditional raster image in that the alternating lines of data, measured signals are not taken in backward directions. When scanning, measured data are collected only in one direction, usually called as the direction of fast scanning, to minimize errors of registration, which occur due to scanner hysteresis. The perpendicular direction in which the scanner moves from line to line is referred to as the direction of slow scanning [2].

While the scanner moves along the scanning line, the image data are digitized at equally located intervals. The data are the scanner height in the direction *Z* for constant force mode or direct current mode. For constant height mode, the data are cantilever deviations, or tunnel current.

The space between data points is referred to as a scanning step. The size of a step is defined by the full size of scanning and the number of data points on one line. In a typical scanning probe microscope, scanning sizes change from 10 angstrom up to 100 micron, and from 64 up to 1000 data points on one line. Some systems have 3000 data points on a line. The number of lines is usually set equal to the number of data points on a line. Thus, the ideal data setting corresponds to a square grid of measurements [3].

In scanner operation, there are such undesirable effects as hysteresis, aging, creep, which lead to a distortion of an obtained image.

Piezoelectric scanners are vital elements in scanning probe microscopes which essentially influence the quality of an obtained image. Therefore, the characteristics of a scanner should meet specific requirements. One of the most important requirements for a scanner is the requirement of scanner orthogonality [4].

The piezoelectric effect was discovered in 1880 by Jacques and Pierre Curie. They noticed that in some crystals under mechanical impact there is electric polarization, and its degree is proportional to the impact value. Later on Curie discovered the inversion piezoelectric effect, i.e. deformation of the materials placed in an electric field. These phenomena are also called direct and reverse piezoelectric effects [5].

The piezoelectric effect is inherent in some natural crystals, such as quartz and tourmaline, which were for many years used as electromechanical converters. The lattice of crystals possessing a piezoelectric effect has no centre of symmetry. An impact (compressing or extending) applied to such a crystal leads to polarization after division of positive and negative charges which are available in each individual elementary particle. The effect is practically linear, that is the degree of polarization is directly proportional to the value of applied effort, but the direction of polarization is dependent, as the effort of compression or extension generate electric fields, and consequently, voltage of opposite polarity. Accordingly, when placing a crystal in an electric field, elastic deformation will cause increase or reduction of its length according to the value and direction of field polarity.

Under present-day conditions of processes behavior, special attention is given to exact methods of positioning and moving in vacuum. And there are rigorous requirements applied to precision systems, such as high accuracy of positioning, operating speed, as well as small delay of positioning systems. Precision shifting systems are the prerequisite for increase of production of faultless devices. In modern technological and research equipment various types of precision shifting devices are used. However, we shall focus on devices using piezoelectric transducers whose distinctive feature is lack of inertia. Owing to their rigid structure, piezoelectric scanners are the ideal tool for their fast and accurate adjustment.

The characteristics of a piezoelectric transducer are expressed by simple relationships (Fig.2):

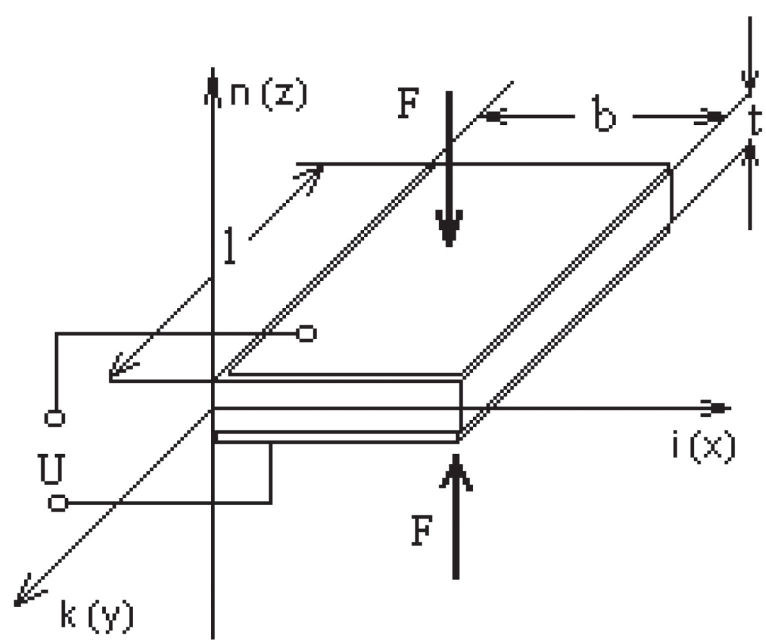

Fig. 2. A piezoelement

$$E_i = g_{in} \times \sigma_n = -h_{in} \times \varepsilon_n; \quad (1)$$

$$\varepsilon_n = d_{kn} \times E_k; \quad (2)$$

$$\sigma_n = C_{nn} \times \varepsilon_n; \tag{3}$$

$$U_i = E_i \times l_i; \tag{4}$$

$$C_n = \varepsilon_r \times \varepsilon_0 \times F_x / l_n, \tag{5}$$

where E_i and E_k are field intensity in a crystal in the direction of the *i* and *k* axes, V/m;
σ_n is mechanical stress in a crystal along the *n* axis, N/m^2;
ε_n is relative deformation of a crystal along the axis;
U_i is voltage on crystal faces along the *i* axis, *V*;
C_n is capacity of a crystal between plates located on crystal faces, perpendicular to the *n* axis;
l_n and l_i are size of a blade along the *i* and n axes (usually it is the blade thickness *t*), m;
ε_r is relative inductive capacity (ε_0 =8.85·10^{-12}, Φ/m is electric constant);
F_x is area of a capacitor plate, m^2;
g_{in}, d_{kn}, C_{nn} are piezoelectric factors.

The indexes *i, k, n* correspond to the directions of axes or to planes, with the directions of the *X*, *Y* and *Z* axes corresponding to the figures 1, 2 and 3, and with the *ZY*, *ZX* and *XY* planes corresponding to the figures 4, 5 and 6. The first index characterizes the applied impact, and the second one characterizes the obtained result. Thus, the index 1 of the factor g_{12} means that the blade is deformed along the *X* axis, and the field intensity is measured along the *Y* axis. The index 3 of the factor d_{36} means that the electric field is applied along the *Z* axis. The index 6 means that the crystal undergoes shift in the *XY* plane [6].

Piezoelectric material is characterized by occurrence of a polarizing charge with its mechanical deformation, and vice versa, if piezoelectric material is brought into an electric field, we can observe how its length changes. Electric polarization $P = D\text{-}\varepsilon_0 E$ which is connected with a surface charge, at the first approximation increases linearly in relation to mechanical stress σ. The material law is expressed as follows:

$$D = P + \varepsilon_0 E = d\sigma. \tag{6}$$

Electric biasing *D* and field intensity *E* are vectors, mechanical stress σ and deformation ε are tensors of the second rank. Consequently, the piezoelectric factor *d* is a tensor of the third rank. As the stress tensor is symmetrical, the piezoelectric factor tensor in the general case has 3×6=18 of independent components. In the componential representation we obtain the following ratios:

$$D = \begin{pmatrix} D_1 \\ D_2 \\ D_3 \end{pmatrix} = \begin{pmatrix} d_{11} d_{12} d_{13} d_{14} d_{15} d_{16} \\ d_{21} d_{22} d_{23} d_{24} d_{25} d_{26} \\ d_{31} d_{32} d_{33} d_{34} d_{35} d_{36} \end{pmatrix} \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{pmatrix} \tag{7}$$

The indexes 1, 2, 3 relate to crystal parameters, and they can be combined with the *x*, *y*, *z* coordinate directions with a corresponding orientation. For example, a positive value means that the extending stress in the z direction leads to a positive charge on the surface laying in the *z* direction.

The reverse or indirect piezoelectric effect provides a ratio between the intensity of electric field E and the mechanical deformation ε:

$$\begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{pmatrix} = \begin{pmatrix} d_{11}d_{21}d_{31} \\ d_{12}d_{22}d_{32} \\ d_{13}d_{23}d_{33} \\ d_{14}d_{24}d_{34} \\ d_{15}d_{25}d_{35} \\ d_{16}d_{26}d_{36} \end{pmatrix} \begin{pmatrix} E_1 \\ E_2 \\ E_3 \end{pmatrix} \tag{8}$$

Factors d_{ij} are identical to a direct piezoelectric effect. Electrostriction is defined as the effect of the second order; it depends on the square of electric field intensity, and is described by the fourth rank tensor

$$\begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{pmatrix} = \begin{pmatrix} d_{11}d_{21}d_{31} \\ d_{12}d_{22}d_{32} \\ d_{13}d_{23}d_{33} \\ d_{14}d_{24}d_{34} \\ d_{15}d_{25}d_{35} \\ d_{16}d_{26}d_{36} \end{pmatrix} \begin{pmatrix} E_1 \\ E_2 \\ E_3 \end{pmatrix} + \begin{pmatrix} \gamma_{11}\gamma_{12}\gamma_{13}\gamma_{14}\gamma_{15}\gamma_{16} \\ \gamma_{21}\gamma_{22}\gamma_{23}\gamma_{24}\gamma_{25}\gamma_{26} \\ \gamma_{31}\gamma_{32}\gamma_{33}\gamma_{34}\gamma_{35}\gamma_{36} \\ \gamma_{41}\gamma_{42}\gamma_{43}\gamma_{44}\gamma_{45}\gamma_{46} \\ \gamma_{51}\gamma_{52}\gamma_{53}\gamma_{54}\gamma_{55}\gamma_{56} \\ \gamma_{61}\gamma_{62}\gamma_{63}\gamma_{64}\gamma_{65}\gamma_{66} \end{pmatrix} \begin{pmatrix} E_1^2 \\ E_2^2 \\ E_3^2 \\ E_2E_3 \\ E_3E_1 \\ E_1E_2 \end{pmatrix} \tag{9}$$

It is characteristic of a piezoelectric effect that with the direction of an electric field changing the extending stress transits into the compressing stress. The electrostriction effect is related to the square of intensity of an electric field which means that it does not depend on polarity. Depending on a crystal structure, some piezoelectric factors become zero, or they can be equated to each other. The actual type of tensor for piezoelectric material is defined by the crystallographic class to which the material belongs. Crystal quartz belongs to the trigonal class: $d_{11} = -d_{12}$; $d_{14} = -d_{25}$; $d_{26} = -2d_{11}$, and the other factors vanish. Zinc oxide and aluminum nitride belong to the hexagonal class, wherein only factors $d_{31} = d_{32}$; $d_{24} = -d_{15}$ and d_{33} are different from zero. Crystals possessing the central symmetry (as silicon) or isotropic materials do not show any piezoelectric effect, however, electrostriction effect takes place in all such materials, including isotropic ones.

A particularly high piezoelectric factor is shown by ferroelectric ceramics. One of the features of any ferroelectric material is that it changes the properties at the Curie point T_c. At the temperature $T > T_c$ the crystal does not behave like a ferroelectric one, though until $T < T_c$ it is ferroelectric. Most of crystals can be in various crystal phases which are stable at different temperatures and pressure ranges. Transition between phases is accompanied by change of thermodynamic characteristics (elasticity, optical and thermal properties, volume, entropy, etc.). During transition, atoms move in such a way that a crystal changes one crystal class for another. In general, transition occurs at various temperatures, at heating and cooling (temperature hysteresis). Phase transition of the first order is distinguished by strong and abrupt changes in the crystal structure. During transition of the second order, changes are less strong, and transition is continuous. Phase transitions of the second order do not possess temperature hysteresis. Phase transitions are often accompanied by the presence of new physical phenomena (ferroelectric effect, ferromagnetism, superconductivity). For $BaTiO_2$, the Curie point is equal to 120^0C. Above this temperature $BaTiO_2$ belongs to a cubic crystal class and thus loses the ferroelectric and piezoelectric properties; below the Curie point the crystal is a tetragonal one. From 0 and up to -70^0C the further phase transitions occur from an orthorhombic to a trigonal crystal class. Change of the symmetry of a crystal group connected with a phase transition becomes the cause for occurrence of new factors in material tensor. Materials with a longitudinal deformation factor suitable for use cover minerals, monocrystal substances and polymers. Usually the piezoelectric effect is most vividly expressed in monocrystal substances. Among materials suitable for use in microsystems, the piezoelectric factor usually is within the range of $1 \div 100 \times 10^{-12}$ m/V.

With the maximum field intensity $E=10^7$ V/m, the relative longitudinal deformation is within the range of $\varepsilon r = 10^{-3} \div 10^{-5}$. As a result, the achievable range of control is small, but it is possible to very precisely operate shifting by means of voltage. Unlike the majority of other principles of activation, it is impossible to achieve a lower limit obtained at the atomic level. This feature is used in a raster tunnel microscope or in a microscope of atomic force, for receiving resolution lower than the nuclear diameter $10^{-10} \div 10^{-12}$ m.

The electromechanical relation factor k_p shows the share of mechanical energy which is transformed into electric energy. It applies both to direct and inverse piezoelectric effects.

$$k_p^2 = \frac{\text{Conversed energy}}{\text{Accumulated energy}}$$

Naturally, a high relation factor should be achieved for effective energy conversion. However, the relation factor cannot be equated to efficiency. As, in principle, restoration of accumulated energy is possible, consequently, efficiency can be much higher than a relation factor.

Designing systems for automatic control of piezoelectric scanners is related to calculating the level of potential reliability for possible variants of their realization. Construction of state-of-the-art microprocessor-based control systems characterized by multifunctionality of modules stipulates the importance of development of methods for estimating reliability that takes into account interdependence of events causing piezoelectric modules to lose their abilities to carry out various functions.

The results obtained in this respect basically concern piezoelectric modules (nodes) whose failure leads either to loss of ability to perform all their functions simultaneously, or to one function only. This paper offers some methods of estimating reliability of scanners made up of multifunctional piezoelectric units with an arbitrary type of overlapping of nanotechnological equipment involved in performing various functions.

The problem is formed as follows. Let a piezoelectric scanner PS performing the function $F = F = \{f_1, f_2, \ldots, f_n\}$ consists of m multipurpose piezoelectric units (MPU), each in initial state performing a set of functions $\{f_1, f_2, \ldots, f_n\}$. For each nanotechnological device, denote as Φ_1 a set of piezoelectric units involved in performing the function f_l. In general, the sets $\Phi_1, \Phi_2, \ldots, \Phi_n$ can be crossed, with that leading to interdependence of events and causing nanotechnological equipment to lose the ability to perform various functions. As to types of overlapping of the sets $\Phi_1, \Phi_2, \ldots, \Phi_n$, sort out the following structures of MPU [7]:

$$(\exists i)(\exists j)[(i \neq j) \rightarrow \Phi_i \cap \Phi_j \neq \acute{\varnothing}]; \tag{10}$$

$$(\forall i)(\forall j)[(i \neq j) \rightarrow \Phi_i \cap \Phi_j = \acute{\varnothing}]; \tag{11}$$

$$(\forall i)(\forall j)[(i \neq j) \rightarrow \Phi_i \cap \Phi_j = \Omega], \tag{12}$$

where $i, j \in N$, $N = \{1, 2, 3, \ldots, n\}$.

MPU structure (10) is characterized by independence of events relating to nanotechnological equipment to lose its ability to perform various functions. MPU structure (11) corresponds to an arbitrary type of the overlapping sets Φ_1, Φ_2, …, Φn, with MPU structure (12) being a particular case in relation to (11). In MPU structure (11) there are some common piezoelectric units Ω whose failure leads to a complete failure of nanotechnological equipment, and piezoelectric units $\Phi_i \setminus \Omega$ (i = 1, 2, …, n) whose failure leads to failure of nanotechnological equipment to perform only one function f_i. The sets $\Phi_i \setminus \Omega$ are not overlapped.

The prerequisite of PS availability is the ability to perform the functions $F = \{f_1, f_2, \dots, f_n\}$. With that said, each function $f_i \in F$ should be performed at least by one MPU, and the waiting time of service of inquiries for performing the functions $f_i \in F$ should be no more than the specified maximum acceptable value. The reliability of PS will be defined using the probability of failure-free operation.

Estimation of PS failure-free operation probability. Let us consider PS for which the condition of availability consists in the possibility of performing each function $f_i \in F$ at least in one MPU. The probability of failure-free operation will be estimated on the basis of a known probabilistic combinatorial method of inclusion and exclusion [8] allowing us to obtain precise estimation as well as approximate estimation with a required inaccuracy.

For MPU of type (11), the probability of PS failure-free operation P is estimated as

$$P = \sum_{i \in N} P(f_i) - \sum_{\substack{i,j \in N \\ i \neq j}} P\left(f_i \vee f_j\right) + \sum_{\substack{i,j,l \in N \\ i \neq j \neq l}} P\left(f_i \vee f_j \vee f_l\right) - \dots$$

$$+ (-1)^d \sum_{\substack{i,j,\dots,a \in N \\ i \neq j \neq \dots \neq a}} P\left(f_i \vee f_j \vee \dots \vee f_a\right) - \dots + (-1)^n P\left(\bigvee_{i=1}^{n} f_i\right) \tag{13}$$

where $P\left(f_i \vee f_j \vee \dots \vee f_a\right)$ is probability of the event that at least one function from a set of functions $\{f_i, f_j, \dots, f_a\}$ in PS can be executed

$$P\left(f_i \vee f_j \vee \dots \vee f_a\right) = 1 - \left[1 - p\left(f_i \vee f_j \vee \dots \vee f_a\right)\right]^m.$$

The probability of the event that PS keeps the ability to perform at least one function from a set

$$p(f_i \vee f_j \vee \dots \vee f_a) = \sum_{i \in N} p(f_i) - \sum_{\substack{i,j \in N \\ i \neq j}} p(f_i \wedge f_j) +$$

$$\sum_{\substack{i,j,l \in N \\ i \neq j \neq l}} p(f_i \wedge f_j \wedge f_l) - \dots + (-1)^d \sum_{\substack{i,j,\dots,a \in N \\ i \neq j \neq \dots \neq a}} p(f_i \wedge f_j \wedge \dots \wedge f_a), \tag{14}$$

where $N_1 = \{i, j, \dots, a\}$, $p\left(f_i \wedge f_j \wedge \dots \wedge f_a\right)$ is probability of the event that the piezoelectric unit involved in performing the functions $f_i, f_j, \dots, f_a$ in nanotechnological equipment is in good state.

The value $p\left(f_i \wedge f_j \wedge \dots \wedge f_a\right)$ is defined as the probability of serviceability of piezoelectric units $\Phi_1 \cup \Phi_2 \cup \dots \cup \Phi_a$

For exponential distribution of time to failure

$$p\left(f_{ü} \wedge f_j \ \wedge \ ... \ \wedge f_a\right) = \exp\left(- \wedge \left(\Phi_1 \cup \Phi_2 \cup \ ... \ \cup \Phi \ \ \right) t\right),$$

where $\Lambda\left(\Phi_1 \cup \Phi_2 \cup \ ... \ \cup \Phi_a\right)$ is total failure rate of MPU involved in performing the functions f_i, $f_j, \ldots, f_a$; t; t is operating time.

For MPU of type (12), the probability of PS failure-free operation is calculated as

$$P = \sum_{k=1}^{m} C_m^k p_\Omega^k \left(1 - p_\Omega\right)^{m-k} \prod_{i=1}^{n} \left[1 - \left(1 - p_i\right)^k\right], \qquad (15)$$

where p_Ω is probability of failure-free operation of piezoelectric units making a set Ω; p_i is probability of failure-free operation of piezoelectric units relating to a set $\Phi_i \setminus \Omega$.

If the possibility of piezoelectric units losing various functions is equiprobable ($p_i = p_j = p$), then

$$P = \sum_{k=1}^{m} C_m^k p_\Omega^k \left(1 - p_\Omega\right)^{m-k} \left[1 - \left(1 - p_i\right)^k\right]^n.$$

For MPU of type (10), the probability of PS failure-free operation is calculated as follows

$$P = \prod_{i=1}^{n} \left[1 - \left(1 - p_i\right)^m\right].$$

Let us consider the probability of failure-free operation of some structure, with service time limiting taken into account.

Let w_0 be specified as a maximum acceptable average waiting time of servicing requests to perform the functions $f_i \in F$, $i \in N$. Each piezoelectric unit will be represented as the elementary system of mass service of M/M/1 type [9]. Now define the number of piezoelectric units m_0 at which requests are served with acceptable average time as follows

$$m_0 = \rho\left(1 + \frac{v}{w_0}\right),$$

where $\rho = v\lambda$;
λ is total rate of requests to perform the functions $f_i \in F$;
v is average time of their performance.

Let us assume that PS is operable, if the ability of performing each type of the functions $f_i \in F$ is kept at least by m_0 of MPU. In this case the probability of PS availability is defined by the formula (13), differing in that $P(f_i \vee f_j \vee \ldots \vee f_a)$ is the probability of the event that at least one function from a set $\{f_i, f_j, \ldots, f_a\}$ can be executed not less than by m_0 of piezoelectric units [10]:

$$P\left(f_i \vee f_j \vee \ldots \vee f_a\right) = \sum_{g=m_0}^{m} C_m^g p\left(f_i \vee f_j \vee \ldots \vee f_a\right)^R \times \left[1 - p\left(f_i \vee f_j \vee \ldots \vee f_a\right)\right]^{m-g},$$

where the probability $p(f_i \vee f_j \vee \ldots \vee f_a)$ is calculated by the formula (14).

For direction of the total flow of m_0 MPU requests, calculation of the value m_0 leads to the lower (pessimistic) estimation of the probability of PS availability.

For MPU of type (12), the probability of PS failure-free operation is calculated as

$$P = \sum_{k=m_0}^{m} C_m^k p_\Omega^k \left(1 - p_\Omega\right)^{m-k} \prod_{i=1}^{n} \left[\sum_{s=m_0}^{m} C_t^s \left(1 - p_i\right)^{k-s}\right], \tag{16}$$

For MPU of type (10) the probability of PS failure-free operation is

$$P = \prod_{i=1}^{n} \left[\sum_{s=m_0}^{m} C_m^s p_t^s \left(1 - p_i\right)^{m-s}\right].$$

Let us estimate the probability of PS failure-free operation with MPU functional heterogeneity.

PSs considered so far were assembled from identical MPUs. Now move over to PS containing z types of MPU different as to lists of functions performed. Assume that sets of the functions which are performed by MPUs of various types are not overlapped. In this case the set of functions carried out in PS and a set of MPUs can be divided in z non-overlapped subsets which allows us to estimate the probability of PS failure-free operation as

$$P = \prod_{i=1}^{z} P_i,$$

where Pi is probability of failure-free operation of PS subsystem including MPU of the *i-th* type (as per functional composition).

The value P_i is calculated by the formulas presented above for PS with functionally homogeneous piezoelectric units.

The estimation of probability of failure-free operation by the method of inclusion and exclusion for PS made up of piezoelectric units of general type (11) is connected with complicated calculations. It is easier to obtain the approximate estimation of failure-free operation probability by representing the structure of piezoelectric units of type (11) as the structure of piezoelectric units of type (12).

For the lower (pessimistic) estimation of the probability of failure-free operation, we shall assume that for transformation of nanotechnological equipment to the MPU structure Ω, we have piezoelectric units $\Phi_i \setminus \left(\bigcap_{j=1}^{n} \Phi_j\right) \bigcup \left(\bigcup_{k=1}^{i-1} \Phi_k\right)$, that is, failure of any piezoelectric unit involved in performing more than one function causes failure of the entire nanotechnological equipment.

For the upper (optimistic) estimation of failure-free operation probability, for the structure of nanotechnological equipment transformed into the MPU structure Ω whose failure causes failure of the entire nanotechnological equipment, we have piezoelectric units $\bigcup_{i=1}^{m}\Phi_i$.

The tasks of a piezoelectric unit used for realization of several (but not all) functions are distributed among the non-overlapped sets $\Phi_i \setminus \Omega$. For example, there is a possible distribution when the piezoelectric unit $\Phi_i \setminus \Omega$ includes $\Phi_i \setminus \left(\bigcap_{j=1}^{n}\Phi_j\right) \bigcup \left(\bigcup_{k=1}^{i-1}\Phi_k\right)$. It should be noted that the more even (as to total failure rate) the distribution of piezoelectric units is on the set $\Phi_i \setminus \Omega$, the more optimistic the upper estimation is.

Relative error of the offered estimation is

$$\delta = 0{,}5\frac{P_B - P_H}{P_H},$$

where P_B and P_H are probabilities of PS failure-free operation calculated by the formula (15) or (16) when representing the MPU structure for the upper and lower estimations respectively.

The estimated error of the offered method depends on the evenness of distribution of piezoelectric units on a set $\Phi_i \setminus \Omega$, with this being minimal for the case of the most uneven distribution.

If the obtained accuracy of calculations is insufficient, then it is possible to refine it based on the method of inclusion and exclusion which, though rather bulky in terms of calculations, allows us to reach any required approximation. The approximate estimation using the method of inclusion and exclusion is made on the basis of the formula (13) taking into account that when restricting the accuracy of calculations up to a term with the plus sign we obtain the upper estimation, and when restricting to the minus we obtain the lower estimation [10].

Series and parallel arrangement of piezoelectric units.

Reliability of MPU systems depends on a system of automatic control of these piezoelectric units, and as a whole, on PS automatic control, as well as on reliability of piezoelectric units operation wherein electric energy is conversed into mechanical one.

All PSs can be divided into structures with series, parallel and serial-parallel connection of piezoelectric units. For series connection of piezoelectric units (fig. 3.), the error of PS positioning represents the vector

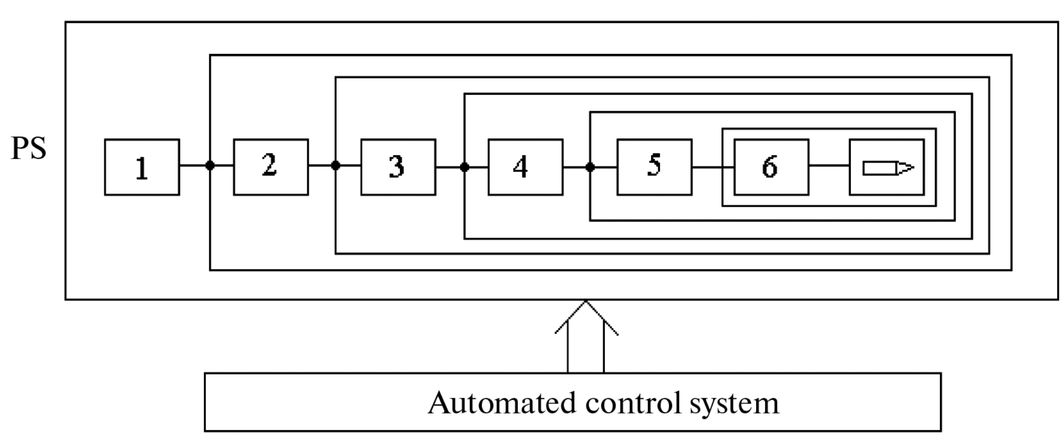

Fig. 3. Block diagram of PS with a series arrangement of piezoelectric units

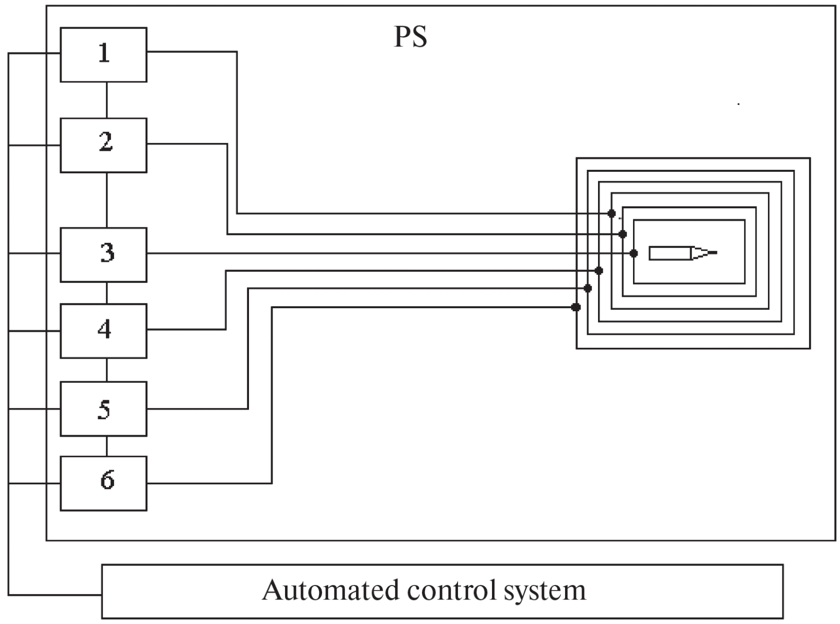

Fig. 4. Block diagram of PS with a parallel arrangement of piezoelectric units

sum of errors along all the degrees of mobility. For parallel connection of piezoelectric units (fig. 4.), as it takes place, for example, in piezoelectric scanners (PS) on the basis of *l*-coordinates, the error of the position of one piezoelectric unit is independent of that of other PSs. This is a big advantage of such PSs in terms of the accuracy of a work tool's position.

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