Automated system for monitoring and predicting the state of photoelectronic separators complex for processing agricultural raw materials

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Abstract. The paper proposes an automated procedure for assessing the actual state of photoelectronic separators in real time. Random process outliers over tolerance zones are proposed as the main controlled parameter. In contrast to traditional methods, several threshold levels are used to provide the flexibility of control and forecasting. Measurement of the amplitude and duration of the outliers of random processes over the tolerance zones helps to collect statistical samples, which become the basis for statistical models in the form of distribution law. The automated system makes it possible to identify the distribution law by classical methods if the samples are of sufficient statistical volume.

1. Introduction

In modern economic conditions, the rational use of natural resources is a strategic task of the national government. The negative impact of many technological factors on the environment led to the development and adoption of the strategy of adaptive intensification of agriculture and environmental management [1, 2]. This strategy involves the improvement of plant protection (primarily cereals) against pests and diseases, which should guarantee the country’s food security. An increase in grain yield and the production of environmentally friendly foods directly depends on the quality of the seeds. To ensure high yield of seeds, control should be carried out at every production stage, from preparing seeds for sowing to their cleaning before storage or packaging for sale.

Evaluating the quality of seed material is a time-consuming and tedious task, which is done manually in state seed inspections. In addition to time losses and many subjective factors that affect the results of analyzes, the existing technology has a negative effect on the health of workers conducting these analyzes.

To perform high-quality final cleaning, it is necessary to use modern highly automated tools. The proper organization of the cleaning process allows removal of all substandard seeds remaining from previous operations as well as extraneous inclusions. The result is homogeneous product, which, after a visual inspection, is ready for packaging or storage. Automation of the last seed processing stage is achieved using photo separators – machines for sorting out the seeds according to color parameters. Ensuring high reliability
and efficiency of the operation of photoelectronic separators used in the final cleaning of seed material is a topical task. If successfully solved, many economic and technical indicators of this process can be improved dramatically.

Modern industrial technological equipment used in agriculture is characterized by high cost and increased requirements for the quality of operation, operational safety, maintainability and restorability in case of possible failures [3-5].

Scheduled maintenance is a prerequisite for the stable operation of technological and technical objects and systems of any agro-industrial complex; however, for low-inertia systems such as photoelectronic separators used in heavy duty operation, maintenance alone may prove insufficient to ensure the required reliability, safety, and quality indicators. In addition, the periodicity of maintenance is determined based on the design calculations of reliability which do not necessarily correspond to the actual performance indicators for the following objective reasons:

- standard guidelines for determining the reliability of photo-separator systems are based on the use of \( \lambda \)-characteristics (failure rates). For highly reliable, complex technical systems, the determination of \( \lambda \)-characteristics can be rather inaccurate due to the high cost of these systems and limited time resources for testing;
- during operation, the equipment is exposed to destructive effect of various environmental and industrial factors, which generates a systemic effect that is not taken into account in design calculations, where various types of impacts are traditionally studied independently of each other. Ignoring the systemic effect [6-8], leads to significant errors in assessing the reliability and quality of operation of industrial equipment.

In view of the above, in addition to scheduled maintenance, it is advisable to perform maintenance and repair on demand, depending on the actual state of equipment, as well as to forecast the state of technological objects in real time. This may prevent serious accidents and failures, therefore minimizing financial losses associated with the elimination of the consequences of hardware failures.

2. Problem formulation and analysis

There are various ways to solve the problem outlined above: in [9-11], the use of original design solutions is proposed; the creation of specialized tools for monitoring and diagnosing the state of photoelectronic separators, the use of redundancy and highly reliable blocks and subsystems of the separator is suggested for use in [10]. Each of these solutions allows achieving a certain effect. One of the priority areas for improving the reliability and safety of operation of agricultural equipment is the automation of technological processes. The design and construction of automated systems embedded in industrial complexes to monitor and predict the state of technological equipment and lines, as well as parts and units of machines and mechanisms is particularly important.

The reliability and efficiency of using a modern photo separator is largely determined by the quality of information management systems, functional capabilities for the timely detection of malfunction and failures, state forecasting, and prevention of emergencies. The existing experience obtained during the design and operation of photo separators [8, 9, 14], showed that monitoring the status of systems, processing information flows, and making management decisions no longer meet modern requirements, while the state forecasting function is often not implemented at all. Known approaches to solving the problems of predicting the state of complex technical objects are reduced to the use of design calculations of reliability indicators such as the average product life, MTBF, etc. In addition, the of a systemic effect occurring as a result of the negative impact of various production factors (elevated temperatures, incorrect actions by the operating personnel,
high level of pollutant particles in the air, high humidity) is not taken into account. Obviously, in these conditions, it is necessary to assess the actual state of the equipment in real time.

An equally important problem is the collection of primary information about equipment failures and malfunctions. Modern high-tech equipment [12, 13] is designed to be highly reliable and for the long-term use. As a result, the amount of statistical data on failures is extremely small. Using standard methods for processing statistical data represented by shortened samples or samples of critically small volume is not acceptable; therefore, special models for processing small samples are required.

The aim of the study is to develop an automated system for monitoring and predicting the state of photoelectronic separators, which allows evaluating the residual reliability resources and predicting the condition of the equipment in real time. This will allow timely preventive and/or repair work, and prevention of accidents.

The mathematical basis of the proposed models is the applied theory of random function outliers, the theory of reliability, the theory of statistics of small samples [15-18].

Let the industrial object under study (photoelectronic separator) be represented by $M$ independently controlled parameters $x_i(t), (i = 1, M)$ with the corresponding tolerances of the operating $[x_i^{\text{low}}, x_i^{\text{up}}]$ and emergency $[x_i^{\text{low, em}}, x_i^{\text{up, em}}]$ ranges [18]. We assume that the selected set of parameters ensures complete observability of the object. Changes in controlled parameters over time are responses to the integral effects of the external environment and are described by random functions. The limits of changes in which the product can be considered workable are set by the values of tolerance areas. Each parameter is a continuous random function $x_i(t, \xi, S)$ of time $t$, dynamic state $S$, and operating mode $\xi$. Obviously, the process of normal functioning corresponds to a change in the random process within the working tolerance zones, while the destructive effects of the external environment cause random outliers from the tolerance zones. We assume that a decrease or disappearance of the destructive effect will lead to the return of the controlled parameter into the tolerance zone. The destructive effect of negative factors on an industrial facility can be reflected by the sequence of outliers of random processes over the tolerance zone, which can be characterized by two samples of small volume — the amplitudes and, accordingly, the durations of the outliers of the random function over the tolerance zone [17].

The onset of instantaneous failure is characterized by a single outlier of any parameter value beyond the emergency tolerances, i.e. $x_i(t, \xi, S) \notin [x_i^{\text{low, em}}, x_i^{\text{up, em}}]$, whereas the process of destructive impact is characterized by a sequence of outliers $X = \{x_1(t, \xi, S), ..., x_N(t, \xi, S)\}$ of values of one or more controlled parameters beyond the boundaries of working tolerances $[x_i^{\text{low}}, x_i^{\text{up}}]$. The ranges $[x_i^{\text{low}}, x_i^{\text{low, em}}], [x_i^{\text{low}}, x_i^{\text{up, em}}]$ are split into $q$ quantization levels, which allow integer-valued display of the magnitude of the outlier amplitude and a simple statistical calculation. These values will also be used to determine the transition intensities in the model in the form of states of a probability-oriented graph. The transition from one state to another will be represented by the intensity of the outlier amplitude entering the quantum region (figure 1).
The most important outlier parameters include [7, 18]: 1) the average values of the probability characteristics of the outliers (average value, variance, probability density, the intensity of the intersection of a certain number of quantum levels by the outlier path $x_i = n_i/N$, where $N$ is the size of outlier sample, $n_i$ is the number of outliers, whose amplitude reached the $i$-th quantization level); 2) probability characteristics of the duration of the outliers $\tau(x_i)$ of the random process $x_i(t)$ over a given level; 3) probabilistic characteristics of the values of the outlier amplitudes $A(x_i)$ (maximums and minimums).

The transition from continuous random functions showing the values of the controlled parameters to a set of discrete value arrays of the probability characteristics of the outliers of a random process allows creating a procedure for automated control and prediction of the state of technological objects based on the following models:

- Markov approximation of parameter changes;
- approximation of reliability indicators by calculating the characteristics of the outliers of the value trajectories of the controlled parameters;
- additive approximation of parameter values by symmetric distributions (contributions);
- interpolation of limited data in the basis of limited polynomials.

Thus, the problem of assessing and predicting the reliability of technological equipment is reduced to determining the probabilistic characteristics of the time that random functions take to reach the parameters of the boundaries of the tolerance areas, the deviations of the trajectories of the parameters from the boundaries of the tolerance areas and the time spent outside them. The functioning of the automated control system in real time is ensured using processing methods for small samples, while the increase in the reliability of the results is achieved using alternative models and the majority principle of decision making.

3. Problem solution

To process arrays of amplitudes and durations of outliers of controlled parameters, we apply the techniques of statistical processing for limited-volume samples proposed in [18, 19]. The experimental determination of the probability characteristics of the outliers of random processes of controlled parameters must be carried out using non-traditional methods, because due to the high reliability of the equipment and the requirement that monitoring of the system were conducted in real time, the number of recorded emissions $N$ cannot be large (typically, $N = 5 \div 10$); correspondingly, the arrays of diagnostic data $A(x_i), \tau(x_i)$, will be small samples that cannot be processed by traditional methods.
Additive approximation method. There are special methods for processing arrays of small samples [22], in which an estimate of the probability distribution density is presented as the sum of standard distributions $f_0(x_i)$ and $\psi_{x_i}(x_i^{(j)})$:

$$f^*_i(x) = \frac{1}{N+1} \left( f_0(x_i) + \sum_{j=1}^{X} \psi_{x_i}(x_i^{(j)}) \right)$$

(1)

where $f_0(x_i)$, $\psi_{x_i}(x_i^{(j)})$ are the a priori and empirical components, respectively, which are used as symmetric distributions, called contributions. For example, in the method of rectangular contributions as $f_0(x_i)$, $\psi_{x_i}(x_i^{(j)})$ a uniform distribution is used, while in the method of triangular contributions the Simpson distribution is used. An empirical histogram of the distribution density $f^*_i(x)$ is constructed by geometric summation of the contributions. A prerequisite is that $x_i \in [x_i^{\text{up}}, x_i^{\text{up}}, x_i^{\text{low}}, x_i^{\text{low}}]$ is limited by the range of the standard data volume, which is an additive superposition of $(N+1)$ pseudo-realizations, the main of which is evaluated using well-known agreement criteria, for example, Pearson’s agreement criterion. The values of the contributions that go beyond the tolerance region are uniformly redistributed within the region.

Thus, (1) is an empirical function of the probability density of the outliers of the value of the parameter $x_i(t)$ beyond the tolerance zone.

The simulation method. Each sample value $x_i^{(j)}$, $j = 1, N$, $i = 1, k$ of random process X is equated to the mathematical expectation of a random variable and in the d-neighborhood of these values, equally distributed pseudorandom numbers are generated. Thus, a transition is made from a small sample ($N = 5+10$) to a sample of the standard data volume, which is an additive superposition of $(N+1)$ pseudo-realizations, the main of which is limited by the range $[x_i^{\text{up}}, x_i^{\text{up}}]$, $[x_i^{\text{low}}, x_i^{\text{low}}]$ with mathematical expectation $0.5(x_i^{\text{up}} - x_i^{\text{up}})(0.5(x_i^{\text{low}} - x_i^{\text{low}}))$. Such a sampling model makes it possible to construct an empirical histogram according to the principle of classical statistics, to determine estimates of the standard deviation and mean value of the process X, asymmetry and excess coefficients, etc.

To identify the empirical function, a modified multimodel method is used, according to which a finite set (bank) of standard distribution laws in differential and integral forms corresponding to certain technical conditions of the equipment set is used. The degree of proximity of the empirical and theoretical distributions is evaluated using well-known agreement criteria, for example, Pearson’s agreement criterion. The values of the Pearson agreement criterion for different models are presented in the form of a non-decreasing ordered series: $P_1(x^2, r) > P_2(x^2, r) > ... > P_k(x^2, r)$. The maximum (first) element of the series indicates the most appropriate statistical model of the controlled parameter.

Simultaneous processing of arrays of amplitudes and durations of emissions of controlled parameters allows us to obtain statistical models in the form of density functions of distributions $f_i(A)$ and $f_i(\tau)$ with confidence $P_i(x^2, r)$. Now, statistics on each $i$-th parameter can be represented by the two-dimensional probability density distribution of the parameter $x_i(t, \xi, S)$ going beyond the tolerance zone $[x_i^{\text{low}}, x_i^{\text{up}}]$ under the assumption that the amplitude and duration are obviously dependent quantities:

$$f_i(A, \tau) = f_i(A) \times f_i(\tau|A) = f_i(\tau) \times f_i(A|\tau)$$

(2)

where $f_i(A)$ is the density distribution of the amplitudes of the outliers of the $i$-th parameter over the tolerance zone; $f_i(\tau/A)$ is the conditional density distribution of the duration of the outlier of amplitude $A$ over the tolerance zone.
The Markov model. Since the control object is operated in random dynamic modes, we present a particular model of the i-th controlled parameter as an inhomogeneous Markov model of reliability for three states. The graph of the model is shown in figure 2, where S₀, S₁ are operation states, S₂ is a failure state; η₀(t) are η₁(t) are the intensities of deterioration of the controlled parameter or gradual failures; λ₀(t) is the intensity of sudden failures. Intensities η₀(t), η₁(t), λ₀(t) in the general case are functions of time, and if λ₀(t) can be determined at least approximately from the test results (equipment passport data), then there is no acceptable methodology for determining η₀(t), η₁(t) from small-volume statistics on the outliers of random functions of controlled parameters beyond tolerance limits.

![Figure 2. The model of the i-the controlled parameter.](image)

The intensities η(t) of gradual failures are proposed to be determined as follows: the j-th level of quantization (j=1, q) is singled out, relative to which the outliers of a random function characterizing the time variation of the i-th controlled parameter are recorded. Obviously, the j-th quantization level uniquely determines the magnitude of the outlier amplitude, then based on the two-dimensional probability density function (2) we obtain the conditional distribution and the conditional distribution density of the outlier duration of the i-th controlled parameter over the j-th quantization level F_i(τ|A_j) and f_i(τ|A_j). The intensity of the gradual failure of the system corresponding to the i-th controlled parameter can be set in the form [19]:

\[ \eta_i(t) = \frac{f_i(\tau | A_j)}{F_i(\tau | A_j)}. \]

After determining the parameters of the inhomogeneous Markov model η₀(t), η₁(t), λ₀(t), it is possible to compose and solve a system of Kolmogorov-Chapman stochastic differential equations. The solution of this system for the i-th controlled parameter allows us to determine the probabilities of an individual element (block) being in different states. The reliability characteristics of the separator are determined using the results of the study of all controlled parameters.

The polynomial interpolation model. When processing statistical data on outliers of a random process, the proposed methods did not account for the sequence of their appearing; therefore, it was difficult to assess trends in outliers’ increases or decreases. In this regard, a polynomial interpolation model is proposed, which allows predicting the values of the outlier parameters, which will become the basis for making decisions on the technical condition of the separator and the need for preventive actions to avoid possible failures.

In accordance with the proposed method, the studied parameter (duration τ or outlier amplitude A) is displayed in the coordinate system (τ, T_n) or (A, T_n), where T_n is the observation time of the controlled parameter. In the coordinate system (τ, T_n) the empirical values of the durations of 5 outliers, found by time t_i are presented as interpolation nodes. Using interpolation, through the points belonging to one sample we can construct a random function f(τ₁, τ₂, …), called the implementation of an empirical random process. The interpolating functions may be different, but they must satisfy the computability properties of values τ for any time values, computational stability when new outlier data are input, and function smoothness.
The results of the interpolation depend on the degree of the interpolating polynomial. Interpolation was carried out using linear, parabolic functions, Lagrange functions and spline functions. Studies have shown that with a degree of polynomial less than the third, in almost all cases, testing the hypothesis for agreement between the original and the obtained laws of the distribution of probability densities of intervals gives positive results. The best coincidence of the laws occurs when interpolating with cubic spline functions.

An empirical random process of changing the time values of the parameter trajectory outside the tolerance zones is used to predict the estimates of the separator reliability indicators by the i-th parameter. This method allows accounting for the dynamic nature of the empirical random parameter, since the type of the predicted distribution function of its parameter depends on the type of the distribution function of the random value of the trajectory's residence time outside the tolerance zones. The algorithm for predicting the moment and nature of the next outlier is simple to implement and has a clear geometric interpretation.

4. Conclusions
Based on our research, the following main points and practical results can be distinguished:

- A method for monitoring the state of operability of a photo separator is proposed, based on quantization by the level of a random function of a controlled parameter and modeling of degradation processes.
- Outliers of random functions beyond the tolerance limits characterizing the temporal change of the state of the photo separator were used as a controlled parameter. The values of amplitudes and durations of outliers were used as statistical data, as the most informative features.
- The effective functioning of the monitoring and predicting system in the conditions of limited data is ensured using a modified multimodel method, in which unconventional algorithms processing small samples are implemented.
- The multimodel approach involves the use of the following specific models and methods: 1) graphical models that implement the additive approximation method for sample values by symmetric standard distributions, followed by the adoption of the reliability distribution hypothesis based on the known agreement criteria; 2) the method of simulation modeling, consisting in the generation of random variables distributed according to the law of symmetric standard densities of probability distributions in the neighborhood of each sample value on the area of a predetermined dispersion; 3) the reliability assessment is carried out by displaying the trajectory of random processes of the parameters of the photodetector in the form of probability-oriented graphs and the corresponding systems of Kolmogorov differential equations; 4) the method of interpolating the values of the amplitudes and durations of the outliers of the controlled parameters outside the tolerance zone by the most effective interpolation polynomial with the subsequent reliability assessment for each parameter. Interpolation of values of amplitudes and durations of outliers allows predicting their next values.
- The final assessment of the reliability of the separator is carried out by comparative analysis of the reliability indicators for the presented models.

Acknowledgements
The research was carried out in the framework of the project "Creation of high-tech production of hardware and software systems for processing agricultural raw materials based on microwave radiation" (SFU Agreement no. 18 of 20.09.2019, work number in SFU no. X/D19-25-RT).

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