

## Method of machine reliability optimization using integral indicator

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*Introduction.* For a long time, the issues of improving the reliability of machines using the integral indicator have remained relevant. The operation of hydromechanical excavator elements is considered from the standpoint of structural safety.

*Problem Statement.* The paper shows the method and algorithm used to calculate the stretching of the excavator implement.

*Theoretical Part.* The study has identified the ways to improve reliability using the integral reliability indicator. The authors have obtained the equations: for the steel fatigue strength; for the stress concentration factor; for the effective stress in the dangerous section and the stretch life. The distribution of methods for managing the integral reliability indicator by the stages of the machine's life cycle is presented. It is noted that in order to obtain an optimal strategy for improving the excavator reliability, it is necessary to minimize the value of the integrated reliability indicator. The method of complex analysis of input factors is developed, and for serial and mass production — a general set of recommendations for increasing the component life. The distribution of disadvantages by structural, technological and operational factors for shafts, axles, gears, metal structures, chains, and special parts is obtained. The methodology for creating virtually trouble-free machines, including principles, a comprehensive program and a reliability management system, is described.

*Conclusion.* The use of the proposed system makes it possible to develop and manufacture high-reliability machines and to ensure a systematic reduction in the integral reliability indicator. The functioning of the machine reliability management system guarantees their creation with the same level of reliability, which will ensure the competitiveness of the equipment and the absence of consumer complaints.

**Key words:** reliability of machines, integral reliability indicator, gamma-percentile life.

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**Introduction.** Early failures during operation of the machine significantly reduce its life. Moreover, failures can provoke situations that affect the safety of special equipment operation. Thus, an urgent issue is to improve the reliability of the machine using an integral indicator. Operation of elements of the EO-4117 hydro-mechanical excavator is considered from the point of view of structural safety.

**Problem statement.** This paper shows the method and algorithm used to calculate the stretching of the EO-4117 excavator implement [1-3].

### Theoretical part

**Determination of ways to improve reliability with an integral reliability indicator.** Empirical integral distribution curves of the parameters are approximated by the curve parameter of the Weibull law, and the  $i$ -th parameter value is calculated according to the formula

$$X = C + A\sqrt[3]{-\ln P(x)} \quad (1)$$

using probability values  $P(x) = 1 - F(x)$  of a random value, which is calculated using a table of uniformly distributed random numbers between 0 and 1 (random number generator).

The resulting equations are presented below.

— For the endurance limit of steel 15HSND:

$$F(\sigma_{-1}) = 1 - \exp \left[ - \left( \frac{\sigma_{-1} - 168,8}{6,04} \right)^{2,57} \right]. \quad (2)$$

— For the stress concentration coefficient (from the roughness of the stretch surface):

$$F(k_{F\sigma}) = 1 - \exp \left[ - \left( \frac{K_{F\sigma} - 0,85}{0,07} \right)^{2,65} \right]. \quad (3)$$

— For operating voltage in a dangerous stretch section:

$$F(\sigma_{ce}) = 1 - \exp \left[ - \left( \frac{65,0 - \sigma_{ce}}{12,1} \right)^{2,32} \right]. \quad (4)$$

— For a stretch resource:

$$F(T_p) = 1 - \exp \left[ - \left( \frac{T_p - 10,1}{28,1} \right)^{1,49} \right]. \quad (5)$$

Having considered the structure of the integral reliability indicator and analyzed the results of calculations of individual reliability indicators, we have established controlled indicators (parameters). Control actions for changing the values of managed indicators are ways (measures) to improve reliability (table 1)

Table 1

Distribution of methods for controlling the integral reliability indicator by stages of the machine life cycle

Methods for controlling the integral reliability indicator	
Development stage	<ol style="list-style-type: none"> <li>1. Increasing the resource of parts of the limiting group.</li> <li>2. Optimization of the range and quantity of spare parts.</li> <li>3. Optimization of differences on the parameters of parts that cause resource dispersion.</li> <li>4. Increasing the frequency and reducing the volume of maintenance operations.</li> <li>5. Optimization of the range and quantity of spare parts, tools and accessories.</li> <li>6. Adjusting the machine design to reduce the complexity of replacing parts and assembly units.</li> <li>7. Optimization of the resource, weight and cost of parts with fatigue failures.</li> <li>8. Reducing the metal content of parts and assembly units that do not fail for the resource (service life).</li> <li>9. Optimization of the machine diagnostics system.</li> <li>10. Optimization of the volume and frequency of preventive replacement of parts (assembly units).</li> <li>11. Optimization of the volume and frequency of the current repair of the machine.</li> </ol>
Production stage	<ol style="list-style-type: none"> <li>12. Introduction and optimization of: <ul style="list-style-type: none"> <li>— input control of main materials and components;</li> <li>— operational control of manufactured parts;</li> <li>— output (acceptance) control.</li> </ul> </li> </ol>
Operation stage	<ol style="list-style-type: none"> <li>13. Selective implementation of methods from 1 to 11 based on the analysis of operational information about the reliability of serial (mass) machines in various operating conditions.</li> </ol>

The structures of the integral reliability indicator and ways to increase the reliability of the excavator and reduce its integral indicator are synthesized (Fig. 1).

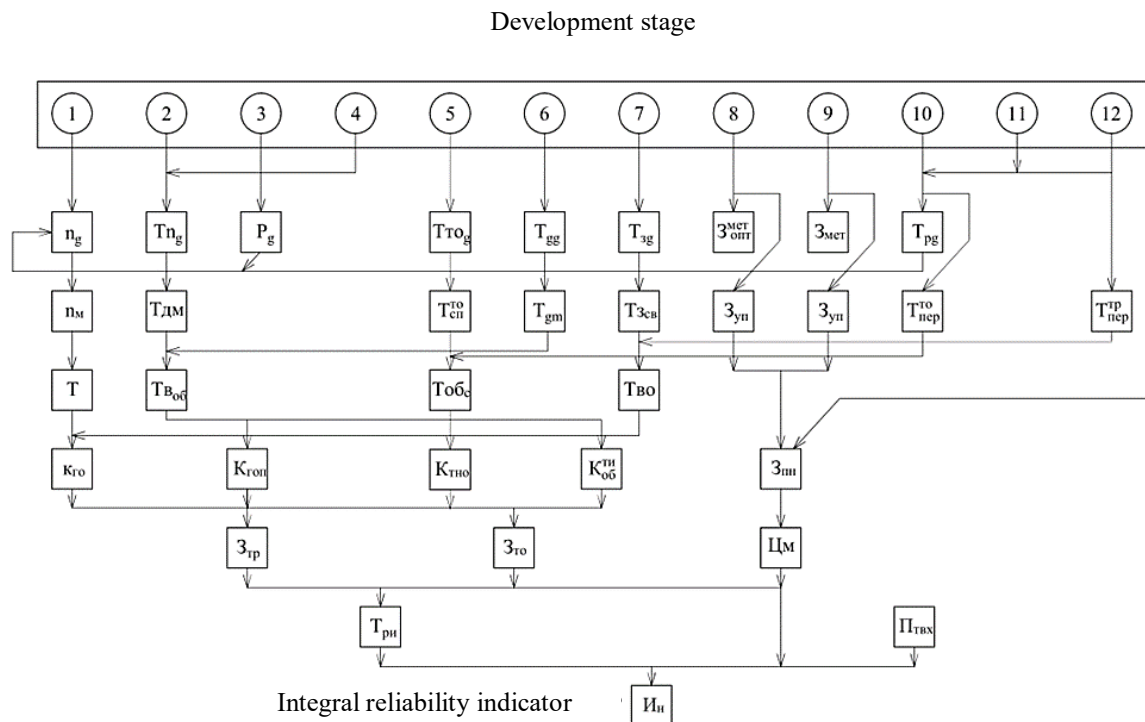


Fig. 1. Relationship of methods for increasing reliability with the integral reliability indicator

**Determination of integral indicator control methods.** To obtain an optimal strategy for improving the reliability of the excavator, it is necessary to minimize the value of the integral reliability indicator:

$$I_H = f(C_{cj}) \rightarrow \min, j = 1, 2, \dots, n. \quad (6)$$

Here  $C_{cj}$  — the total cost per unit. These include operating costs, damage from insufficient reliability, and the cost of developing and implementing the  $j$ -th strategy to improve the reliability of the machine:

$$C_{cj} = \sum_{i=1}^n C_{ci}, i = 1, 2, \dots, m, \quad (7)$$

where  $C_{ci}$  — specific total costs (including operating costs from insufficient reliability, the cost of developing and implementing the  $i$ -th method of increasing the reliability of the machine).

Building an optimal strategy for controlling the process of increasing the machines reliability is in optimizing each control step—the implementation of the  $M_i$  method (event) in accordance with the degenerate problem of dynamic programming [4–6].

As an optimal criterion  $\omega_i$  for the control step  $U$  the efficiency of increasing the reliability  $K_j$  of the machine is accepted:

$$\omega_i = \mathcal{E}_i / \mathcal{Z}_i,$$

where— the economic effect of using the  $M_i$  method;  $\mathcal{Z}_i$  — costs for the development and implementation of the  $M_i$ -method.

Efficiency at the  $i$ -th control step

$$\omega_i = \omega_i(k_j, U), \quad (8)$$

and the optimal control strategy is as follows

$$k_{jc} \rightarrow u_1(k_{jc}) \rightarrow k_{j1} \rightarrow u_2(k_{j1}) \rightarrow \dots \rightarrow k_{jm-1} \rightarrow u_m(k_{jm-1}) \rightarrow k_{jm}. \quad (9)$$

The optimal control strategy depends on time constraints or funds (in most cases simultaneously for these two indicators) for the development and implementation of activities. An additional condition of the task is a forced sequence in the implementation of certain measures.

Additive performance indicator for all steps of the process:

$$W_i(k) = \max_{U_i} \{w_i(k_j, U) + W_{i+1}(F_i(k_j, U_i))\} \quad (10)$$

provided that maximum efficiency must be obtained in the shortest possible time, i.e.

$$w_i(k_{ji}, U_i) \geq w_{i+1}(k_{j+1}). \quad (11)$$

The value of the reliability indicator for the  $i$ -th control step:

$$k_{ji} = F(k_{ji-1}, U_i). \quad (12)$$

Three variants of the strategy were developed to improve the reliability of excavators, and the total effectiveness of measures was calculated.

**Improving the structural reliability of machines.** Considering ways to improve the structural reliability of machines, it is advisable to show the principles of establishing and classifying the causes of failures of parts caused by a deviation of any parameter (factor) of strength and load from the nominal value (or going beyond the tolerance range). A comprehensive (system) analysis of parameters and their structure allows you to set drop-down parameters and determine the proportion of their impact on the component life. To determine the causes of fatigue failures we applied functional method by which the relationship was found between input and output parameters (resources) of the part (Fig. 2).

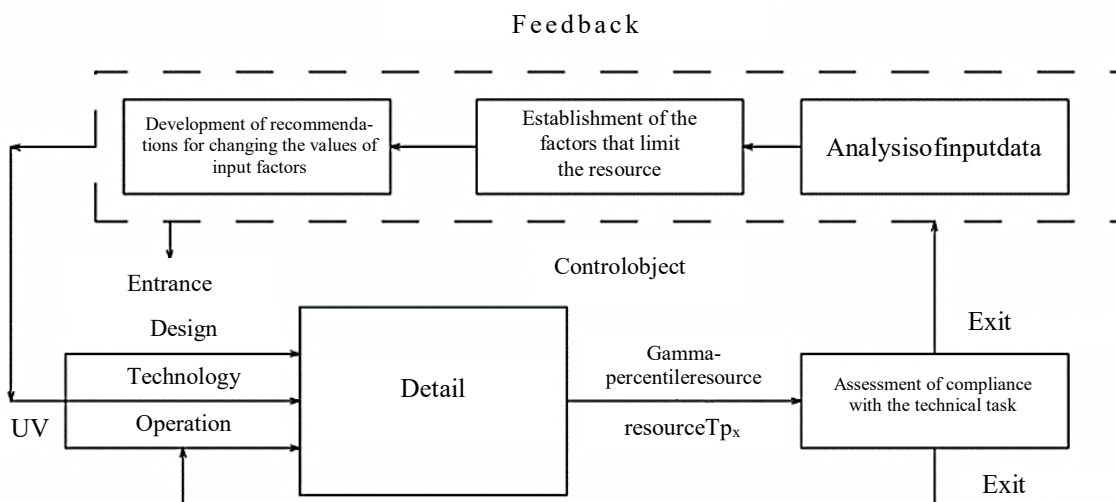


Fig. 2. Block diagram of the functional method to determine the causes of failures and increase gamma-percentile component life

The authors have developed a method of the complex analysis of the input factors (Fig. 3), and for batch and mass production — a general set of recommendations to increase components life [7, 8].

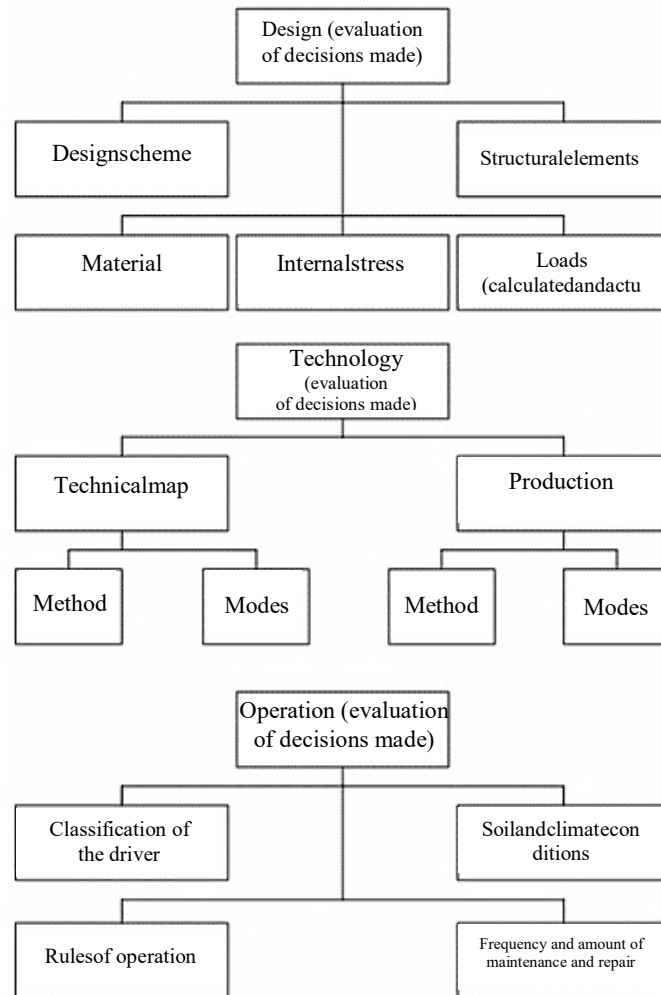


Fig. 3. Structure of complex analysis of input factors of a detail

The conditions are obtained (depending on the necessary information) under which one of the three developed functional models should be applied. A functional model with strain-gage testing and refined parameters was applied to determine the causes of failure and increase the life of the axis in the support of the E-652B excavator boom. Another functional model (with updated parameters) is used for gears, shafts, metal structures of excavators E-652B, EO-4111V, EO-3322A, EO-3322B.

As a result of research to eliminate the causes of failures of various parts of excavators E-652B, EO-4111B, EO-3322A, EO-3322B using the functional method, the following distribution of disadvantages by design, technological and operational factors was obtained:

- shafts and axles — 29 %, 59 % and 12 %;
- gears — 36 %, 55 % and 9 %;
- metal structures (frames, arrows, handle, bucket) — 31 %, 51 % and 18 %;
- chains with steps of 14.5 and 87.1 mm — 34 %, 62 % and 5 %;
- special parts — 42 %, 51 % and 7 %;
- average values are 34 %, 55 %, and 11 %.

The design includes 37% of the recommendations, 28 % — technology 5 % — equipment, 11 % — snap-in, control operations — 19 %.

It is established that in some cases, the reasons for short component life are significant deviations in the parameters of loading and load-bearing capacity. Thus, the radii of the shaft and spline shafts are understated by 2-3 or more times. The roughness of the surface of the sprockets of gears and shafts is significantly lower than the requirements of the drawing. The legs of the weld metal are understated by 2-3 times. The hardness of the surface and core of shafts, gears, chains is 1,2–2 times lower than the requirements of the drawing (Fig. 4) [9-12].

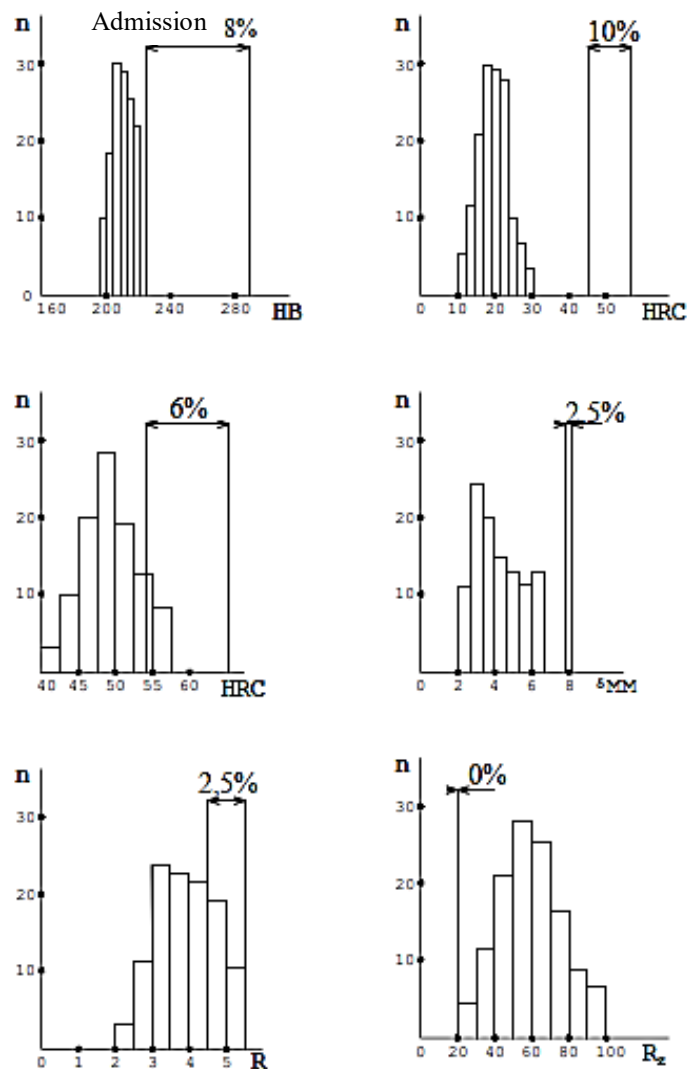


Fig. 4. Dispersion of part parameters and tolerance values in drawings: HB — Brinell hardness, HRC — Rockwell hardness, n — sample values

From a sample analysis of detailed drawings of several models of excavators with mechanical and hydraulic drive, it is clear that the tolerances for these parameters are almost not set. Working drawings for various parts have up to 50-80 or more sizes, as well as strength data. However, only 2-5 dimensions, including strength data, affect the dispersion of the components life.

Theoretical basis is developed for a multilevel connection of tolerances on the parameters of loading and the bearing capacity with the components life. A multi-variant dependence of the coefficient of change in the components life on the coefficients of change in load and load-bearing capacity is obtained (power dependence with a power indicator from 1 to 20). The structure of endurance and load factors is compiled. The types of detail parameters (geometric, strength and dynamic), as well as the types of its factors (simple and complex) are classified. The structure of the main composition of factors and parameters of typical parts in the system "factor — parameter — value — tolerance for the coefficient of increase or decrease in load capacity or load — this coefficient with a tolerance — tolerance for the parameter" is obtained. The types of statistical distributions of part parameter values depending on the features of technological processes are considered. The densities of the components life distribution are compared in two cases: with and without tolerances for the part parameters [13-15].

The methodology for creating virtually trouble-free machines, including principles, a comprehensive program and a reliability management system, is described. Based on the generalization of the accumulated experience in ensuring reliability, 16 principles for creating virtually trouble-free machines have been formulated for the first time (table 2).

Table 2

## Principles for creating virtually trouble-free machines

1.	Changing the reliability of the machine entails a change in the cost of its development, production, and operation	9.	For the main parameters of parts, tolerances are assigned to ensure an acceptable dispersion of their resource
2.	To measure changes in the reliability of a machine, a single indicator is used that generalizes all the reliability properties (i.e., the integral reliability indicator)	10.	Considering random variables (strength, load, operating time) that are bounded from above or (and) from below, theoretical laws are applied with similar restrictions (limits)
3.	To evaluate the changes and optimize the reliability of the machine (element), the specific total costs for the development, production, and operation is used as an integral indicator	11.	To calculate the distribution function and the minimum resource, dependencies are used that relate the resource to the load capacity and bearing capacity, and the Monte Carlo method
4.	Virtually trouble-free resource of the machine should be optimal	12.	The calculated reliability of the machine is confirmed experimentally before the start of mass production: for the full life of the machine and with the acceptable reliability
5.	The minimum resource of each part must be greater than the specified (optimal) resource of the machine $\min T_{Pgi} > T_{PIopt}$	13.	Control in production provides a predetermined distribution of the bearing capacity of the part
6.	Planned replacements of some parts are allowed	14.	The design, technical parameters and operating conditions of the machine ensure the specified load dispersion
7.	For details, there may be rare accidental failures, the causes of which cannot be determined, since there are no necessary methods and technical means	15.	Maintenance (lubrication, adjustment, diagnostics, etc.) of the machine maintains the specified level of reliability
8.	To produce spare parts for planned replacements, to eliminate accidental failures to have a stock of parts	16.	If the test conditions of experimental machines (units, assemblies) do not meet all operating conditions, you must additionally obtain information about the reliability of serial machines

These principles formed the theoretical basis for the methodology of system-based step-by-step reliability assurance at all three stages of the machine's life cycle. The basic principle of creating virtually trouble-free machines: the minimum resource of each part (shift parameter, three-parameter Weibull distribution) must be greater than the specified resource of the machine.

Technical and economic calculations for the design of the hydro-mechanical excavator EO-4117 showed that repair costs are reduced by 10-20 times, and the integral reliability indicator — by 3-6 times. To increase the life of the machine from 10 to 20 thousand hours, you will need to increase, for example, the section of metal structures by 19 %, transmission parts — by 9 %. The cost of steel for one excavator increases by 0,45 thousand rubles. (from 3 to 3,45), and the price — from 20 to 20,45 thousand rubles, i.e. by 2,3 %. The integral reliability indicator is reduced by 1,97 times, and the weight of the excavator increases by about 15 %.

**Conclusion.** The application of the proposed system makes it possible to develop and produce high-reliability machines and ensure a systematic reduction in the integral reliability indicator. The functioning of the machine reliability control system guarantees their creation with a level of reliability that will ensure the competitiveness of equipment and the absence of consumer complaints.

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V.E. Kasyanov — scientific supervision, formulation of the main idea of research, verification of formulations and terminology. D.V. Demchenko — analysis of literary sources, control of the adequacy of the research. E. E. Kosenko — research, participation in theoretical research, setting up and description of scientific experiment. S. V. Teplyakova — research, participation in the formulation of scientific experiment, description of scientific experiment.