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ТЕХНОСФЕРНАЯ БЕЗОПАСНОСТЬ

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Original article

Production Facilities Safety Assessment According to the Maximum Values of Machines Reliability

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Abstract
Introduction. At the stage of designing technical devices and performing appropriate strength calculations of metal structures, sufficiently large reserves of strength are taken, which, theoretically, exclude any failures of parts. In fact, the machines work with frequent failures. Of interest are undiagnosed failures that lead to a critical decrease in safety, especially at hazardous production facilities. It is assumed that the previously applied approaches of selective determination of the maximum (minimum) reliability value, based on point estimates of the distribution parameters of the two-parameter Weibull law, lead to an overestimation of the calculated indicators of the probability of failure-free operation, i.e. underestimation of risk. Therefore, the work objective is to consider an approach to assessing the risk of operating production facilities in a situation of accidental occurrence of dangerous and undiagnosed failures in systems.
Materials and Methods. Methods for technical devices safety assessment based on probability theory were used in the work, and the probability of machine failure was determined based on the well-known method of reliability theory. This method consists in calculating and constructing distribution functions of random variables (load-bearing capacity and loading) that influence the occurrence of failure. The level of increase in the reliability index was determined, leading to frequent unpredictable failures of technical devices (machines) and a decrease in the safety of their operation.
Results. The signs of inconsistency of strength calculations based on overestimated safety margins, which in theory exclude failures of parts and machines in general, are identified and substantiated. A new approach to risk assessment of operating production facilities in a situation of accidental occurrence of dangerous and undiagnosed failures by safety systems has been developed and implemented. An algorithm for determining the three parameters of Weibull's law for a population based on sample data has been developed. The resource distribution densities of the boom of the single-bucket excavator EK-14 are constructed. The recommendations are given to increase the probability of failure-free operation to 0.9989.
Discussion and Conclusion. The results of the conducted research allow us to substantiate a new approach to risk assessment of operating production facilities in the event of dangerous and undiagnosed failures of basic parts by safety systems, leading to negative consequences.

Keywords: industrial safety, safety, reliability, maintainability, durability, persistence, failure, machine, resource.

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Научная статья

Оценка безопасности производственных объектов по предельным значениям безотказности машин

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Аннотация

Введение. На этапе проектирования технических устройств и выполнения соответствующих прочностных расчетов металлоконструкций принимаются достаточно большие запасы прочности, теоретически исключающие какие-либо отказы деталей. В действительности машины работают с частыми отказами. Интерес вызывают недиагностируемые отказы, приводящие к критическому снижению безопасности, особенно на опасных производственных объектах. Предполагается, что ранее применяемые подходы выборочного определения предельного (минимального) значения безотказности, основывающиеся на точечных оценках параметров распределения двухпараметрического закона Вейбулла, приводят к завышению расчетных показателей вероятности безотказной работы, т.е. занижению риска. Поэтому целью работы явилось рассмотрение подхода к оцениванию риска эксплуатации производственных объектов в ситуации случайного возникновения опасных и недиагностируемых отказов в системах.

Материалы и методы. В работе применялись методы оценивания безопасности технических устройств, основанные на теории вероятностей, а вероятность отказа машины определялась на основе известного метода теории надёжности. Данный метод заключается в расчете и построении функций распределения случайных величин (несущей способности и нагруженности), оказывающих влияние на возникновение отказа. Определился уровень повышения показателя надежности, приводящий к частым непрогнозируемым отказам технических устройств (машин) и снижению безопасности их эксплуатации.

Результаты. Выявлены и обоснованы признаки противоречивости прочностных расчетов, основанные на завышенных запасах прочности, в теории исключающие отказы деталей и машин в целом. Разработан и реализован новый подход к оцениванию риска эксплуатации производственных объектов в ситуации случайного возникновения опасных и недиагностируемых отказов системами безопасности. Разработан алгоритм определения трех параметров закона Вейбулла для совокупности по выборочным данным. Построены плотности распределения ресурса стрелы одноковшового экскаватора ЕК-14. Даны рекомендации по увеличению значения вероятности безотказной работы до 0,9989.

Обсуждение и заключения. Результаты проведенных исследований позволяют обосновать новый подход к оцениванию риска эксплуатации производственных объектов в случае возникновения опасных и недиагностируемых системами безопасности отказов базовых деталей, приводящих к негативным последствиям.

Ключевые слова: промышленная безопасность, надежность, безотказность, ремонтопригодность, долговечность, сохраняемость, отказ, машина, ресурс.

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Introduction. Key factors that determine safety of hazardous production facilities are the so-called "human factor", the availability of safety systems and the reliability of machines and mechanisms used at the facility. As it is known [1–4], reliability is a complex parameter, including reliability, maintainability, durability and persistence. This article examines the impact of the reliability of the machine, as one of the main reliability parameters, on the safety of its operation. At the same time, for the analysis of reliability indicators, traditional methods of reliability theory and some new approaches to determining the parameters of random variable distributions are used to estimate the maximum values of reliability [1]. It should be noted that the safety assessment methods used here are based on the basic concepts of probability theory, the main one of which is the concept of a random variable[1]. Therefore, this paper considers only accidental failures that lead to a decrease in safety. At the same time, it should be noted that not all machine failures are accidental. For example, failures related to systematic errors of measuring instruments and the "human factor" are not accidental[2]. In this case, the proposed approaches cannot be used for their analysis without strict mathematical justification[3].

There are four types of accidental failures that occur during the operation of machines and mechanisms used at hazardous production facilities (Table 1).

The study of the diagnosed failures within the framework of the described work is not of interest, since in this case the equipment (devices, sensors) of the industrial facility safety system perform their functions in full and a catastrophic decrease in safety is excluded. In case of dangerous and undiagnosed failures, a situation may arise when the safety system is vulnerable. At the same time, in accordance with GOST ISO 12100-2013, safety is understood as the ability of a machine to perform its function(s) throughout its service life with adequate (sufficient) risk reduction.

Table 1

Types of accidental failures of machines and mechanisms

Type of failure	Description of failure	Example of failure
Dangerous	It has a significant impact on safety up to the occurrence of an accident with possible injury to personnel	Destruction of load-bearing structures of machinery (equipment) due to fatigue failures
Safe	It does not affect the safety of operation. As a result of the occurrence, the parameters of economics, aesthetics, ergonomics and others may decrease	Manifestation of corrosion phenomena, occurrence of paintwork defects
Diagnosed	Equipment (devices, sensors) of safety security system diagnose failures of this type	Occurrence of a malfunction of the hydraulic system of the machine (equipment). Violation of load capacity limits
Undiagnosed	Equipment (devices, sensors) of safety security system do not diagnose failures of this type	Manifestation of hidden defects during expansion, for example, fatigue cracks

It follows from the definition that the key concept of safety here is risk, which is defined as the possibility of an undesired event, that is, a combination of the degree of negative consequences with the possibility of its occurrence.

Materials and Methods. Usually, a negative consequence is the infliction of injuries or other harm to health during the operation of the machine. At the same time, the consequence of an accidental dangerous failure of the machine can be economic damage. In this case, the risk is assessed by the so-called functional safety of the production facility [3–5]. Consequently, the methods of reliability theory as part of probability theory should be applied to the study of the safety

[1] GOST R 53195.3-2015. *Functional safety of building/erection safety-related systems. Part 3. Requirements for systems*. Electronic fund of legal and regulatory documents. URL: https://docs.cntd.ru/document/1200124221 (accessed 23.01.2023). (In Russ.).
[2] GOST R 51901.14-2007. *Risk management. Reliability block diagram and boolean methods*. Electronic fund of legal and regulatory documents. URL: https://docs.cntd.ru/document/1200065647 (accessed 23.01.2023). (In Russ.).
[3] GOST R 50779.27-2017 *Statistical methods. Weibull distribution. Data analysis*. Electronic fund of legal and regulatory documents. URL: https://docs.cntd.ru/document/1200146523 (accessed 23.01.2023). (In Russ.).

of the production facility in which an accidental dangerous and undiagnosed machine failure occurs. It is the risk that is the link between the reliability of machines and the safety of hazardous production facilities, including their functional safety.

An increase in the probability of an undesired event due to the occurrence of a dangerous and undiagnosed failure leads to the need to predict and assess the risk of negative consequences, the severity of which is difficult to determine. In the work, the severity of the likely negative consequences arising from a dangerous and undiagnosed failure is assumed to be the same, and risk assessment is reduced to assessing the probability of an undesired event.

The probability of machine failure is determined by the well-known methods of reliability theory [6], which consist in constructing distribution functions of random variables that influence the occurrence of failure. When considering the power elements of the structure, the distribution functions of the load-bearing capacity and loading characteristics were constructed.

To construct the distribution function of the general population of a random variable, a representative sample of values obtained on the basis of tests is usually formed. However, in real conditions, it is often difficult to conduct tests due to financial, technological and time constraints. To save costs, a number of studies [6-10] use the approach of adjusting the parameters of sample distributions. This approach is used in the work to determine the maximum (minimum) reliability value, which makes it possible to ensure maximum safety of the object under consideration by increasing the minimum calculated reliability and minimizing the risk of an undesired event. The required reliability is achieved by adjusting the parameters of the distribution of random variables that affect the probability of a dangerous and undiagnosed failure.

From the point of view of reliability, the machine is ideally trouble-free if there is no failure within a given life. In this case, the parts of this machine will fail approximately at the same time, having worked out the specified life value T_p [10, 11].

The practice of determining the reliability of domestic machines shows that the average failure interval is T = 20–200 hours, therefore, for a time between overhauls T_p=8 000–10 000 hours, from 40 to 500 failures occur, that is, tens and hundreds of failures [12–15]. Many of them are dangerous and undiagnosed. In this case, the actual life of $T_{pф}$ is significantly less than the specified one T_p, and the probability of failure tends to one. At the same time, to ensure the required level of safety, it is necessary to reduce the risks of undesired events, i.e. the probability of failures.

It is impractical to consider the option of increasing the machine safety by reducing the probability of failure of one part, since hundreds and thousands of parts are operated simultaneously in the machine, so the risk of undesired events is growing.

When drawing up a structural diagram of reliability among all machine parts, we will single out a group of parts, which we will call the basic one. This group includes parts, the failure of one of which leads to a dangerous and undiagnosed failure of the machine. In this case, it is necessary to use the sequence of the structural scheme of the reliability of the machine. Then the risk of failure is determined by the well-known formula [15]:

$$Q = 1 - \prod_{i=1}^{m}(1 - Q_i), \tag{1}$$

where Q — risk (probability) of machine failure; Q_i — probability of failure of the i-th part, m — volume of a group of parts.

For example, if the probability of failure of one part in the base group is the same and is equal to Q_1 = 0.05, which is a completely acceptable condition for the reliability of the part in operation, and the volume of all parts in the base group of the machine is m = 200, then the probability of a dangerous and undiagnosed failure of the machine will be:

$$Q = 1 - \prod_{i=1}^{200}(1 - 0{,}05) = 0{,}997.$$

Such a risk indicator is unacceptable. That is, it can be assumed that in order to reduce the risk, it is necessary to increase the life of each part, in this case the risk will decrease. For example, if you increase the life of each part by an order of magnitude, namely, if the probability of failure is $Q_1 = 0.005$, then the probability of machine failure will remain significantly high:

$$Q = 1 - \prod_{i=1}^{200}(1 - 0{,}005) = 0{,}63.$$

The development of recommendations to increase the life of the second group of parts (all other parts and assemblies that are not included in the first group), which includes consumables and spare parts, leads only to minimizing the total costs of eliminating failures, without affecting the safety of operation in any way.

Improving reliability by reducing the dispersion of failures of parts from the base group reduces the risks associated with dangerous and undiagnosed failures. As a result, the average time to failure will increase, and failures will occur less frequently. The number of failures will decrease, but it will not be possible to completely eliminate them, the risk of undesired events will remain. The actual life, although it will approach the specified one that determines the acceptable risk, will be lower.

Then an increase in the life of parts from the base group within the specified limits does not allow achieving a high level of reliability and a different methodological approach is needed to solve this problem. The proposed new approach should provide for the appearance of calculated failures of parts from the base group only outside the specified machine life. In the future, we will talk only about the parts from the base group, which we will call critical parts.

New approach to assess reliability

The study of the reliability of machines has shown that the life of parts can be dispersed within significant limits. Let us consider this fact on the example of one part from some set of the same parts. Its life is a random value determined by the parameters of the aggregate, the true parameters of which are unknown and are estimated only by the parameters of the sample distribution. The relative scope of the sample distribution can be determined by the formula:
where Tp_{max} — the maximum life value in the sample; Tp_{min} — the minimum life value in the sample.

$$R = \frac{Tp_{max} - Tp_{min}}{Tp_{min}} \quad (2)$$

It should be noted here that for the sample, as for the aggregate, the fundamental condition is fulfilled: $Tp_{min} > 0$. Therefore, to describe statistical patterns, it is recommended to apply the probabilistic Weibull shift law (for strength and life) and the Fisher-Tippett law (for operating stresses). The distributions obtained using these laws have restrictions on the left and right, respectively. In addition, the shape of the distribution function can be used to analyze the change in the failure rate over time.

Then the relative range estimated by formula (2), reflecting the deviation of the extreme upper value of the sample distribution relative to the extreme minimum value, can range from several units to hundreds or more. Therefore, the distribution density of the parts life for the sample and the aggregate may be located differently relative to a given machine life, for example, as shown in Fig. 1.

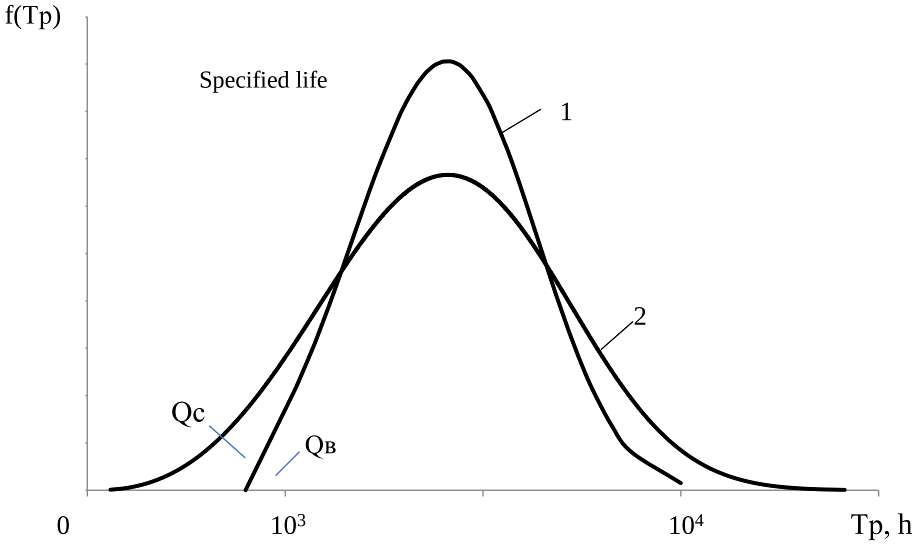

Fig. 1. Curves of the density distribution of the probability of failure for the sample (1) and the aggregate (2) for the three-parameter Weibull law

It can be concluded that the result of estimating the probability of trouble-free operation of a part is determined by the degree of adequacy of transferring the results of sample tests to the aggregate. It is obvious that the spread of point estimates of the distribution parameters of the two-parameter Weibull law obtained by the least squares method can lead to an overestimation of the calculated indicators of the probability of trouble-free operation, i.e. underestimation of risk. The main reason for this lies, as noted in [1], in the estimation of the shift parameter only based on the results of sample tests. At the same time, the volume of the aggregate is not taken into account in any way. However, we can assume that by increasing the volume of the considered aggregate, there will be a decrease in the real value of the minimum life $Tp^{и}_{min}$, i.e., in the aggregate, there will always be a part, the life of which is less than the specified value during random tests: $Tp^{и}_{min} < Tp_{min}$.

Therefore, in order to increase the reliability of the safety assessment of parts from the sample and bring it closer to the true value determined from the aggregate, it is necessary to adjust the distribution density curve for dangerous and undiagnosed failures.

To adjust the distribution parameters, it is proposed to use the following methodology.

At the first stage, according to the test results, in accordance with recommendations [4], parameters of shape $\beta_в$ and scale $\eta_в$ for a sample of volume n are determined. The minimum life value in the sample is taken as a sample parameter of shift $T_{0в} = Tp_{min}$.

At the second stage, the shift parameter for the aggregate is determined. First of all, the shift parameter requires a physical justification. For the random variable under consideration — technical life — such a physical limitation is zero life. Therefore, a probabilistic approach is proposed here. In accordance with it, the volume of population N is set, the quantile of Student's distribution $d = t_p(N - 1)$, which has degree of freedom (N – 1) and confidence probability level p. Next, the shift parameter for the population is determined by the following formula:

$$T_{0c} = T_{0в}(1 - e^{-\frac{d}{\beta\sqrt{N-n}}}). \quad (3)$$

It follows from formula (3) that as (N – n), increases, i.e. as the volume of the population increases, the shift parameter decreases in the limit to zero, which corresponds to the existing physical constraint.

At the third stage, there is a correction of parameters of shape β_c and scale η_c for the aggregate in accordance with the formulas proposed in [5, 6]. The reliability of such an adjustment is proved in [5].

The algorithm for constructing a three-parameter Weibull's law for a population based on sample data is shown in Fig. 2 and represents the following scheme for calculating parameters.

1. The following numerical characteristics are estimated from the initial sample series X: average value x, standard deviation σ_x, coefficient of variation C_v, coefficient of asymmetry C_s and the minimum value x_{min}.

2. Depending on C_s coefficient of variation C_v for the population is determined using the approximating expression:

$$C_V = 0.0009 \times C_S^4 - 0.0105 \times C_S^3 + 0.0277 \times C_S^2 + 0.3234 \times C_s + 0.31,$$

3. Coefficient of variation C_v determines the value of the coefficient of the distribution form of set β_c according to the formula:

$$\beta_c = 0.9889 \times C_V^{-1.093}.$$

To confirm the methodology, we will conduct a numerical experiment, the essence of which is to carry out the following sequence of actions:

– recognition of the parameters of a given set as true;
– modeling of the variation series of the aggregate of the required volume;
– formation of a true sample distributions set of volume n in the amount of m;
– determination of the most unfavorable option with the maximum value of the sample shift;
– correction of the shift and calculation of shape and scale parameters for the adjusted sample;
– comparison of the corrected parameters with the true ones.

It is obvious that in real conditions of observations (tests) during the operation of the machine, only the initial section of the left branch can be obtained. At the same time, the batch of machines should be representative and consist of at least 30 machines with an operating time of 8-10 thousand hours. Obtaining experimental data for statistical processing and constructing the entire distribution curve of the object's resource over the entire period of operation is an impossible task.

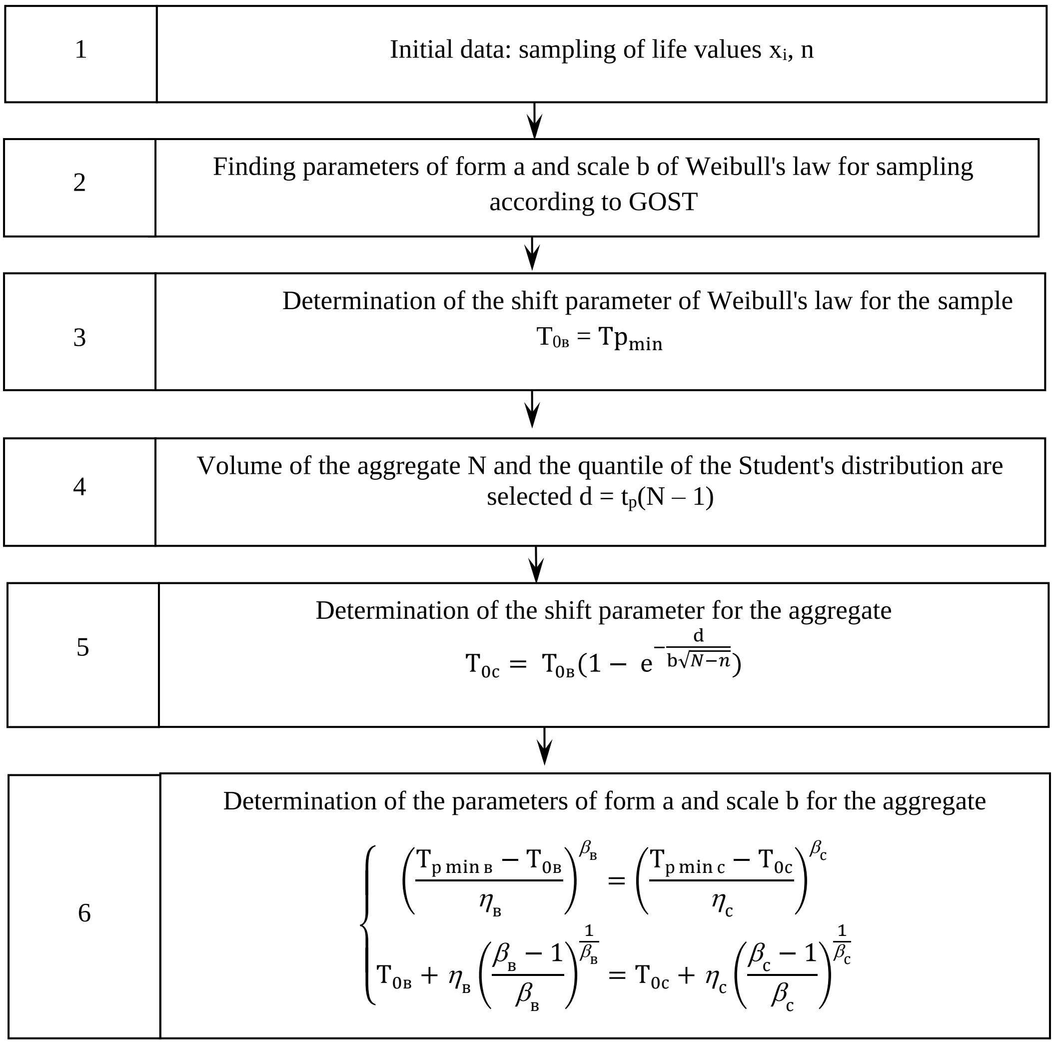

Fig. 2. Algorithm for determining the three parameters of the Weibull's law for a population based on sample data

Therefore, a computational experiment was carried out, during which the parameters of the three-parameter distribution of the Weibull sample were determined for the sample data of the part (parts) life with volume of n=50.

Results. According to the algorithm and sequence of actions proposed above, a numerical experiment was carried out. Initially, the parameters of the true population were set, a variation series of population $N=10^4$ was modeled, samples of n=50 in the amount of m=5 were randomly extracted from it; n=100 in the amount of m=1; n=150 in the amount of m=1 and n=1000 in the amount of m=1 were selected. Next, we chose the worst sampling option corresponding to the maximum deviation of the shift value from the shift of the population. The distribution densities of the Weibull's law for the initial population and the samples obtained from it are shown in Fig. 3.

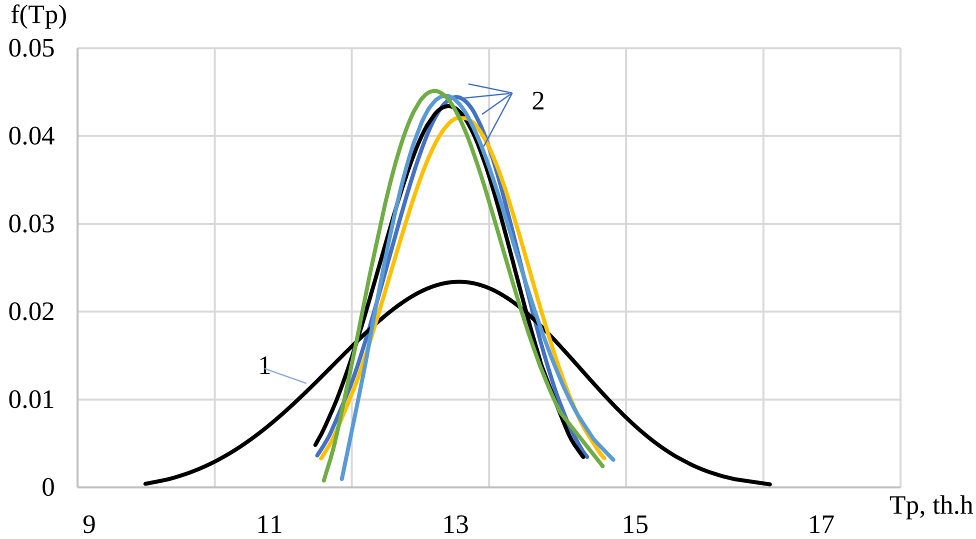

Fig. 3. Distribution densities of population (1), samples modeled from it with a volume of n=50 (2)

Based on the calculation results, we estimate the parameters by comparing the shift value of the true population and samples taken from it (Table 2).

Table 2

Parameters of samples and aggregates

Parameters	Aggregate	Samples of volume n=50					
			1	2	3	4	5
a	155 900	Initial	132 787	154 333	143 348	138 096	167 488
		Corrected	135 008.7	159 917.03	151 330.36	143 957.4	166 778.2
b	1.07	Initial	1.07	0.98	0.96	1.02	0.92
		Corrected	1.19	1.20	0.95	1.13	0.94
x min	5 509	Initial	7 344	6 007	6 813	5 962	7 491
		Corrected	8 160.36	6 675.00	7 569.74	6 625.23	7 490.71
Δ,%			10.004	10.007	9.997	10.011	0

The analysis shows that the sample parameters of the shift differ significantly from the shift of the population. The probability of falling into the real value of the shift is minimal, and an increase in the volume of samples does not guarantee that the minimum value of the population will fall into it. Therefore, in order to reduce the risks of a dangerous failure, it is necessary to adjust the parameters.

To determine the confidence level when adjusting the shift parameter of the three-parameter Weibull distribution, a parametric confidence criterion is proposed:

$$D_{\text{ВБР}} = e^{-\left(1-\frac{n}{N}\right)\cdot\Delta} \quad (4)$$

where n and N — respectively, the volumes of samples and general aggregates of a finite volume; Δ — deviation of the parameters of sample distributions from the true value of the parameters of the population.

The calculations have shown that the criterion of parametric reliability for a sample with the maximum shift value is 0.67.

To make the adjustment, we take the most unfavorable option, that is, with the maximum value of the sample shift relative to the value of the population. A graphical representation of the distribution densities of these samples is shown in Fig. 4.

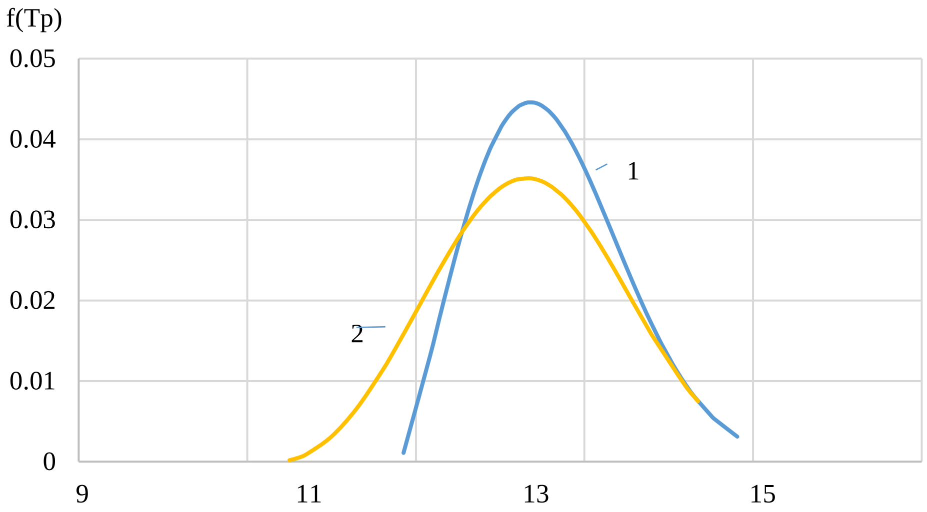

Fig. 4. Distribution densities of the initial (1) and the corrected (2) samples

Determination of the risk of uncontrolled dangerous failure of the boom part of the single-bucket excavator EK-14

As an evaluation of the proposed method for determining the parameters of the aggregate based on sample data, an example is considered for a responsible part of a single-bucket excavator —the side wall of the boom with a fatigue life before write-off T_p=20 thousand hours. The specified life is determined by the manufacturer as a life before write-off. For the boom, as the basic element of the excavator, the specified life is 20 thousand hours.

The boom of the single-bucket excavator EK-14 has a box section made of St3 rolled steel, with a side wall thickness of 10 mm. The operational experience has shown that the boom failure consists in the appearance of a fatigue crack in a dangerous section, and various kinds of repair measures did not solve the problem of crack growth. The only solution to the problem is to replace it. Therefore, sample data on the life were determined for the boom and the transition from sample data to aggregate parameters was carried out [14, 16, 17].

Numerical and full-scale experiments show that the reliability of determining the shift parameter of the aggregate according to the data of sample tests does not meet the necessary requirements. Therefore, it is necessary to adjust the data obtained according to the proposed methodology.

Further, according to the proposed sequence, a sample was obtained from the aggregate and corrected. The adjustment of the parameters of the sample distribution allowed us to approach the parameter of the population shift, but not to achieve it. Moreover, the shift parameter of the aggregate did not reach a value of 10 thousand hours, which is twice lower than the specified life, and confirms the presence of premature failures.

Therefore, for parts from the base group, it is proposed to shift (increase) the life value by changing the design parameters. For example, to increase the endurance limit of steel by replacing the steel of the serial production of the part with a stronger one, and (or) to reduce the effective stress by increasing the wall thickness or cross-section dimensions. In [14, 15], the life values for the side wall of the boom were calculated and compared with the variants of recommendations for the manufacture of the part. The recommendations provided for: increasing the wall thickness from 10 to 12, and then to 14 mm of the rolling sheet in the dangerous section of the part; replacement of the used grade of steel St3 (low-carbon) with low-alloy 09G2S or 15KHSND; increase in the dangerous cross section of the boom up to 20 %.

Load parameters are set deterministically. The fatigue strength of the part is limited from below by the available control of the material and the finished part, and the load is limited from above by the calculated operating modes and the presence of safety elements (safety valves, torque-limiting clutches, etc.). Therefore, in case of fatigue failure of parts for the general population, there are cases when the load parameters exceed the fatigue strength parameters due to the influence of uncontrolled random factors. The consequence of this is the need to limit the resource of the part from below, determined by the distribution of the general population, and not by the sample.

The calculations have shown that the probability of trouble-free operation is 0.9989 for the boom of a single-bucket excavator made of 15KHSND steel with a rolling sheet thickness of 12 mm, and the probability of failure, respectively, is 0.0011.

Discussion and Conclusion. To create safe machines, it is necessary that the minimum life of basic parts, justified by the proposed methodology, tends to the value of the specified machine life. The exception to this rule is only some parts with premature failures, the causes of which cannot be determined due to the lack of appropriate methods and means. In addition, planned replacements of individual parts with a low life are acceptable (increasing their life is impossible or impractical). Failures of such parts do not affect the safety of the machine.

Thus, a new approach to assessing the risk of operating production facilities in the event of dangerous and undiagnosed failures of basic parts by safety systems, leading to negative consequences, is justifie.

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