Safety assessment of technical systems based on limit values

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Abstract. Ensuring the safe operation of complex technical systems is an urgent task. Complex technical systems include lifting, mobile, agricultural machinery, etc. Absolutely every complex system fails during operation. At the same time, failures can have different effects not only on reliability indicators, but also on the degree of safety. The degree of safety of operation of complex equipment is directly influenced by the probability and nature of the occurrence of failures. Thus, in order to increase operational safety, it is necessary to reduce the risk of a negative event, which is defined as the possibility of an adverse event occurring, that is, a combination of the degree of negative consequences with the possibility of its occurrence. The article provides an example of calculating the risk of failure; a method for calculating the parameters of the three-parameter Weibull distribution is proposed; an algorithm for determining three parameters of the Weibull law for a sample is given; the results of parameter calculations are presented; Proposals have been put forward for ways to increase the level of reliability and safety, respectively.

1 Introduction

Ensuring the safe operation of complex technical systems is an urgent task. Complex technical systems include lifting, mobile, agricultural machinery, etc. Absolutely every complex system fails during operation. At the same time, failures can have different effects not only on reliability indicators, but also on the degree of safety. The degree of safety of operation of complex equipment is directly influenced by the probability and nature of the occurrence of failures. Previous studies show that the probability of failure is determined using known methods of reliability theory [1-3]. If we consider specifically the strength (basic) elements of the structure, then the random characteristics in this case are the indicators of bearing capacity and load.

Thus, in order to increase operational safety, it is necessary to reduce the risk of a negative event, which is defined as the possibility of an adverse event occurring, that is, a combination of the degree of negative consequences with the possibility of its occurrence.

The most dangerous failures are sudden fatigue failures, resulting in harm to human health during operation of a technical system [4, 5].

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Risk in the event of a failure as a relationship between the reliability of an object and its functional safety in operation. The level of damage to production is not always easy to determine; it is a multifactorial indicator. Therefore, it is proposed to accept an equal level of negative consequences from a dangerous failure that causes harm to human health and life, and from a diagnosed failure leading to significant economic losses. Then the risk can be assessed by the level of probability of an adverse event occurring, determined by a dangerous and undiagnosed random failure.

The probability of failure is determined by known methods of reliability theory. In this paper, we will consider a method for constructing a distribution function of quantities that influence the onset of failure. As an example of a power element in the design of a complex technical system, consider a loader boom. Then a random variable influencing the value of operational safety will be the load-bearing capacity and load of the metal structure [6, 7].

To determine the distribution of a random variable, it is necessary to specify a general population of values of a given value or at least a sample of values that meets all indicators of representativeness. But this process is practically impossible to implement due to the complexity, high cost and duration of data acquisition. Therefore, a number of studies [8-10] proposed either a transition from sample data to the parameters of a general population of a finite volume, or the use of methods for adjusting the distribution function in order to obtain a minimum value. This method is suitable for our case when it is necessary to determine the value of the minimum resource. After all, it is with the development of this clock value that a fan of failures begins, which directly affects the risks of adverse events.

Using the adjustment method, namely increasing the minimum value of the resource distribution, by changing the design parameters of the machine, for example, the thickness of the material, the power parameters of the structures, loading, etc. Then it is possible to ensure maximum safety if you achieve the level of required reliability when adjusting the distribution parameters of random variables.

If we consider the loader from the point of view of the reliability of the metal structure, then the best option for safety and reliability is a machine with no failures within a given resource. In this case, failures of this machine will begin approximately simultaneously after the corresponding resource value $Tr$ [11].

2 Material and research methods

The work examines the increase in the service life of one part - the loader boom. However, if you try to increase the safety and reliability of a machine by increasing the service life of only one part, it is a deliberately wrong approach. At the same time, hundreds and thousands of parts are used in a machine, so the risk of adverse events increases. An approximate test calculation confirms this.

For example, let's select a group of parts, for example, parts related to the frame metal structures of the machine (frame, boom, etc.). This group contains precisely those parts, the failure of which can affect the reliability and safety, characterized by the lack of possibility of early diagnosis of machine failure.

Then the risk of failure can be determined by the formula:

$$Q = 1 - \prod_{i=1}^{m}(1 - Q_i)$$  \hspace{1cm} (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 basic group is the same and is taken to be $Q_1 = 0,05$, which, in a situation where a single sample of a part is considered,
can be considered a completely acceptable indicator of the reliability of the part in operation. However, in the matter of ensuring the required level of reliability of the entire machine, it is necessary to take into account the entire volume of parts of the basic group of the machine, and this is already an order of magnitude $m = 200$, then the probability of a dangerous and undiagnosed machine failure changes significantly and corresponds to:

$$Q = 1 - \prod_{i=1}^{200} (1 - 0.05) = 0.997$$

The data obtained confirm that in order to achieve the set level of reliability, it is necessary to take into account the level of reliability of each element, then the level of reliability of each machine will increase.

Let's make an estimate. If you increase the resource of each part under consideration by an order of magnitude, that is, if you initially considered the probability of failure $Q_1 = 0.05$, and had a probability of failure of the machine as a whole $Q = 0.997$, then with an increase in reliability and a decrease in the probability of failure of each part to $Q_1 = 0.005$, the car will decrease significantly:

$$Q = 1 - \prod_{i=1}^{200} (1 - 0.005) = 0.63$$

All parts that do not belong to the category of basic parts that affect safety (consumables and spare parts) do not require the development of recommendations for increasing the service life, since in fact this will only lead to a reduction in the total costs of eliminating failures and will slightly increase the level of failure-free operation in no way affecting operational safety.

In order to take into account the value of the resource not only of one product, but to take into account a representative sample that meets all the requirements of a set of products, in our case a loader boom, we will use the three-parameter Weibull probabilistic law to determine strength and service life, and the Fisher-Tippet law for effective stresses. The analysis is carried out according to probability distributions with restrictions on the left and right, respectively, and the geometric form of the distribution function will allow us to analyze changes in the failure rate over time [12].

The main task is, as noted in [13], to determine, evaluate and select ways to increase the resource. The resource can be analyzed by changing the shift parameter of sample tests. In this case, the volume of the population is not taken into account in any way. However, it can be assumed that with an increase in the volume of the population under consideration, there will be a decrease in the true value of the minimum resource $T_{p_{\text{min}}}^n$, thus, in the aggregate there will always be a part whose service life is less than that determined during random tests: $T_{p_{\text{min}}}^n < T_{p_{\text{min}}}$. Therefore, in order to increase the accuracy of assessing the increase in the reliability of parts based on a sample and bringing it closer to the required value, it is necessary to adjust the distribution density curve for dangerous and non-diagnosable failures.

To adjust the distribution parameters, it is proposed to use the following method for calculating the parameters of the three-parameter Weibull distribution.

1. Initially, based on the initial variation series of the resource for each type of steel, the following characteristics of the series are determined: average numerical value value $T_{p_{\text{cp}}}$, standard deviation $\sigma_x$, the coefficient of variation $C_v$, asymmetry coefficient $C_s$ and minimum value $x_{\text{min}}$. Understanding that the error of the asymmetry coefficient can take
significantly larger values, therefore it is allowed to be taken depending on \( Cv \) and average regional ratio (Cs/Cv) according to the formula

\[
C_s = C_v \left( \frac{C_s}{C_v} \right)
\]  

(2)

2. Next, by analyzing the value of Cs, the coefficient of variation \( Cv^* \) of the Y series is determined. The X and Y series are related by the relation \( yi = xi - c \). An approximating expression can be used to determine \( Cv^* \).

3. Determination of the value of the shift parameter is determined by the formula

\[
c = \bar{x} - \frac{\sigma_x}{C_v^*}
\]  

(3)

If the resulting shift value is less than the numerical value of the distribution variation series \( c > X_{min} \), then the shift is taken equal to this first value \( c = X_{min} \), then the coefficient of variation \( Cv^* \) is determined by the formula

\[
C_v^* = C_v / (1 - k_{min})
\]  

(4)

where \( k_{min} \) is the minimum modular coefficient.

However, in such a situation, there is a probability of obtaining an asymmetry in the analytical Weibull curve that is significantly less than the empirical one, and as a result, the approximation will have an error.

4. The next step is to determine the average value of the Y series using the formula:

\[
\bar{y} = \bar{x} - c.
\]

5. From the obtained coefficient of variation \( Cv^* \) we obtain the Weibull distribution parameters of scale \( a \) and shape \( b \).

The algorithm for constructing a three-parameter Weibull law from sample data is shown in Figure 1 and represents the following scheme for calculating parameters.

Let’s conduct a numerical experiment to determine the distribution parameters.

Sequence of numerical experiment:
- obtaining initial values of variation series of the required volume;
- determination of the average value of the series, standard deviation, coefficient of variation, coefficient of asymmetry and the minimum value of the variation series;
- determination of the coefficient of variation;
- determining the value of the shift parameter;
- obtaining parameters of the Weibull distribution of scale and shape;
- comparison of the adjusted parameters with the true ones.
3. Results and discussion

According to the algorithm and sequence of actions proposed above, a numerical experiment was carried out. Initially, by calculation, a variation series of resource distribution was obtained based on the measured steel hardness data. Using the proposed algorithm, the sampling parameters were determined, the population variation series with a volume of N=104 was modeled, and samples with a volume of n=50 in the amount of m=5 were randomly extracted from it. Next, we selected the worst sampling option, corresponding to the maximum deviation of the shift value from the population shift.
The Weibull law distribution density (logarithmic scale) for the obtained samples is shown in Figure 2.

![Graphs showing distribution densities of simulated samples with a volume of n=50: a) 09G2S, b) 10HSND, c) 15HSND.]

**Fig. 2.** Distribution densities of simulated samples with a volume of n=50: a) 09G2S, b) 10HSND, c) 15HSND

Based on the calculation results, we evaluate the parameters, adjusted and obtained according to GOST Weibull, comparing the shift values with each other (Table 1-3).

**Table 1.** Sample parameters for steel 09G2S

<table>
<thead>
<tr>
<th>Options</th>
<th>Totality</th>
<th>Samples by volume of n=50</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>a</td>
<td>18706.93</td>
<td></td>
</tr>
<tr>
<td></td>
<td>By method</td>
<td>19351</td>
</tr>
<tr>
<td></td>
<td>Corrected</td>
<td>19013</td>
</tr>
<tr>
<td>b</td>
<td>1.14</td>
<td></td>
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<tr>
<td></td>
<td>Original</td>
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<tr>
<td></td>
<td>Corrected</td>
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<tr>
<td>x min</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Original</td>
<td>6031.8</td>
</tr>
<tr>
<td></td>
<td>Corrected</td>
<td>6702</td>
</tr>
<tr>
<td></td>
<td>Δ, %</td>
<td>10.004</td>
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Table 2. Sample parameters for steel 10HSND

<table>
<thead>
<tr>
<th>Options</th>
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<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>a</td>
<td></td>
</tr>
<tr>
<td>By method</td>
<td></td>
</tr>
<tr>
<td>According to GOST</td>
<td>249730.62</td>
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<tr>
<td>b</td>
<td></td>
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<tr>
<td>By method</td>
<td></td>
</tr>
<tr>
<td>According to GOST</td>
<td>1.22</td>
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<tr>
<td>x min</td>
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<td></td>
</tr>
<tr>
<td>According to GOST</td>
<td>15014.7</td>
</tr>
<tr>
<td>Δ,%</td>
<td>5.78</td>
</tr>
</tbody>
</table>

Table 3. Sample parameters for steel 15HSND

<table>
<thead>
<tr>
<th>Options</th>
<th>Samples by volume of n=50</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>a</td>
<td></td>
</tr>
<tr>
<td>By method</td>
<td></td>
</tr>
<tr>
<td>According to GOST</td>
<td>245237</td>
</tr>
<tr>
<td>b</td>
<td></td>
</tr>
<tr>
<td>By method</td>
<td></td>
</tr>
<tr>
<td>According to GOST</td>
<td>1.6</td>
</tr>
<tr>
<td>x min</td>
<td></td>
</tr>
<tr>
<td>By method</td>
<td></td>
</tr>
<tr>
<td>According to GOST</td>
<td>15014.7</td>
</tr>
<tr>
<td>Δ,%</td>
<td>5.78</td>
</tr>
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</table>

The analysis shows that the sample shift parameters differ by no more than 10%. Thus, this method can be used to determine the parameters of sample distributions.

After calculating the sample life of the boom with subsequent approximation by the Weibull law with three parameters, it is necessary to transition to the parameters of the three-parameter Weibull law for a set of finite resource volumes. To determine the parameters of a population of a finite volume, the “Grapho-analytical method” was used [14].

For basic parts, it is proposed to increase the resource value by changing design parameters, for example, increasing the endurance limit of steel by replacing the serial production steel of the part with a stronger one, and (or) reducing the effective stress by increasing the wall thickness or section dimensions, provided that the requirements are met [15-17].

In work [14], the service life values for the side wall of the boom are calculated and compared with variants of recommendations for the manufacture of the part. The recommendations included increasing the wall thickness from 10 to 12, and then to 14 mm of rolled sheet in the dangerous section of the part; replacing the used steel grade St3 (low-carbon) with low-alloy 09G2S or 15HSND; increase in the dangerous section of the boom up to 20%.
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