Prediction of service life of auto-tractor engine parts

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Abstract. Wear and fatigue are phenomena that limit to some extent the reliability of mechanical systems in almost any modern machine. Traditionally, reliability indicators of power parts of machines are evaluated differentially, according to individual criteria. This is often justified, since in the design of machines there are a lot of parts that “work” only on fatigue under repeated-variable loads. There are also parts that “work” exclusively in conditions of friction, sliding or rolling. However, in reality there are also mechanical systems in which a combination of both phenomena takes place. For example, these are such systems: “crankshaft-connecting rods of piston engines”; "gearing, camshaft-cam follower”; "axis bearings of centrifugal machines”; "details of the chassis of the car and tractor”; "wheels of rolling stock-rails of the railway track” and a large number of other critical structural elements of various machine components. Consequently, the entire range of scientific research in the design, manufacture and repair of machines should be aimed at ensuring fundamental transformations in technology and creating the prerequisites for the scientific justification of both methods for calculating the accuracy of mechanisms and all technological problems, from the design of the technological process as a whole to a thorough mathematical modeling of its individual components. The currently used methods for calculating the strength by safety factors in a deterministic formulation do not sufficiently take into account the scattering of the characteristics of fatigue resistance, the random nature of the loading of parts and do not provide an estimate at the design stage of the distribution function of the resource of machine elements. At the same time, it is possible to correctly determine the indicators of machine reliability and durability on the basis of these functions.

1. Introduction
At the present stage of mechanical engineering development, two directions in forecasting the resource of machines have steadily developed. The first area involves the study of operational reliability, having a formalized methodology in the form of guiding technical materials, standards, etc. The main disadvantages of this technique should be recognized as the significant duration of the initial information collection procedure and its quality.

The second direction in predicting the life of machines has been introduced in a number of engineering industries and is based on probable methods of calculating endurance under the condition of multi-cycle loading. The main advantage of this area is the ability to assess the durability of machines in specific operating conditions based on the results of laboratory and bench tests.
Often, the existing loads and stresses that occur in machine parts are random functions of time, and the characteristics of the component's fatigue resistance, such as service life, endurance limit, are random variables that have significant scattering.

The variability of the main factors that determine the strength characteristics of machines under operating conditions is the reason for the dispersion of their durability, especially with respect to machines of serial and mass production. The practice of operation and the results of fatigue tests of large batches of machines and their parts show that significant dispersion of their service life takes place before cracks or fatigue failure occurs. Based on this, methods for calculating strength should be based on the methods of probability theory and mathematical statistics [1-3].

Using probable methods when calculating fatigue, it is possible to determine the distribution function of the part’s life and to establish a relationship between its service life and reliability, estimated by the probability of failure-free operation.

The spread of fatigue properties also depends on possible deviations from the normal technological process (variation of the modes of heat and mechanical processing, welding, hardening processes, etc.).

It should be noted that the endurance limits of parts must also be considered as random. It is quite correct, when carrying out practical calculations, to accept the distribution of endurance limits as normal.

The variability of the degree of loading and tension for a sample of products, which is characterized by the distribution function of the stress amplitudes and the dispersion indices of the parameters of these functions, reflects the variability of the load of the general population of products in serial or mass production. These distribution functions describe the variability of the degree of loading of parts in various operating conditions of machines for which reliability and durability are determined by the criterion of fatigue resistance. Such distribution functions are established by measuring the loading and tension in the samples, sufficient for a statistical assessment of the parameters of these functions in a typical range of machine operating conditions (parts).

The choice of one or another method of calculating the strength at variable loads is determined by:

- the stage of calculation and design; the level of predicted reliability of the machine (product); the volume of the experimental data base; the nature of changes in loads and bearing capacity over time, etc. [4-7].

Nevertheless, even despite the significant advantages of this approach, methods for predicting the resource of machine parts at the design stage are practically not used. The reasons for this are mainly as follows: the reliability of the calculated indicators of resources; lack of sufficient skills necessary to schematize load conditions and determine indicators of fatigue resistance.

Their joint use can be considered the best way to overcome the shortcomings of the analyzed areas.

2. Research results

The results of theoretical and experimental studies indicate a significant effect of the wear processes on the fatigue resistance of the product under alternating loads and cyclic stresses in the volume of the part on the wear resistance of the counter body associated with it. Therefore, ignoring these factors in the traditional assessment of the reliability indicators of machine parts will contribute to the distortion of the results obtained, that is, the operational durability of the system elements can be significantly less than predicted based on the calculation results [8-11]. Therefore, an integrated approach is needed to assess the reliability indicators of mechanical systems according to the criteria of fatigue resistance and wear resistance.

The resource of machine parts with parallel and independent \( i \) of failure causes is determined by the minimum uptime \( \tau_i \):

\[
\tau_i = \min(\tau^{(1)}, \tau^{(2)}, \ldots, \tau^{(n)})
\]
Distribution function $Q_u(\tau_i)$ and probability density $q_u(\tau_i)$ of the minimum value $\tau_i$, are accordingly equal to:

$$Q_u(\tau_i) = \sum_{i=1}^{k} f_i(\tau) \left( 1 - \prod_{j=1}^{k} [1 - F_j(\tau)] \right),$$

$$q_u(\tau_i) = \sum_{j=1}^{k} \frac{f_i(\tau)}{1 - F_j(\tau)} \prod_{j=1}^{k} [1 - F_j(\tau)],$$

where $F_j(\tau), f_j(\tau)$ is distribution function and probability density of the $i$-th cause of failure as a result of separate consideration; $F_j(\tau), f_j(\tau)$ is distribution function and probability density of the remaining causes of failures.

The work of machine parts often occurs under the imposition of several causes of failure, the most typical of which are the combined effect of wear with cyclic (crankshaft), contact-cyclic (camshaft) and shock-cyclic (connecting rod head) loads.

In the case of resource distribution during normal wear and cycles to failure under cyclic loading (normal distribution of the transformed random variable $\ln(N_i - N_n)$), the distribution density can be calculated by the expression:

$$q_u(\tau) = \frac{1}{\sigma_e \sqrt{2\pi}} \exp\left\{ -\frac{(T_i - \bar{T})^2}{2\sigma^2} \right\} \left[ 1 - \Phi\left( \frac{\ln(N_i - N_n) - a_e}{\sigma_e} \right) \right] +$$

$$+ \frac{1}{\sigma_e (N_i - N_n) \sqrt{2\pi}} \exp\left\{ -\ln(N_i - N_n) - a_e \right\} \left[ 1 - \Phi\left( \frac{T_i - \bar{T}}{2\sigma^2} \right) \right].$$

where $\bar{T}, \sigma_i^2$ are, accordingly, average value and variance during wear; $a_e, \sigma_e$ – transformed random variable distribution parameters $\ln(N_i - N_n)$; $N_n$ – sensitivity threshold for cycles; $\Phi$ – Laplace function.

The value of the average resource of the crankshafts under the combined action of wear and cyclic loading can be calculated as follows:

$$\tau_{u-un} = \int_{0}^{\infty} T_i q_u(T_i) dT_i = \frac{AT_i}{2} \left[ 1 - \Phi\left( \frac{-\sqrt{2}}{2} \cdot \frac{\bar{T}}{\sigma_i} \right) \right] +$$

$$+ \frac{B}{2} \frac{\sigma_i^2}{\sigma_e^2} \sum_{k=0}^{n-2} (-1)^{n-k} \cdot \left( \frac{\sigma_i}{k} \right) \cdot \frac{(-\bar{T})}{\sigma_i}^{n-k} \cdot \left[ \frac{1}{\sqrt{2\pi}} I\left( \frac{k+1}{2} \right) - \Phi\left( \frac{T_i - \bar{T}}{\sigma_i} \right) \right],$$

where $A = 1 - \Phi\left( \frac{\ln(N_i - N_n) - a_e}{\sigma_e} \right)$ – the probability of failure of the shaft $N$ for cycles of multi-cycle fatigue; $B = \frac{1}{\sigma_e (N_i - N_n)} \exp\left\{ \frac{\ln(N_i - N_n) - a_e}{2\sigma_e^2} \right\}$ – ordinate of density of shaft $N$.
life distribution for fatigue failure cycles: 
\[ P \left( \frac{k+1}{2} \right) - \text{gamma function; } \Phi \left( \frac{-T}{\sigma_1}, k+1 \right) - \text{generalized probability function; } \left( \frac{n}{k} \right) - \text{binomial coefficient.} \]

The dispersion of the minimum shaft resource in the case of the combined action of wear and cyclic loading can be calculated by the expression:

\[
S^2(\tau_n - \tau_{nn}) = \int_0^\infty (T_i - \bar{T}_i)^2 g_n(T_i) dT_i - \frac{AT_i}{\sqrt{2\pi}} \sigma_i \exp \left( -\frac{\bar{T}_i}{(2\sigma_i)^2} \right) + \frac{A\sigma_i^2}{2} \left[ 1 - \Phi \left( \frac{\sqrt{2T_i}}{2\sigma_i} \right) \right] + \frac{B\sigma_i^3}{3\pi} + \frac{BT_i^3}{3} \left[ 1 - \Phi \left( \frac{T_i}{\sigma_i} \right) \right].
\]

Expressions (5) and (6) were obtained under the assumption that the performance of the crankshafts in the case of the combined action of two causes of failure is limited by wear. Similarly, the average shaft durability is determined when its destruction is limited by high-cycle fatigue.

We will consider the methodology for solving this on the example of camshafts of internal combustion engines. During operation of the camshaft, the cams are subject to wear and contact-cyclic loading. Thus, we write the distribution function \( q_n(N) \) of the minimum number of cycles before failure, taking into account the established laws of the distribution of the longevity of the cams during wear and contact-cycle loading as follows:

\[
q_n(N) = \frac{1}{\sigma_1 \sqrt{2\pi}} \exp \left[ \frac{(T_i - \bar{T}_i)^2}{2\sigma_i^2} \right] \left[ 1 - \Phi \left( \frac{\ln N - a_{e_2}}{\sigma_{e_2}} \right) \right] + \frac{1}{\sigma_{e_2} N \sqrt{2\pi}} \exp \left[ -\frac{\ln N - a_{e_2}}{2\sigma_{e_2}^2} \right] \left[ 1 - \Phi \left( \frac{T_i - \bar{T}_i}{\sigma_i} \right) \right],
\]

where \( a_{e_2}, \sigma_{e_2} \) are, accordingly, the parameters of the center and the scale of contact life distributed according to the normal law.

The value of the average number of cycles \( \bar{N}_p \) of contact destruction of the cam in the case of the combined action of two causes of failure is determined by assuming that the performance of the pair is limited by the contact durability of the surface layers

\[
\bar{N}_p = C \int_0^\infty \left[ 1 - \Phi \left( \frac{\ln N - a_{e_2}}{\sigma_{e_2}} \right) + \Omega \int_0^\infty \frac{1}{\sigma_{e_2} \sqrt{2\pi}} \exp \left( -\frac{\ln N + a_{e_2}}{2\sigma_{e_2}^2} \right) \right] dN,
\]

where \( C = \frac{1}{\sigma_1 \sqrt{2\pi}} \exp \left[ -\frac{T_i - \bar{T}_i}{2\sigma_i^2} \right]; \Omega = 1 - \Phi \left( \frac{T_i - \bar{T}_i}{\sigma_i} \right). \)

Taking into account that \( a_{e_2} = \ln \bar{N}_2 \) (\( \bar{N}_2 \) is a random value median of \( \bar{N}_{2n} \)) and successively replacing the variables, we will have:

\[
\frac{N_z}{\bar{N}_2} = x; dN = N_x dx; \ln x = z; dx = e^z dz.
\]
\[
\bar{N}_p = \frac{N_3^2 C}{2} \left[ \exp \left( \sigma_{T_2}^2 \right) - 1 \right] + \bar{N}_2 \exp \left( \frac{\sigma_{T_1}^2}{2} \right). \tag{10}
\]

Similarly, calculations are performed in the case of a minimum resource of machine parts that experience the combined effect of wear and shock-cyclic loading. In this case we will get:

- for density distribution:
  \[
  q_u(T_{\text{min}}) = f_1(T_1)[1 - F_2(T_2)] + f_2(T_2)[1 - F_1(T_1)]. \tag{11}
  \]

- for the minimum average resource:
  \[
  \bar{T}_u(T_{\text{min}}) = \Omega \sigma_2^2 \exp \left( \frac{-T_2^2}{2\sigma_2^2} \right) + \frac{T_2 \Omega}{2} \Phi \left( \frac{\sqrt{2}T_2}{\sigma_2} \right) + \frac{C \sigma_2^2}{2} \sum_{k=0}^{n} (-1)^{n-k} \left( \frac{n}{k} \right) \left( \frac{\bar{T}_2}{\sigma_2} \right)^{n-k} \left[ \frac{1}{\sqrt{2\pi}} f \left( \frac{k + 1}{2} \right) - \Phi \left( \frac{T_2}{\sigma_2}, k + 1 \right) \right]; \tag{12}
  \]

- for dispersion of the minimum durability:
  \[
  S^2(T_{\text{min}}) = \frac{T_2^2 \sigma_2^2}{2\pi} \exp \left( \frac{-T_2^2}{2\sigma_2^2} \right) + \frac{T_2 \Omega}{2} \left[ 1 + \Phi \left( \frac{\sqrt{2}T_2}{\sigma_2} \right) \right] + \frac{C \sigma_2^2}{3\sqrt{2\pi}} \left[ 1 - \Phi \left( \frac{T_2}{\sigma_2} \right) \right] \tag{13}
  \]

where \( T_2, \sigma_2 \) are parameters of the resource distribution of parts in the case of shock-cyclic loading; \( f_1(T_1), F_1(T_1) \) and \( f_2(T_2), F_2(T_2) \) are accordingly, the probability density and the distribution function of resources in the event of wear and shock-cyclic loading separately.

3. Conclusion
The durability of parts experiencing cyclic and contact-cyclic loading is adequately described by a log-normal distribution. For products operating under shock cyclic loading, it is legitimate to adopt the normal distribution law. The obtained theoretical dependences are recommended to be used for predicting the minimum average resources and indicators of their dispersion while imposing various causes of failure.

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