Stabilization of the loading characteristics in the durability analysis of the suspension components of tracked vehicles

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Abstract. For a reasonable and reliable assessment of durability at the design or operation stage of the tracked vehicles, it is required information about the loading process, which is usually obtained by registering the load by various methods, such as strain measurement. For a reliable assessment of loading and, consequently, durability, the question arises about the representative length of the loading process recording. The paper proposes a method for determining the necessary and sufficient realization length using various methods of processing of the recorded random loading realization. The efficiency of the proposed method is demonstrated by the example of the evaluation of the random loading processes in torsion shafts of the suspension systems of a high-speed tracked vehicle. The justification of the necessary and sufficient length of the record of the random loading process is given.

1. Introduction
The loads acting on a suspension system of tracked vehicles are random and depend on the movement conditions, as well as road conditions [1]–[4]. To assess the durability of suspension system elements, it is necessary to have information about the operational loading level, which can be obtained both experimentally[5]–[7] and using methods and means of numerical modeling of working processes [8]–[11].

Information about the loading process is usually presented in the form of distribution of stress amplitudes with the corresponding number of repetitions during operation. The distribution of stress amplitudes is usually obtained by processing the loading processes recorded during service with performing of some of cycle counting methods or by considering random processes of the structural elements by using the spectral density [12].

While planning an experiment for the collection and processing of information about the loading, a number of methodological issues arise that have not yet received the final scientific recommendation, in particular, about the necessary and sufficient length of the registered loading process. It should be noted that the analysis of random processes for the purpose of subsequent evaluation of durability has its own specifics due to the fact that information about the amplitude spans and the number of repetitions of spans is the most important for the fatigue evaluation [13]. They are the characteristics of the random process that have the greatest impact on the accumulation of fatigue damage, both at the stage of origin and at the stage of development of fatigue cracks [14]. In work [15] the example of
stabilization of the value of mathematical expectation (MO) with an increase in length of realization of the loading process is considered. It is recommended to consider the realization length at which the value of the MO of the loading process is stabilized and does not go beyond the previously accepted error sufficient for a reasonable assessment of realization durability.

The choice of the required length of realization depends on the considered structural elements and their operating conditions. The standard recommends the use of realizations with at least 1000 extremums length. This recommendation needs to be clarified. First, the number of selected extremums strongly depends on the number of partition classes of the random process by ordinate, i.e. is determined by the accuracy of registration of the random loading process. According to GOST the process is previously divided into classes, the width of the class Δ is by the formula:

\[ \Delta = \frac{\sigma_{\text{max}} - \sigma_{\text{min}}}{M} \]  

where \( \sigma_{\text{max}} \) and \( \sigma_{\text{min}} \) — are the maximum and minimum of the random process in this realization; \( M \) — is the classes number, which is chosen in the interval.

Secondly, the experimental data are known [16], when the number of extremes in the realization can be reduced by 10 times with proper selection of the filtration band of the process. In this case, the value of durability, expressed in the number of loading blocks, changed only by 10%.

In the analysis of loading in General, it is necessary to consider a generalized process consisting of partial random processes recorded under different operating options, which will be further used to assess the durability in service [17]. The purpose of this work is to select the required length of realization to assess the durability of the chassis elements of high-speed tracked vehicles. To obtain a stable estimate of the loading it is necessary that at each of the partial loading modes its characteristics should be stable. At the same time, the load characteristics of each mode are evaluated. To justify the selection of the length the realization of random processes it was considered how the changes in the value of the calculated longevity \( N_\Sigma \) with the increasing length of the realization varies. Measure responsible for the value of \( N_\Sigma \) might be a function of accumulated cycles \( \Omega = n(\sigma_a) \), or block loading, where \( n \) is the number of cycles of repetition of the stress amplitude \( \sigma_a \). The function \( \Omega \) is defined by processing a random process using one-parameter, or two-parameter schematization method [18]. The characteristic of the loading unit \( \Omega \) is also its length \( l_b \), the value of which, depending on the type of problem, can also be expressed in the numbers of loading cycles, hours, kilometers, etc.

If the realization by which the durability of the stationary process is evaluated is short, the evaluation of \( \Omega \) of the resulting load spectrum is unstable, which leads to significant deviations in the durability evaluation. The longer the realization, the less deviation. The evaluation of durability expressed in the number of blocks of loading calculated for a hypothetical infinite realization denoted as \( N_\Sigma (\infty) \). We denote the evaluation of durability for the realization of the limited length \( L \) as \( N_\Sigma (L) \). When increasing the length of the realization of a stationary random process, a limit exists:

\[
\lim_{L \to \infty} \frac{N_\Sigma (L)}{N_\Sigma (\infty)} = 1
\]  

where \( N_\Sigma (\infty) \) is a hypothetical infinite realization; \( N_\Sigma (L) \) — realization of the limited length.

Since there is no physical possibility to measure the stresses on infinite realization, it should be limited by the available length of realization, providing the required accuracy \( \varepsilon \) of the assessment of \( N_\Sigma \). The error of the evaluation of the durability of \( \varepsilon \) depending on the length of the realization is set in each case, taking into account the requirements for the accuracy of the evaluation of the durability. In this regard, you can determine the necessary and sufficient length of the realization \( L_{NS} \). If there is a limit (2) for some random loading process, the necessary and sufficient realization length \( L = L_{NS} \) can be determined from the condition:
\[
\left| \frac{N^*_{\Sigma}}{N_\infty} - 1 \right| < \varepsilon (3)
\]

where \( \varepsilon \) is a accuracy \( \varepsilon \) of the assessment of \( N_{\Sigma} \).

2. Research Methodology
For the durability estimation of the torsion shaft of the suspension system for tracked vehicles, the stress recording was conducted (torsion in the high-cycle domain) while driving tracked vehicles on forest dirt roads (Fig. 1), which corresponds to the actual operating conditions.

![Figure 1. The test tracks](image1)

![Figure 2. Measuring equipment mounted on the hull and suspensions of the tracked vehicle](image2)
Determination of kinematic and loading parameters was carried out with the use of specialized measuring equipment installed on the machine hull (Fig. 2), by recording the angles of twist torsion shafts.

The system of reception and processing of data is implemented on the basis of a portable computer. As the sensors of the angle of twist of the torsion shafts resistors - potentiometers R-24N1-B10K firms HUEI SONG with a nominal impedance of 10 kΩ were used. To convert the analogue signal into digital code, an analogue-to-digital Converter (ADC) E14-140M, was used. The sensors were connected to the ADC via three channels using a differential connection scheme, which ensures optimal suppression of interference from the external environment induced on the connecting wires (Fig. 3).

Figure 3. Electrical diagram of the measuring system

The total mileage of the vehicle on the test tracks of latching the input signal was of the order of 50 km. In the course of the experiment was formed by 18 independent samples. Recording of the input signal was carried out at a frequency of 20 Hz, which is sufficient to record low-speed suspensions at high speeds.

A set of programs in the R language was developed to process the obtained random processes [19]. In accordance with the software provides the following operations preceding cycle-counting:

- Quantization - splitting the process by levels horizontally;
- Discretization - replacing a continuous process with a sequence of random ordinates;
- Selection of extremes;
- Calculation of the coefficient of irregularity \( \chi \).

Since the loading processes are random, the spectral analysis was often used for their study. As a rule, in terms of the spectral density of a random process, the researchers use the coefficient of irregularity of the random process \( \chi \) [12, 20], which serves as a measure of the complexity of the random process and is defined as the ratio of the number of intersections of the average level to the number of extremes:

\[
\chi = \frac{N_0}{N_e} \tag{4}
\]

where \( N_0 \) — is the number of intersections of the middle level process, \( N_e \) — is the number of extremums.
After the preliminary stage, the random sequence is undergone by cycle-counting procedure. The results of the method of extrema, the range method scope and the rain-flow method were compared. As it was shown earlier, the longevities, estimated by the method of extrema and the range method, can serve as top (for range method) and lower (for the extrema method) the evaluation of durability. The most preferable method is the rain-flow method. The fatigue curve equation in the following form was used to estimate the durability:

$$\sigma_a^m N = \sigma_{-1}^m N_G$$  \hspace{1cm} (5)

where $\sigma_a$ — is the amplitude of stress, MPa; $N$ —is the limit number of cycles to failure for $\sigma_a$; $\sigma_{-1}$ — is the endurance limit; $m$ —is the fatigue exponent; $N_G = 2.106$.

In this study, the fatigue curve was recorded in relative terms:

$$N = N_G \left( \frac{1}{n_p} \right)^m$$  \hspace{1cm} (6)

where $n_p = \frac{\sigma_a}{\sigma_{-1}}$.

To justify the required realization length, it is necessary to assess the influence of stability of information on loading on the error of durability estimation. To assess the durability, it is necessary to know not only the fatigue resistance characteristics of the considered structural element (5) and their scattering, which are obtained experimentally or by calculation, but also the hypothesis of fatigue damage accumulation. It is recommended to use a simplified corrected hypothesis of fatigue damage summation, obtained as a result of the analysis of a large number of experimental data on the evaluation of durability at different distributions of stress amplitudes:

$$\lambda_b \sum_{i=1}^{k} \frac{n_i}{N_i} = 0.25$$  \hspace{1cm} (7)

where $\lambda_b$ — is the estimated number of blocks to failure; $n_i$ — is the number of cycles of repetition of the amplitude of the stress $\sigma_i$ in a block loading, $N_i$ —is the limit number of cycles on the fatigue curve obtained with regular loading, corresponding to the amplitude $\sigma_i$ determined from the equation of the curve of fatigue.

The total number of cycles before failure:

$$N_x = \lambda_b L$$  \hspace{1cm} (8)

Using formula (7) after substitution in (8) we obtain:

$$N_x = \frac{0.25 L}{\sum_{i=1}^{k} \frac{n_i}{N_i}}$$  \hspace{1cm} (9)

In the formula (9) the numerator and denominator increase with increasing length of the realization $L$. The Denominator is increasing, since the longer the realization, the more cycles recorded $n_i$. With increasing $L$, the value of the calculated resource $N_x (L)$ is stabilizing. Length of realization, in which the value of $N_x$ is stabilizing will be necessary and sufficient for a given random process realization of the loading $L_{s0}$ to compute durability with the acceptable accuracy.

3. Research results

As a result of the experimental study, time diagrams of changes in the angles of torsion shafts twist when moving a tracked vehicle over rough terrain are obtained. The conversion of the initial kinematic parameters to the values of shear stresses was carried out according to the following dependence
\[ \tau = \frac{((\beta_{st} - \beta_0) + \gamma) \cdot G \cdot d_m}{2 L_m} - \tau_{rs} \] (10)

where \( \gamma \) — is the angle of twist of the torsion shaft; \( \beta_{st} \) — is the static angular position of the road arm; \( G \) — is the modulus of elasticity of the second kind of material of the torsion shaft; \( \beta_0 \) — is the angular position of the road arm at zero twist position of the torsion; \( L_m \) — is the length of the torsion shaft; \( d_m \) — is the diameter of the torsion shaft; \( \tau_{rs} \) — is the level of the residual stresses in the torsion shaft.

The value of the residual stresses in the surface layers of the torsion shaft approximately can be determined by the formula:

\[ \tau_{rs} = \tau_y \left( 1 - \left( \frac{\eta}{R_T} \right)^3 \right) \] (11)

where \( \tau_y \) — is the yield strength; \( \eta \) — is the radius of the elastic layer of the material of the torsion shaft; \( R_T \) — is the radius of the torsion shaft.

The most stable mechanical characteristics of the material of the torsion shaft after the operation are obtained at the following ratio, characterizing the depth of plastic deformation:

\[ \frac{\eta}{r} \approx 0.5 - 0.6. \] (12)

The obtained implementations of the random loading process with the indication of the main statistical characteristics are shown in figure 4.

It should be noted that the value \( \chi \) is very conditional and is strongly dependent on the number of quantization levels of the random process \( M \), as can be seen in Fig. 5, where the dependencies \( \chi (M) \) are shown for the resulting implementations. The coefficient of irregularity of processes determined by the formula (4) on average for the considered processes was estimated as \( \chi = 0.55 \). As the number of classes \( M \) increases, the value \( \chi \) increases. It is shown that with a decrease in the number of partition classes, the value of \( \chi \) increases by almost 1.5 times compared to a more detailed division.

Fig. 6 shows the relationship estimated on the basis of the method of extrema and the method of ranges calculated life \( N \) to \( N_d \) calculated based on the method of rain flow with variable fatigue exponent \( m \). We see that the difference in calculated longevities is quite valuable, especially with increasing of \( m \). This discrepancy is especially important for the processes with complex structure.

In Fig. 7 the dependences of the calculated life obtained for the realizations presented in Fig. 4 are shown. The fatigue curve was recorded in relative form (6). For realizations No2, No3 and No4 the condition (3) is performed at a necessary and sufficient length, that is \( L_{NS} = 1.5 \) min. To realization No1 stabilization is not observed even when the record length reach 2.5 min.
Figure 4. Implementation of random processes of shear stress changes in the torsion shaft of a tracked vehicle.
Figure 5. The dependence of the calculated coefficient of irregularity $\chi$ on the number of classes of a random process $M$.

Figure 6. Comparison of relationships of life calculated by the method of extrema and the range method to one, calculated by the method of rain flow.
Figure 7. Dependence of calculated durability on realization length, \( m=6 \).

4. Conclusion
As a result, the technique on the determination of necessary and sufficient length of realization of a random process is offered. Using the developed technique, the problem of determining the necessary and sufficient length of the realization of a random loading process is solved by the example of assessing the durability of the torsion shaft of an individual suspension system. The proposed method can be used in planning the investigation of the loading of high-speed tracked vehicles suspension system elements.

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