Fatigue Life Prediction of Track Link of a High-Speed Vehicle

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Abstract The paper presents a methodology for calculating the fatigue life of tracks of a high-speed tracked vehicle. The methodology includes computer simulation of motion of the machine on the road, calculation of loads acting on the tracks of tracks, stresses in the most stressed areas of the tracks, and prediction of durability by the criterion of fatigue failure. In the simulation of motion, the dynamic properties of the projected machine and the typical operating conditions in different climatic conditions are taken into account. The characteristics of loading are determined by the results of full-scale field tests. The maximum stresses in the tracks occur under the action of random loads from the ground. Ground is regarded as a Winkler half-space with randomly distributed elastic elements. To calculate the stresses in the most loaded zones of the tracks, a technique based on the principle of independence of the action of forces and the use of the finite element method is proposed. In different loading cycles, the relationship between the components of the stress tensor in the most stressed zone is different. The loading of the track is multiparameter. Therefore, a special method was used to calculate the accumulated fatigue damage. The article presents the results of using the proposed methodology for predicting the fatigue life of tracks of tracked transport vehicles.

Keywords Tracked vehicle · Track link · Stochastic load · Winkler foundation
Fatigue failure

1 Introduction

At present, caterpillars with rubber–metal hinges are widely used on high-speed cars. The use of such hinges allowed to increase 2–3 times the average life of caterpillars due to the replacement of abrasive friction in hinged joints by torsion of

a clamped rubber mass. In this case, mass fatigue destruction of the tracks, which limit the further increase in the reliability of caterpillars began to appear. In this regard, the actual task is to predict the fatigue life of tracks of caterpillars in the early stages of design [1–4].

Features of loading during machine movement were investigated on the basis of experimental data. With the help of special measuring devices, the processes of time variation of stresses in the most stressed sections of the examined track were recorded. The experiments were carried out with the movement of a high-speed tracked vehicle at various speeds in various road conditions Analysis of the data shows that the maximum stresses occur in the supporting part of a caterpillar, as well as the passage of the idler wheel and the drive sprocket [5, 6]. In this case, the main accumulation of fatigue damage occurs.

In the supporting part, the greatest stress pulses occur when the track under test is loaded with support rollers. The load acting on the support rollers changes with the machine body oscillating. The track under investigation with each loading by the support roller interacts with different parts of the soil, which have a different surface shape and different rigidity. Therefore, the magnitude and sign of the stresses in the most stressed zone of the track change randomly during each loading. A soil model in the form of a Winkler half-space with randomly distributed elastic elements was proposed in [7–9]. The use of this model allows to describe the random nature of loading the track from the side of the ground. The parameters of the soil model and the results of the calculations are presented in [9].

The solution of the task of predicting the resource of tracks of caterpillars includes four consecutive stages [10]:

- Computational modeling of the movement of a machine along a path using a mathematical model [11, 12]. Traffic conditions correspond to a typical route in a given region. As a result, continuous random processes of changing the roller loads are obtained. These processes are converted into random impulse flows of forces acting on the tracks from the side of the track rollers, the drive, and the steering wheel.
- Modeling the interaction of the tracks with the ground and suspension elements (support rollers, adjacent tracks, drive sprocket, and idler wheel). In this case, the loads obtained at the previous stage are used. Soil is considered as an accidental pliable environment [11].
- Calculation of the values of stress pulses in the investigated zone of the track. Evaluation of the longevity of vehicles by the criterion of fatigue failure.

In the article, the methods of calculation of stresses in the most loaded zone of the track and the estimated evaluation of durability by the criterion of fatigue failure are presented.

2 Methods

The procedure for calculating the values of the stress pulses in the area of the track under investigation is based on the assumption that the body of the track operates as a linearly elastic system [13]. Since in the investigated point of the detail with the number "k" in the general case a volumetric stress state is realized, calculations must be performed for all components of the stress tensor. In the future, the calculation technique is illustrated by the example of one component of the stress tensor σ^k.

In accordance with the principle of superposition, the stress at the considered point of the construction can be represented as the sum of the products of the loads by the corresponding coefficients of influence. The coefficient of influence is equal to the stress arising in the considered zone of the track under the action of a unit force. The stress that occurs at the kth point of the track when it is loaded by the support roller is

$$\sigma^k = [R_i]^{\mathrm{T}}[\omega_{\mathrm{gi}}^k] + P_{\mathrm{r}}\omega_{\mathrm{r}}^k + F_{\mathrm{t}}\omega_{\mathrm{t}}^k \tag{1}$$

where $[R_i]$—a column of forces acting on the supporting surface of the track from the side of the ground; $[\omega_{\mathrm{gi}}^k]$—column of the corresponding coefficients of influence for the point under study; ω_{r}^k, ω_{t}^k—the coefficients of influence from the action of the force on the side of the supporting roller and the tensile force from the side of the neighboring tracks; P_{r}—force from the side of the skating rink; F_{t}—tensile force from neighboring tracks (Fig. 1).

The magnitude of the stress pulse arising in the track as the guide wheel passes (σ_{gw}^k) is proportional to the force in the free branch F_{fb}. The magnitude of the stress pulse arising when the drive wheel passes (σ_{dw}^k) is proportional to the tension of the working branch F_{wb}.

Fig. 1 Loads acting on the track
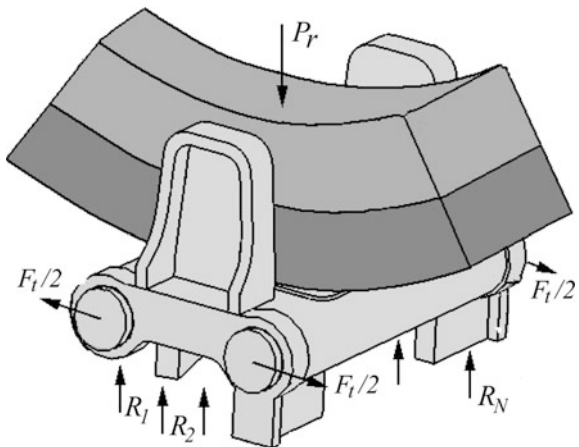
$$\sigma_{\mathrm{gw}}^{k} = \omega_{\mathrm{gw}}^{k} F_{\mathrm{fb}}, \quad \sigma_{\mathrm{dw}}^{k} = \omega_{\mathrm{dw}}^{k} F_{\mathrm{wb}} \tag{2}$$

where ω_{gw}^{k}, ω_{dw}^{k}—coefficients of influence. Similar expressions can be written for each component of the stress tensor at the point under consideration.

Each of the coefficients ω_{gi}^{k} is equal to the voltage arising at the point "k" of the track from the action of a single force $R_i = 1$. To calculate these coefficients, the finite element method is used. It is practically impossible to determine the ω_{gi}^{k} loading of a track with only one force, since in this case the conditions for the equilibrium of the track will not be fulfilled. In accordance with the proposed method, when calculating the track, they are fixed in three arbitrarily chosen points. Then, successively, one unit of force is applied at the points of supposed support on the ground and the stresses are calculated at the point under study. The resulting voltages are the coefficients of influence [ω_{gi}^{k}]. Analogously determine the coefficient of influence from the side of the skating rink. In the future, when loading the track with a system of self-balanced reaction forces in additional supports, they will be zero, so their presence does not affect the result. Verification of this method has shown its effectiveness in practical use [13].

The coefficient of influence from the action of the tensile force in the caterpillar belt is determined when the track is loaded with individual tensile forces. The influence factors for the loads of the master and guide wheels are calculated in a similar way.

Thus, at this stage, an array of values of the stress tensor components is obtained at the track point under consideration at each loading by the rolling machine roller, and also when the driving and guiding wheels pass.

At the next stage, the longevity of the tracks is evaluated by the criterion of fatigue failure. The methods [14–17] are used for calculating the fatigue life of a multivariable random loading. Loading of the track is a special case of a multivariable random loading. Studies have shown that, in the process of each loading, the components of the stress tensor change proportionally at the point under consideration, the position of the main sites remains unchanged. For this type of loading, a special method of calculating fatigue life is proposed in [18, 19]. The accumulation of damages in a series of different inclined areas in the vicinity of a dangerous point is considered. It is assumed that the accumulation of damage in each site occurs independently of the remaining sites. For each site, the accumulation of damage is determined by tangential stresses and is calculated in accordance with the linear hypothesis of summation of damage. The fracture occurs on the site that has accumulated the greatest fatigue damage.

To obtain a computational estimate of the longevity of the track, a simulation of the movement of the machine along a typical route having sections with different surface profile is performed. The notion of specific fatigue damage equal to the fracture fraction accumulated at the point "k" per kilometer over the section of the route with a typical surface profile number "j" is introduced. The subsequent analysis of the values of specific damages makes it possible to identify the most

dangerous point that determines the fatigue life of the track. When driving along the road, the average fatigue life of the track, expressed in kilometers of run before the formation of a fatigue crack, is determined by the following expression:

$$L_{cp} = \left[\sum_{j=1}^{M} v_j \psi_j \right]^{-1} \tag{3}$$

where v_j—the proportion of total destruction accumulated per kilometer over the section of the route with a typical micro profile number "j"; ψ_j—the relative length of the sections with such a micro profile for the path being investigated; M—the total number of typical plots.

The presented technique was used to predict the longevity of track tracks of the CHETRA TM-140 tracked transport vehicles manufactured by the "Kurganmashzavod" [20]. Tracks caterpillars are made of alloy steel. Fatigue characteristics of the part are as follows: mathematical expectation of the endurance limit of 165 MPa; the coefficient of variation of the endurance limit is 0.1; the slope of the endurance curve 7; basic number of cycles $N_0 = 2 \times 10^6$. To calculate the coefficients of influence, the ANSYS MCE software package was used. The finite element model of the track is shown in Fig. 2a; a picture of the stressed state when the track is loaded by a single force from the side of the support surface—in Fig. 2b. As shown by the analysis of the results of preliminary calculations, the most loaded are the belt edges of the track. In these zones, the most loaded points were chosen, and for them the calculations of the accumulated damage were subsequently performed.

The load on the side of the support roller is transmitted to the tract via a flexible rubber tire; the contact area depends on the load. Therefore, in calculating the coefficient of influence, the model of the supporting roller, which has an internal metal part and a compliant rubber tire (see Fig. 1), was additionally introduced. To determine the coefficient of influence from the tensile load acting in the caterpillar
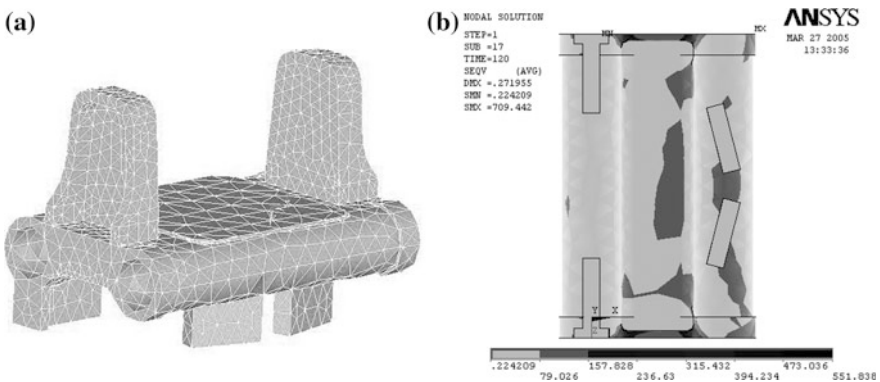

Fig. 2 **a** Finite-element model of the track; **b** stressed state when the track

Table 1 Characteristics of the typical surface profiles

Type of surface profile	Average height of unevenneess, sm	Average length of unevenness, m	Mean square deviation, sm
I	1.7	4.8	0.73
II	7.4	10.1	2.04
III	12.4	12.2	5.44
IV	18.6	12.9	11.94
V	31.7	15.8	17.62

Table 2 Characteristics of the run

Type of surface profile	Relative length of sites (ψ_j)	The speed of movement (m/s)	Percentage of fatigue damage per km (v_j)
II	0.182	11	2.814×10^{-5}
III	0.309	8	4.048×10^{-5}
IV	0.364	7	5.262×10^{-5}
V	0.145	6	9.024×10^{-5}

belt, a model of the track with the fingers and rubber elements of the hinges was used. A tensile load was applied to the fingers.

Calculations of the longevity of the track were performed for a route having sections with different surface profiles (Table 1). Areas with a surface profile type I are the lightest and allow the greatest speed of movement, type V—the heaviest. The relative length of sites with surface profile of different types, the speed of movement along these sections and the percentage of fatigue damage per km of run are shown in Table 2. The case of movement along a rigid road (rocky terrain, frozen soil, foundation modulus of 40 MN/m³) was considered when the greatest accumulation of fatigue damage occurs.

In the process of calculations, studies were conducted aimed at identifying the influence of various factors on the life of the track. With an increase in the speed of the machine along the road, the body oscillations increase, which leads to an increase in the loads on the support rollers and, consequently, to an increase in the accumulated damage. The results of calculations for the traces with a surface profile type III are shown in Fig. 3a. Increasing of the rigidity of the soil leads to an increase in the damage accumulated per kilometer of run (Fig. 3b).

The average estimated longevity of the track when driving the machine under conditions analogous to this route is 20,000 km. Figure 4 represents the functions of failure-free operation, corresponding to the moment of origin of fatigue micro-cracks on the track surface. The gamma-percentage resource ($g = 0.9$) is equal to 8000 km. The results obtained are in satisfactory agreement with the data on mass exploitation.
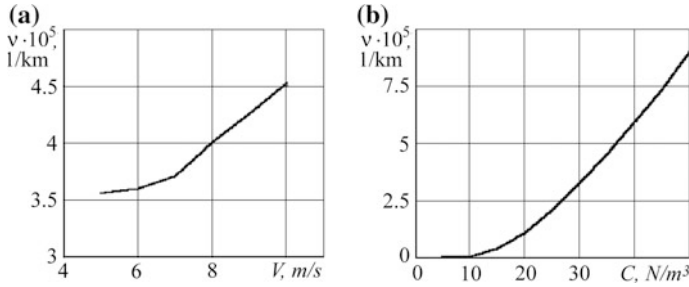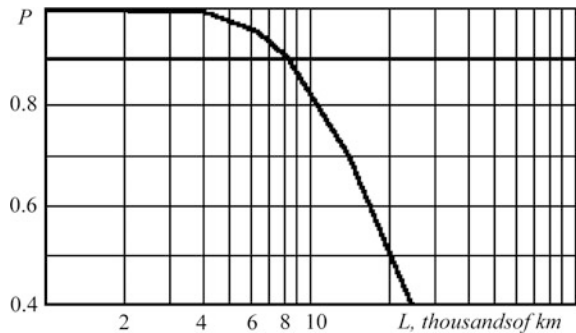
Fig. 3 **a** Dependence of damaged from the speed of movement; **b** dependence of damaged from the foundation modulus

Fig. 4 Function of failure-free operation

3 Conclusion

The article presents the results of using the proposed methodology for predicting the fatigue life of tracks of tracked transport vehicles. The use of the proposed methodology makes it possible to take into account the influence of operating conditions and the characteristics of machine on the fatigue life of the tracks. The influence of operating conditions on the longevity of tracks was investigated. The results predicting of fatigue life are in good agreement with the data on the mass exploitation of machines.

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