

## FATIGUE LIFE PREDICTION OF THE GEAR BOX IN TRACKED VEHICLES BASED ON RUNNING SIMULATION TESTS

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*The static strength theory became the basis for the design of the gear box in tracked vehicles. The dynamic characteristics of the gear box under different working conditions cannot be evaluated accurately, the reliability and fatigue life are difficult to study due to the limit dons of conventional tests and experimental techniques, the service life of the gear box was much shorter than the design one, thus the reliability of tracked vehicles was also affected deeply. The dynamic load of each part of the gear box under different working conditions was evaluated by setting up an MSC.ADAMS test program. The actual load applied to the fatigue life prediction system of the gear box provides the fatigue lives of box-related parts. The fatigue life prediction method of the gear box was verified as to its feasibility with running simulation tests.*

**Keywords:** gear box, running simulation, fatigue life prediction.

**Introduction.** Tracked vehicles, which play an important role in modern military, agricultural, construction and other fields with good cross-country ability, usually have gear boxes in their chassis system [1, 2]. About 50~70% of mechanical parts of tracked vehicles undergo the fatigue failure, due to their heavy-duty working conditions [3], while the actual life of gear box designed via static strength theories with no account of true operational loads is was shorter than the design life. Therefore, the gear box fatigue life has to be predicted for the dynamic loads sustained by the particular tracked vehicle.

However, the dynamic load data for the transmission case of tracked vehicles are limited by the test conditions and the measuring methods. There are always differences between the true operational and laboratory test conditions, so the determination of working load becomes the bottleneck constraint in determining the fatigue life of each critical component of tracked vehicle. With the increasing development of computer simulation technology and multi-body dynamics, it became possible to alleviate these drawbacks of traditional design methods and solve complicated problems [4–6]. In this study, a running simulation platform of a tracked vehicle's transmission system was built, which can obtain dynamic load of the tracked vehicle gear box under different conditions. It was significance in life prediction of the tracked vehicle transmission, especially in predicting life of heavy machinery or very large machinery, determining the overhaul cycle of tracked vehicles and preventing accidents.

### 1. Dynamic Load Suffered by Tracked Vehicles.

**1.1. Traditional Methods of Load Determination.** The load-caused fatigue damage can be called fatigue load, which can be divided into two categories [3]:

(1) Identified fatigue load. It changes by a certain rule and can be described by a definite time function. The simplest form is the constant amplitude sinusoidal load.

(2) Random fatigue load. It is an irregular load that cannot be described by a definite time function. Most of the working loads of vehicle transmission systems are random fatigue loads, which can only be statistically described.

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At present, the study of determining the random load belongs to an immature stage. Therefore, the accumulation of data is insufficient, while traditional methods of load determination are experimental determination and mathematical analysis. The introduction of two methods can be found in reference [3].

Random fatigue load can be measured by road tests, where the total load statistics is provided and working life can be properly estimated. However, the life of a new designed part is often difficult to accurately estimate. In fact, it needs to be tested through 50–100 thousand km of roads testing, which requires from one to two years, is cost- and labor-consuming. Moreover, the operating conditions are very complicated, and the measured load under all driving conditions has to be adopted. Theoretically, the obtained data are more reliable but the test period is too long to be used in the design phase. Instead, most of the typical short-distance measurement is applied to a typical pavement, and then the principles of mathematical statistics are used to organize and infer, and finally compile the load spectrum. Although there is still a high requirement for the selection of test sections and data-processing devices for them [7–9], there is a big difference between the true load and that obtained by the short-distance test, and the commonality of data is poor. Therefore, fast and accurate requirements to obtain dynamic data were put forward.

Due to the limitations of test conditions and means, the tracked vehicle transmission system was designed without random load test. Only the empirical design and static strength design theory were used to determine the structural parameters. The life of the tracked vehicle was not evaluated. In fact, the fault frequency of tracked vehicles was so high that it seriously affected the reliability of the tracked vehicle. Although the load suffered by the transmission system was significant, the test data measured by the training site was poor commonality. It was not possible to make a reasonable analysis of the component load under all load conditions. Therefore, rapid and accurate access to dynamic load observed in different mission profiles was an important factor for accurately estimating the residual life of the tracked vehicle.

With the successful application of computer simulation technology in vehicle engineering, running simulation test provides a reasonable, rapid and accurate technical approach for obtaining the dynamic load of transmission system in different driving conditions. And it not only provides reliable load data for dynamic analysis and life prediction, but also furnishes a quantitative basis for dynamic optimization design of tracked vehicles.

## **2. Running Simulation Test Based on ADAMS.ATV.**

**2.1. Construction of the Running Simulation Test Platform.** The ATV Toolbox is the ADAMS's specialized toolbox for tracked or wheeled vehicles, which is used to study the dynamics of vehicle models on a variety of road surfaces at different speeds. It was widely used to analyze the dynamic performance of various types of military and commercial tracked or wheeled vehicles. The running simulation can obtain dynamic data, which are closely related to the structural design and dynamic performance of tracked vehicles. The data can provide an effective technical approach for the ultimate realization of virtual manufacturing, optimization design and performance prediction of tracked vehicles [1]. In this paper, the inverse Fourier transform method was used to simulate the roughness signal of A-H road, which was converted into the geometric shape of the road surface at all levels. Two-dimensional step pavement and three-dimensional H-level pavement are shown in Figs. 1 and 2, respectively.

Figure 3 depicts the ATV model of the tracked vehicle in running simulation platform. Based on it, the tracked vehicle system was expanded by applying the load, restraint, and displacement values.

**2.2. Verification of the Running Simulation Platform.** In order to verify the rationality of the established virtual prototype model of tracked vehicle, the time domain history of the vertical acceleration of the second wheel of tracked vehicle was obtained through the real field test. The adopted test scheme is shown in Fig. 4. According to the test requirements, the acceleration sensor was installed on the second axle of the tracked vehicle with its physical installation is shown in Fig. 4. The acceleration sensor was fixed on the bracket convex platform and protected by the protective cover. The fixed bracket convex platform was connected with the load wheel shaft through the thread structure to ensure that the road excitation signal was obtained by the acceleration sensor [10–12].

Tracked vehicle traveled at a constant speed of about 8.1 m/s on the farmland after autumn, as shown in Fig. 5. The measured vibration signal was recorded in the acceleration test system. Time domain response of the vertical acceleration in the tracked vehicle and frequency domain response is shown in Fig. 6, which was obtained by



Fig. 1. Two-step road spectrum.

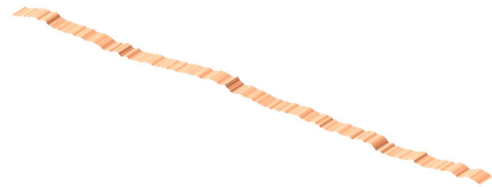


Fig. 2. Three-grade H road spectrum.

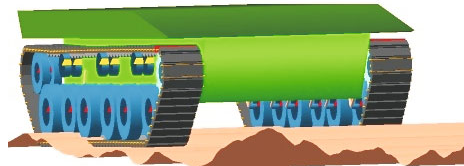


Fig. 3. The model of a tracked vehicle under road spectrum.

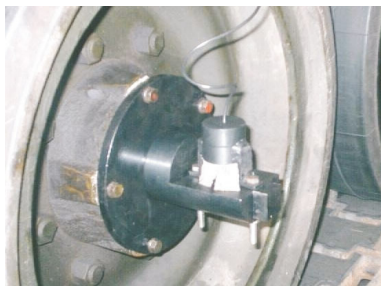


Fig. 4. The assembly location of acceleration sensor.



Fig. 5. Tracked vehicles driving steady on farmland.

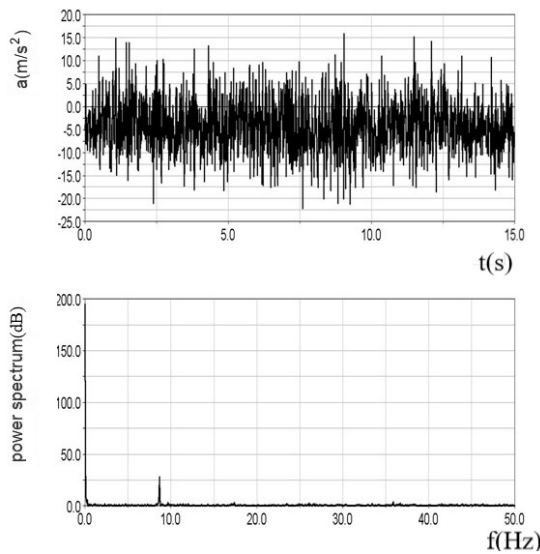


Fig. 6

Fig. 6. Land vehicle road vertical acceleration response and power spectrum.

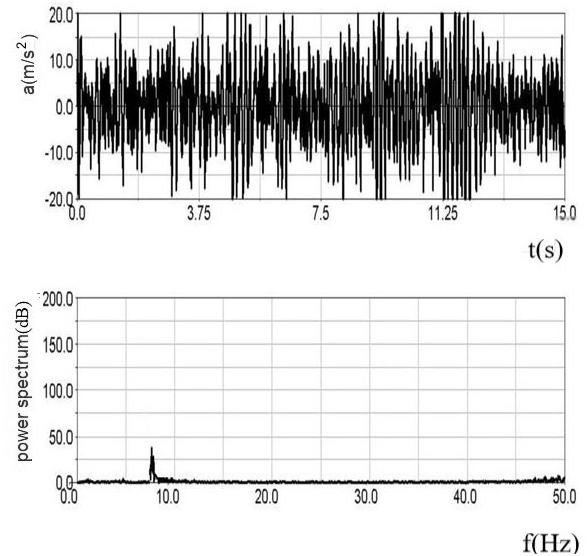


Fig. 7

Fig. 7. Land vehicle road vertical acceleration response and power spectrum (simulation).

processing the measured time-domain signal of the vertical acceleration of the second track wheel in the tracked vehicle into the computer. Time domain response and frequency domain response in the same conditions are shown in Fig. 7 through the construction of the running simulation platform [13–15].

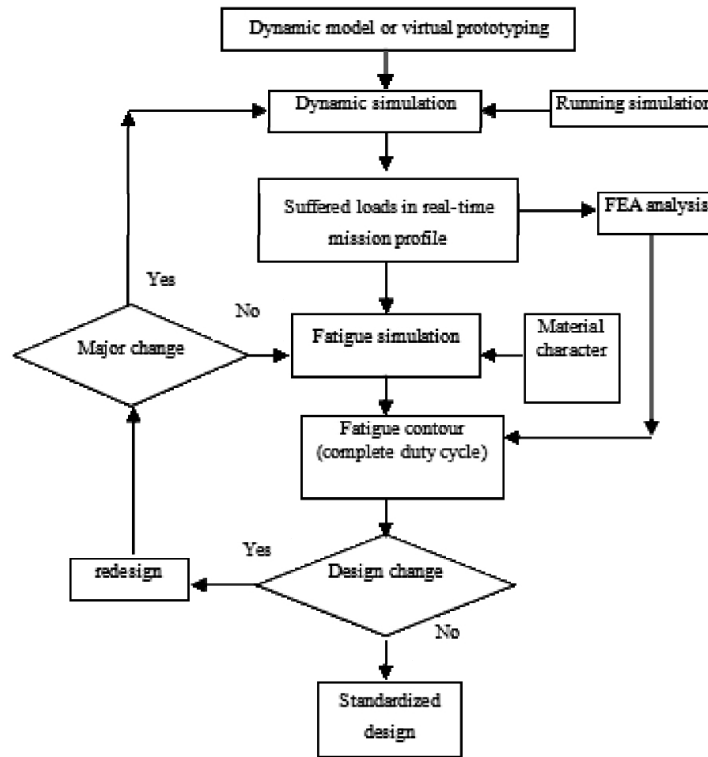


Fig. 8. Flowchart of fatigue life prediction of transmission case based on running simulation.

Comparison of the power spectrum of the simulation results with the experimental results for the tracked vehicle shows that these are basically the same, which verifies the feasibility of replacing the tracked vehicle object by a running simulation platform. However, due to the partial simplification of the tracked vehicle model process, the virtual prototype of tracked vehicle can only approximate the real system of tracked vehicle to a certain extent. If the error between the simulation result and the test data is within the permitted range of the evaluation index, it can be concluded that the model experiment can be used, instead of the actual test of the tracked vehicle.

**2.3. Flow Chart of Gear Box's Fatigue Life Prediction.** In order to simulate the transmission system based on running simulation, the reliability data collection and analysis must be combined with the existing problems of the transmission system in the actual process firstly. This was the most basic and important link. In this paper, we collected and analyzed the reliability data of the transmission system in different working conditions. The specific failures occurred in the transmission system could reflect the corresponding weak links in the transmission system. The identified weaknesses in the reliability of the entire system can be utilized. Simulation analysis was used to analyze the dynamic analysis, life prediction and structural optimization. Figure 8 shows the flowchart of fatigue life prediction based on running simulation test [16, 17].

### 3. Fatigue Life Prediction of Gear Box Based on Running Simulation.

**3.1. Gear Fatigue Life Prediction Method.** Gear box plays a very important role in the machinery and equipment. However, once the damage of gear box occurs, it often caused unprepared, seriously faults, which affected the production efficiency and even endangering the safety in life, causing serious accidents, especially for large or extra large equipment. There were tens of thousands of gear in service each year in our country, and the length of their service varies. Therefore, correctly predicting their residually fatigue life under a certain degree of reliability was significance to engineering for determining the equipment overhaul period and preventing accidents.

There are several methods to estimate the random fatigue life:

- (i) load-life method: calculate the life according to the load–life curve ( $F - N_f$  curve) of the components;
- (ii) stress-life method: calculate according to the nominal stress–life ( $S - t$ ) curve; strain-set life method – calculated life expectancy according to the strain of the light specimen life curve;

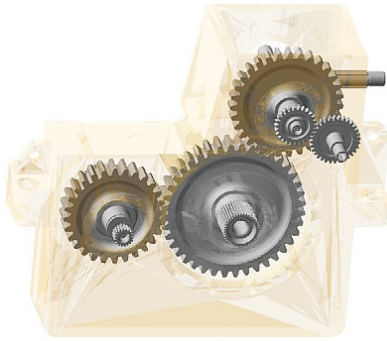


Fig. 9. Virtual prototype of the tracked vehicle gear box.

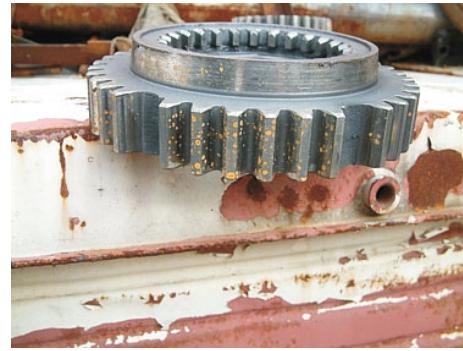


Fig. 10. Passive gear broken tooth diagram.

(iii) power spectrometry: life method acquisition and analysis of the time course;

(iv) record the  $S - t$  history of the key parts of the parts and get the power spectrum by the spectrum method.

In this study, the fatigue life of gear box was determined with the help of the running simulation platform.

**3.2. Virtual Prototype of Gear Box.** Virtual prototype technology is an effective way to design [4, 5]. MSC.ADAMS is a commercial mechanical system simulation analysis software, with powerful model capabilities, powerful solution and analysis capabilities [6]. The MSC.ADAMS and Pro/E dynamic simulation software tools were used in this study. The interface between them adopted the special interface module Mechanism/Pro developed by MSC Company. First, the model of main, passive gear and gear shaft were established in Pro/E and assembled. During assembly, the two teeth surfaces of the initial meshing should be cut as close as possible to reduce the error caused by the initial state of the model when the simulation analysis was reduced.

Figure 9 depicts a virtual prototype model of the gear box of the tracked vehicle (the outer box was made semi-transparent with the purpose of better visualization of its internal structure).

The virtual prototype of the gear box was successfully verified by the model verification. It proved that the virtual prototype of the gear box of the tracked vehicle was correct and can be used instead of the physical prototype.

**3.3. Fault Mode Effect Criticality Analysis.** According to the failure of the transmission case of the tracked vehicle, the main failure mode was cracking and fracture of each component of the transmission box. In this paper, a tracked vehicle gear box was processed with fault investigation statistics. The analysis of the gear box vehicle transmission system reliability and life revealed that it the “weak link”s in the entire gearbox. As an example of such fatigue failure, a photo of broken gear tooth is given in Fig. 10.

#### 3.4. Fatigue Life Prediction for the Gear Box.

**3.4.1. Gear Finite Element Analysis.** MSC/Patran software was finite element analysis software, which allows users to easily through the graphical interface to complete meshing, model description, etc., it can release engineering analysts from big data processing. The calculated results can be easily accessed and used in the post-processing [10]. At present, the software is widely used in aerospace, automotive, shipbuilding, defense and other major areas. The gear finite element analysis of the flow chart is shown in Fig. 11. Taking into account the characteristics of gear force and cantilever beam gear characteristics, the finite model of gears was simplified here, the establishment of only one tooth, a tooth plus wheel gear, and three consecutive teeth plus three wheel gear. Their meshes, as shown in Fig. 11b and 11c, have the reduced number of grid cells, which allows one to save computational time on solving stress distribution in teeth.

Transmission passive gear material was 20Cr2Ni4A, with elastic modulus of  $2.06 \cdot 10^5$  MPa, Poisson’s ratio of 0.3, and density of  $7.9 \cdot 10^{-6}$  kg/mm<sup>2</sup>. After incorporating the input data and generated results’ file into MSC.Patran, the distribution of gear stress was obtained as shown in Fig. 11d, for the load of 10,000 N. In order to optimize the finite element model, authors [10] analyzed gear root stresses using a finite element model containing three consecutive teeth via hexahedron elements and obtained good results. Therefore, the same scheme was used in this study.

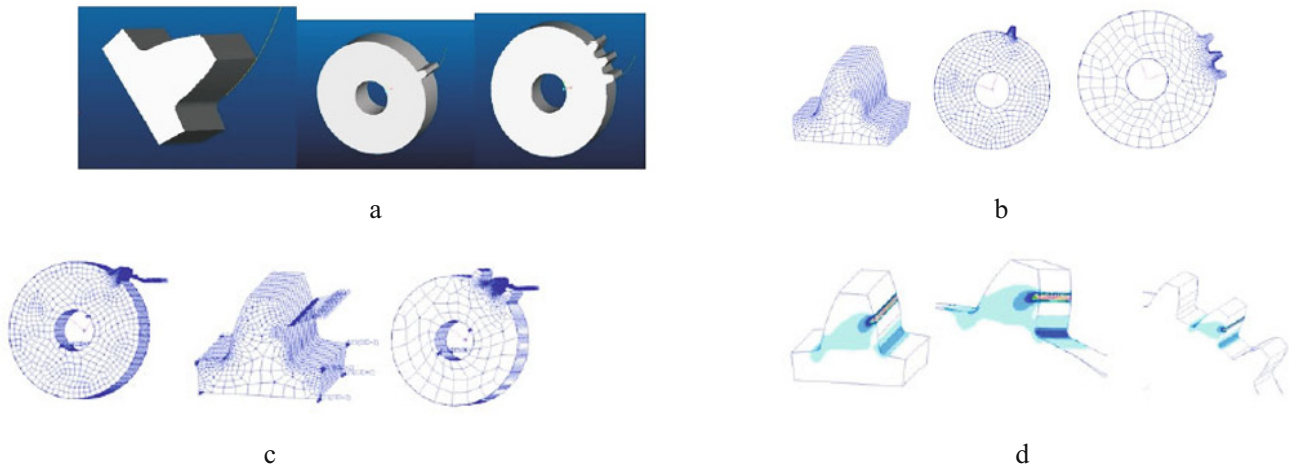


Fig. 11. The finite model of gears.

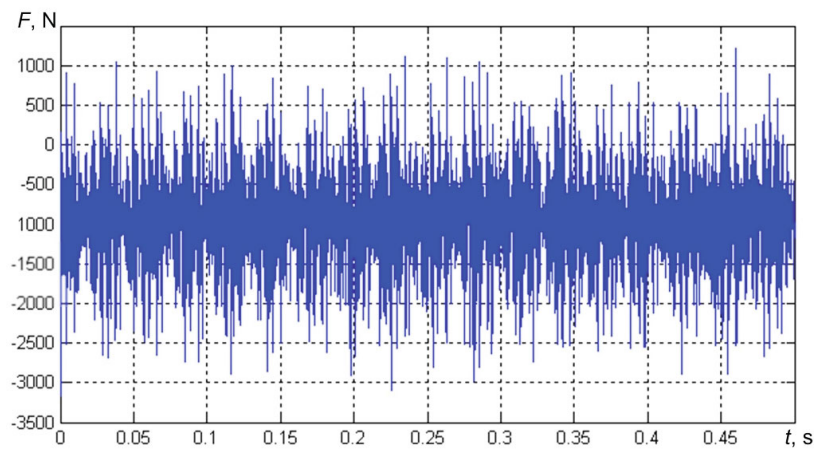


Fig. 12. Dynamic load spectrum obtained from running simulation platform.

3.4.2. *Gear Load Spectrum.* Through the research and analysis in Fig. 11, it can be concluded that the simulation based on the running simulation test provides a convenient and effective way to assess the dynamic load of gearbox. Figure 12 shows the vertical and horizontal load spectra provided in the running simulation test with the help of running simulation platform. The load of the gear was converted into a DAC data file, which was applied to the meshing part of the fatigue-simulated virtual prototype gear. The fatigue damage analysis of the driven gear of the transmission case was realized, and its fatigue life was calculated.

3.4.3. *S-N Curve of Gear Material.* The gear material was 20Cr2Ni4A high-quality steel, which underwent carburizing, quenching, and tempering under low temperature. Its surface has very high hardness, but also the strength and toughness of the core, as same as the plastic cooperation was very good. Passive gear surface with carburizing treatment had a depth of 1.3–1.7 mm and hardness of no less than HRC 59 in the carburizing layer and HRC 35–49 in the core and non-carburized surfaces. The *S-N* curve of material 20Cr2Ni4A is shown in Fig. 13. The tensile strength limit was 1175 MPa and the elastic modulus was  $2.06 \cdot 10^5$  MPa.

3.4.4. *Gear Fatigue Life Prediction Simulation Study.* For the fatigue life prediction of the driven gear in the transmission case, the authors used the data interface between the simulation software FE-FATIGUE and the finite element analysis software MSC.Patran, which was based on the interface-based co-simulation technology. The gear model corresponding to Fig. 11 in Patran was converted to the FE-FATIGUE platform in op2 format file, and a virtual prototype of the gear fatigue life prediction was established. Based on the running simulation test, the dynamic load on the driven gear in the transmission case was plotted in Fig. 14, and the dynamic load in the dac data

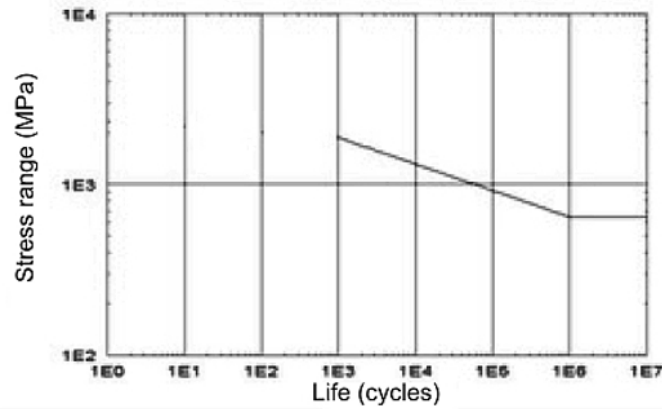


Fig. 13.  $S-N$  curve of 20Cr2Ni4A.

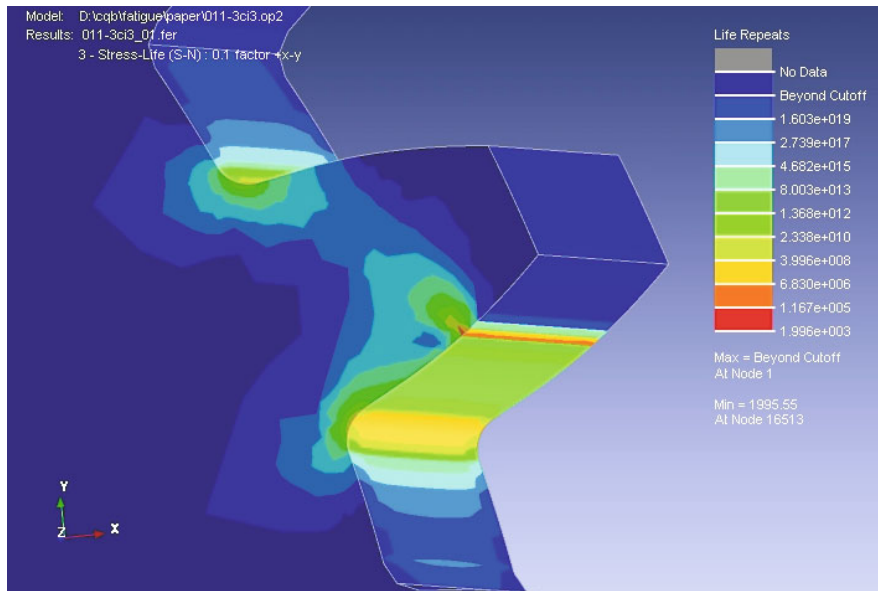


Fig. 14. Gear fatigue damage life distribution cloud chart.

file was applied to the gear fatigue prototype model. The damage accumulation was calculated using the Miner linear damage accumulation criterion, and then the fatigue life was calculated. The results of life cloud are presented in Fig. 14.

The obtained gear fatigue life distribution shows that, regardless of the gear tooth surface contact damage, the most probable cause of fatigue failure was the root fillet. The root of the gear was easiest to break under cyclic loading. This was also consistent with the gear failure mode shown in Fig. 10. The root of the gear was calculated separately. The results are illustrated by Fig. 15. The node 8341 was the most dangerous part of the gear root, with a life of  $9.88 \cdot 10^6$  cycles.

It is noteworthy that the gear meshing force shown in Fig. 12 corresponds to that of 28 teeth within 0.5 s. Since the meshing force acting on each tooth was the same and repetitive, the gear meshing force shown in Fig. 12 was replaced by a single-tooth meshing force when calculating the fatigue life of the gear, that was to say, the tooth acceleration in gear within 0.5 s and the corresponding gear life were multiplied by a factor of 28. Therefore, the bending fatigue life of the root node at 8341 under the action of the gear meshing force in Fig. 11 should be  $N = 2.7 \cdot 10^8$  cycles. After  $2.77 \cdot 10^8$  cycles, the gear tooth root fatigue occurs. The calculated fatigue life was converted into tracked vehicle mileage as follows:

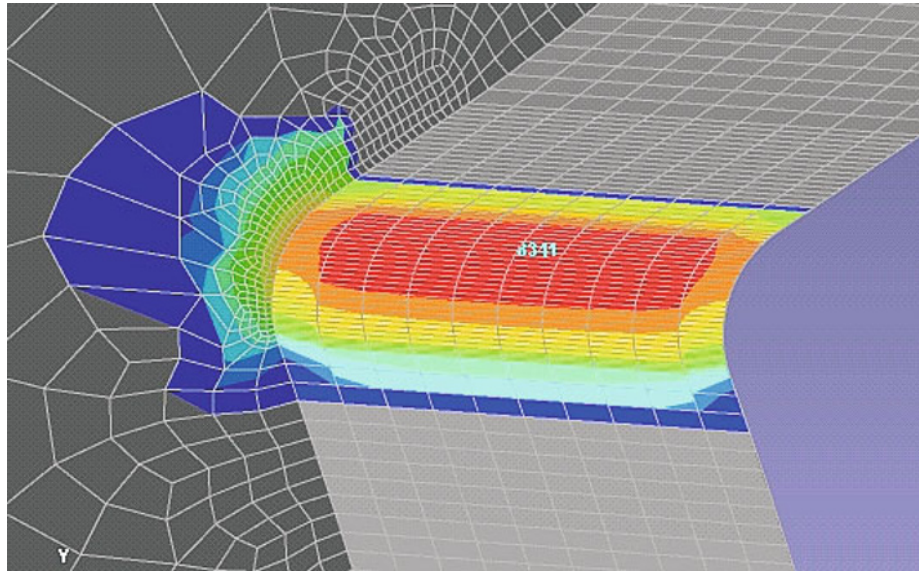


Fig. 15. Gear root damage life cloud.

$$S = N \frac{S'}{1000}, \quad (1)$$

where  $S'$  is travel distance,  $N$  is fatigue life in cycles, and  $S$  is number of km to failure.

From the running simulation test can be 0.5 s load time history, travel distance taken as  $S' = 0.8$  m, according to Eq. (1) to calculate the transmission gear in the working mileage

$$S = N \frac{S'}{1000} = 2.77 \cdot 10^8 \frac{0.8}{1000} = 1.216 \cdot 10^5, \quad (2)$$

when gear fatigue occurred.

## CONCLUSIONS

1. Based on the running simulation, the dynamic load of the gear box in the weak parts of tracked vehicles in different conditions was obtained and used in the further gear box fatigue life prediction.

2. The performed analysis of gear box fatigue life under dynamic loading based on running simulation test provided a theoretical basis for determining the overhaul cycle and the residual life of tracked vehicles.

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