Analysis of virtual fatigue life of welding structure of tracked vehicle based on load spectrum

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Abstract. Welding has become the main processing method of the supporting structures on tracked vehicles. The accurate evaluation of fatigue life of welding structures is of great significance significant to the reliability of tracked vehicle. The whole analysis process, based on strengthened load spectrum and structural stress method, is proposed in the study to predict the fatigue life of welding structures. Initially, the road-load spectrum of different conditions was obtained by vehicle tests. Then, the data which had been preprocessed were compressed based on pseudo-damage editing. Furthermore, the load spectrums were extrapolated and equivalent to program-loaded spectra according to the non-parametric rain-flow extrapolation method. On the other hand, the finite element model of the welding structure of the tracked vehicle was established to calculate the structural stress at the welding seam.

1. Introduction
The load condition of tracked vehicle on the road and the fatigue life prediction of load-bearing structure have always been the focus of attention and research. The main processing method of bearing structure is welding, and its fatigue life prediction mainly includes road test, load spectrum test and weld fatigue life calculation. First of all, load spectrum is the basis of component design and fatigue test, and it is an important premise of life determination design principle. However, due to the harsh working environment of tracked vehicles and the randomness of road excitation load, it is difficult to capture the limit load in some special cases, so a large number of load tests are needed to obtain the corresponding load spectrum in order to obtain the ideal load data. Too long time domain of load spectrum will increase the cost of calculation and test, and too short time domain is difficult to cover the limit load under the whole life service of vehicle.

To get an ideal load spectrum efficiently, the methods for compressing spectrum and extrapolation were proposed and applied in the practical engineering. Conle and Topper introduced fatigue data editing...
They identified and abbreviated low amplitude cycles in the components strain time history [1]. Londhe carried out a proving ground test for body in white and chassis structural of the car, and derived the compressed load cycle from the measured road-load data in order to produce representative and meaningful yet economical load cycle for fatigue simulation [2]. Mattetti et al. utilized a four-post road simulation test bench to study the accelerated durability of a tractor and used the time-domain damage reservation editing method to effectively compress the displacement signal [3]. Yukuan Chen compressed the load spectrum by 40% based on multichannel damage correlation theory and proved the availability of the data by bench test [4]. In addition to the acceleration of time domain road-load, technologies of road-load extrapolation were also investigated by researchers. Xiang obtained the limit load of key components on military equipment through joint distribution function with a single parameter of amplitude and mean [5]. Nagode proposed a method of rain-flow extrapolation based on mixing distribution [6] Haiou Liu and Hewei Yu got a better fitting of amplitude and mean distribution and achieved the reasonable extrapolation of the rain-flow matrix by 2-D kernel density estimation [7,8].

On the other hand, failure of the welding structure always starts at welded joints. Many researches have indicated that cracking and extending at weld toe were the primary failure reason of welding structure [9]. Currently, the fatigue life of welding structure is mainly assessed by using the nominal stress method, the hot spot stress method, the partial stress method, or the structural stress method. Nominal stress method was unreliable because of the welded joints diversity. Even though the study object was a type of welding joints, the predicting outcomes also had a great dispersion. The hot spot stress method was barely considered to assess the welding structures due to the strong dependency of grid density [10]. The partial stress method could predict the fatigue life accurately, but the request to the details of structural model was so high that the method was not suitable to practical engineering [11]. Dong proposed the equivalent structural stress method and derived the master equation for the S-N curve, which could predict the fatigue life of welded joints efficiently [[12-14]. In a word, the treatment of load spectrum and the method of fatigue analysis have been maturely applied in practical engineering. Structural stress is preferred to be used in the fatigue life prediction of the welding joints. However, there is no exact process for tracked vehicle to analyze the fatigue property of welding structures.

In the study, a comprehensive process was proposed (refer with Fig. 1). To obtain a load spectrum of the whole life cycle, the test data of force was compressed and strengthened based on pseudo damage editing and nonparametric extrapolation. Then, the program-load spectrum was equivalent to and served to bench test and fatigue life prediction. Next, the FE model of welding structure was established to compute the structural stress at the welding seam. Finally, the fatigue life of the welding structure was calculated based on the structural stress method and proved by the road test data.

Figure 1 The comprehensive process of fatigue life prediction of welding structure.
2. road test and load spectrums strengthened

2.1. Data test and preprocessing

In order to achieve the load spectrums under load conditions of the tracked vehicle, the road test was conducted on pavement road, rough road, sandstone road and gravel road (refer: with Fig. 2). The journey which spent 600 seconds at the speeds of 20 km/h, 30 km/h and 40 km/h, was 5 kilometers long. The tracked vehicle was controlled at different speeds on each type of road with 50 seconds. The force sensors were respectively arranged at 12 shaft heads of the tracked vehicle. Each shaft head was equipped with three data acquisition channels, which correspond to the force loads in X, Y and Z directions of the shaft head respectively. The load spectrum of the first left shaft head was shown as an example (refer with: Fig. 3).

Figure 2 Road test. (a) pavement road; (b) rough road; (c) sandstone road; (d) gravel road; (e) the assembly of force sensor.

Figure 3 Force load spectra of the first shaft head.
2.2. Compressing of load spectrum.
A lot of cycles of low amplitude, with little damage during the employed process of tracked vehicle, account for a large proportion of time-domain. The aim of compressing is to delete the no-damage cycles and save time and cost of test. The pseudo-damage editing method, which was based on the ratio of retained damage, can be used to edit signals of force, velocity or acceleration directly. It was chosen to compress the load spectrum in this study.

2.2.1. Selection of target damage and time window
It is an important precondition for pseudo-damage editing to select the target damage and time window. Target damage assures the damage characteristic of the load spectrum and the length of time window can impact the efficient of compressing and frequency-domain characteristics of load spectrum. Target damage was set to 80%, 85%, 90%, 95% and 100% which respectively corresponded to 4 kinds of time window, i.e., 0.5s, 1s, 1.5s and 2s. Result after load spectrum compressed showed that pseudo damage could be retained more than 97% when target damage and the length of time window were set to exceed 85% and 1s (refer with Fig. 4(a)). It also indicted that the ratio of compressing has risen above 40% with target damage and the length of time window smaller than 85% and 1s (refer with: Fig. 4(b)). Based on comprehensive analysis of the results, selection of 85% target damage retained and 1s length of time window could provide a good effect of compressing (refer with: Fig. 5).

2.2.2. Analysis of time-domain and frequency-domain of load spectrum.
The statistic of load spectrum (refer with: table. 1) showed that the extreme value and range had no change. The values of mean and RMS increased slightly after compressing, which indicated that the pseudo-damage editing made little effect on the peak-valley value of load spectrum. At the same time, the retaining of damage was higher than 97% and time-domain was

![Figure 4](image)
Figure 4 Selection of target damage and time window. (a) ratio of pseudo damage retaining. (b) ratio of compressing.

![Figure 5](image)
Figure 5 Compressing of load spectrum.
lowered by 40%, which manifested the compressing of load spectrum. Otherwise, the pseudo damage of Z was two orders of magnitude higher than other two directions.

Power spectrum density (PSD) of Z was calculated to analyze the frequently characteristic of load spectrum (refer with: Fig. 6). The regularities of distribution of PSD of compressed signal was similar to original one. Besides, the mean energy density was enlarged due to deletion of small loads.

Table 1  Statistic of load spectrum

| Force signals | Min  | Max  | Range | Mean | RMS  | Ratio of compressing | Retaining of pseudo damage |
|---------------|------|------|-------|------|------|----------------------|---------------------------|
| X Original    | -25.4| 18.3 | 43.7  | 0    | 1.4  | 4.13E-15              | 99.1%                     |
| X Compressing | -25.4| 18.3 | 43.7  | 0    | 1.7  | 4.09E-15              |                           |
| Y Original    | -25.6| 23.2 | 48.8  | -0.004| 2.2  | 1.12E-14              | 41.7%                     |
| Y Compressing | -25.6| 23.2 | 48.8  | -0.008| 2.6  | 1.09E-14              | 97.3%                     |
| Z Original    | -46.5| 102.3| 148.8 | -0.006| 5.8  | 2.68E-12              |                           |
| Z Compressing | -46.5| 102.3| 148.8 | -0.009| 6.9  | 2.63E-12              | 98.3%                     |

2.3. Extrapolation of load spectrum.
The whole life cycles of tracked vehicle cannot be simulated by the small sample load cycles obtained by road test. To predict the fatigue life accurately, the load spectrum needs to be extrapolated to gain the whole load cycles which contain the limit load value.

Nonparametric extrapolation of the rain-flow matrix based on kernel density estimation and m-c method has been applied in intensifying load spectrum. During the kernel density estimation, the rain-flow matrix in the form of From- To was extrapolated by a suitable kernel function [15]. Four kinds of kernel function, including Circular kernel, Mean Based Ellipse, Range Based Ellipse and Epanechnikov, were given in Ncode.2019 (refer with: Fig. 7).

![Figure 6 PSD of load spectrum of Z](image)
Firstly, the Epanechenikov was chosen to intensify the data with the effect of range and mean. Then, a method to calculate the coefficient was given to realize the extrapolation of mileages, as in (1). It is stated that the limit load happened after 107 load cycles in the process of tracked vehicle design. The force load cycles of \( Z \), which caused the primary damage, was counted for \( 51209 \) based on rain-flow counting. Thus, the load spectrum can be extrapolated to \( 980 \) km with the coefficient \( 196 \). Finally, the limit load was strengthened to \( 253.7 \) kN, which was 1.67 times larger than the original value and regarded as the harshest load (refer with: Fig. 8).

\[
K = \frac{N}{n},
\]

(1)

Where \( K \) is the coefficient of extrapolation; \( N \) is 107; \( n \) is the cycles of the original load spectrum.

Figure 7  4 kinds of kernel function; (a) Circular kernel; (b) Mean Based Ellipse; (c) Range Based Ellipse; (d) Epanechnikov.

Figure 8  Result of extrapolation; (a) Curve of extrapolation; (b) From-To matrix of extrapolation.
2.4. Equivalent of load spectrum.

The rain-flow matrix with on immediate applications of bench test has to be turned to two-dimension load spectra, and thereby being equivalent to a program-loaded spectrum. 8 ranks. The levels of range values were divided by 8 scales containing 1, 0.95, 0.85, 0.725, 0.575, 0.425, 0.275, 0.125.

| Range (kN) | 31.71 | 69.77 | 107.82 | 145.88 | 183.93 | 215.64 | 241.01 | 253.7 |
|------------|-------|-------|--------|--------|--------|--------|--------|-------|
| Mean (kN)  | 81.2  | 62.3  | 43.55  | 24.72  | 5.90   | -12.93 | -31.75 | -50.58|
| 42         | 4     | 3     | 10     | 2      | 0      | 0      | 0      | 0      |
| 483        | 266   | 334   | 184    | 40     | 4      | 0      | 0      | 0      |
| 27033      | 4850  | 1825  | 647    | 145    | 20     | 2      | 1      |        |
| 2840000    | 573296| 13782 | 1314   | 191    | 20     | 0      | 0      |        |
| 2120000    | 342000| 3568  | 203    | 9      | 0      | 0      | 0      |        |
| 81400      | 3286  | 156   | 11     | 0      | 0      | 0      | 0      |        |
| 1113       | 216   | 12    | 0      | 0      | 0      | 0      | 0      |        |
| 44         | 3     | 0     | 0      | 0      | 0      | 0      | 0      |        |

The levels of mean values were divided into 8 equal parts. Then, the two-dimension load spectrum could be obtained (refer with: table. 2).

Range and mean values of the load spectrum keep independent distribution. Therefore, dimensionality of load spectrum can be reduced to get the one-dimensional load spectrum (refer with: table. 3) by equivalent of mean [16] as in (2). Then, the program-load spectra, which had a load way of low-high-low, was constituted by sine waves based on one-dimensional load spectrum (refer with: Fig.9).

\[
M_i = \frac{\sum_{j} M_j n_j}{\sum_{j} n_j}.
\]

(2)

Where \( M_i \) is the equivalent mean of the level \( i \); \( M_j \) is the mean of level \( j \); \( n \) is the cycles.

| Mean of equivalent (kN) | Range (kN) | Cycles |
|-------------------------|------------|--------|
| 16.58                   | 253.7      | 1      |
|                         | 241.01     | 2      |
|                         | 215.64     | 44     |
|                         | 183.93     | 387    |
|                         | 145.88     | 2369   |
|                         | 107.82     | 19680  |
|                         | 69.77      | 924371 |
|                         | 31.71      | 5077757|
3. Assessing the fatigue life of the welding structure of a tracked vehicle.

3.1. Finite element analysis of the supporting structure.

The welding structures, which play an important role in support and load transmission between the vehicle body and the torque bar on tracked vehicles, are broken due to fatigue failure of the welding seam. FE analysis is the basis of the design. Firstly, the 3D model of the welding structure was constructed and divided around the welding seam for mesh encryption. Studies have indicated that structural stress is not dependent on the density of the grid [17-19]. Two layers of elements with a size of 8 mm were selected to simulate the welding seam and the direction of the seam was given in this paper (refer to Fig. 10(a)). Then, the Yang’s modulus and Poisson ratio were set to 210 GPa and 0.3, respectively. Finally, a unit load was applied to the shaft head (refer to Fig. 10(b)) and the result was obtained in Abaqus (refer to Fig. 10(c)).

![Figure 10 Finite element analysis of the structure.](image)

3.2. Structural stress simulation of the welding seam.

The results of FEA were used to calculate the structural stress in the verity module of FE-safe [20]. The thickness and direction of the welding seam were necessary in the process. Thickness was set to 8 mm and the direction of the welding seam was expressed by nodes and elements. Thus, the structural stress was obtained (refer to Fig. 11) by membrane stress and bend stress, as in (3).

\[
\sigma_s = \sigma_m + \sigma_b.
\]

Where \(\sigma_s\) is structural stress; \(\sigma_m\) is membrane stress; \(\sigma_b\) is bend stress.
3.3. Prediction of the fatigue life

The method of equivalent structural stress proposed by the American research center Battelle Institute is a new fatigue-life prediction method for welded joints. This method is based on the principles of fracture mechanics and fatigue test data, which utilizes the equivalent structural-stress calculation method and a master S–N curve to predict the fatigue life of the welded joints. The equation of master S-N curve, as in (4), has been put forward through a large numbers of test containing all kinds of welded joint [21] (refer with: Fig. 12).

\[ S \times N^h = C_d. \]  

Where \( S \) is the equivalent structural stress; \( N \) is the cycles; \( h \) and \( C_d \) is the parameter of material.

The program-loaded spectrum and the result of structural stress were input to FE-safe. The material of welding seam assessment was selected to be Steel Weld (50%). The parameter of the material and are 19930.2 and 0.3195, respectively. According to the results of fatigue life prediction (refer with: Fig. 13), the welding seam was destroyed at the end point after 422 cycles of program-loaded spectra. It was equivalent to 413560km load test, which was 41.3 times larger than the design life.
4. Conclusion
A comprehensive process was proposed to predict the fatigue life of welding structure in the study. The main conclusions and study are shown as follows.

- The load spectrum was compressed by 41.7% based on pseudo-damage editing.
- The load spectrum was extrapolated 196 times and turned to program-loaded spectrum which was equivalent to 980 km on the road.
- The fatigue life of the welding structure was predicted to 422 cycles of the program-loaded spectrum, which was equivalent to 413560 km.

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