Research of load spectrum of mechanical drive train by non-parametric statistical engineering extrapolation

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Abstract. This article elaborates the wheel loader transmission load spectrum during the preparation of the key issues - how to determine the shape of the kernel function, chosing three typical operating conditions to illustrate the non-parametric statistical extrapolation of this process. Before sample loading spectrum is pushed forward, of the signal de-noising of time-domain signal load testing should be completed. Thus, samples of the load cycle and the corresponding kernel function shape is obtained by using rain flow counting method, proposing rain flow matrix non-parametric statistical extrapolation lifetime load spectrum estimation. Because it can achieve a good estimate of the load cycle, it does not appear in the sample load cycle, but may be present in the life course of load. It can be easily seen that the extrapolation is valid and reliable.

Introduction

Load spectrum is the base of predicting fatigue life and component design. The researchers could get the load rule, and then whether the components is qualified or not can be estimated. Hence, load spectrum is widely used in the mechanical field.

A whole process of compiling the load spectrum contains several steps, and that is, testing the sample load, extracting the sample load, preprocessing the sample load, statistical treatment and extrapolating the sample load. And, in each step, there are lots of issues to study and many researchers devote their time and efforts and acquire good achievements, following which many articles have been published in recent years [1-9].

However, the whole-life load spectrum cannot be obtained directly by the field test, as the field test is high expensive and can be acquired. And the whole-life load spectrum is obtained by extrapolating the field-tested sample load. Hence, it is critical to well extrapolate the field-tested load spectrum. Various extrapolation methods have been used in many fields, such as offshore [10], wind [11], and airplane [3]. The non-parametric statistical extrapolation method (NSEM) [12-15] and the parametric statistical extrapolation method [16] are the commonly used methods.

The load that engineering machinery experiences is always rather random and the parametric statistical extrapolation method will cause larger error in estimating the whole-life load spectrum. Further, the NSEM is applied more as it has advantage in estimating the load cycles which do not appear in field-tested time-history load signals but may be included in the whole-life load history. Hence, this paper accomplished the work of extrapolating the field-tested same load spectrum of the wheel loader using the NSEM. The kernel function shape is the key point in the NSEM and different with various work conditions. The circular kernel, range based ellipse, mean based ellipse and product kernel are the typical kernel functions, which are based on how the data is primarily located along the diagonal of the From -To histogram.

In this paper, the transmission of the ZL50 wheel loader is chosen to conduct the field test. And the field-tested load of the spacer flange is studied. Three typical working conditions, named loose soil, small stonework and block stone, are selected as the load source to represent the wheel loader. In section 2，the process of the NSEM is reviewed in detail, and the kinds of the kernel function shape and their applied characteristics are discussed. In section 3，how to process the sample load is introduced simply. In section 4，the kernel function of the spacer flange load is determined and the

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corresponding load spectrum is compiled. In section 5， the extrapolation results of the load corresponding to the three typical working conditions are discussed. From the results, it is easy to get that the sample load has been well extrapolated and the extreme load value and the cumulative frequence of the load cycles have all increased.

Review of Non-Parametric Statistical Extrapolation

The tested load time history is limited compared to its entire life, so it must be extrapolated using the method of mathematical statistics [17]. Generally, the current statistical methods related to rainflow matrix are parametric method. The amplitude and mean distribution of the load were discussed respectively. The drawback of rainflow counting method is that the hysteresis loop of starting point and closing point is parted and hysteresis loop structure is destroyed. There are many human factors in this method, so the statistical results are not satisfactory.

To overcome the limitation of parameter estimation, as shown in reference [11,18], the NSEM was studied. We used the NSEM as well as data processing module of nSoft to extrapolate the load spectrum of field-tested signals, and proved the advantages of the proposed method by comparing the results with that of traditional extrapolation method.

The rainflow matrix extrapolation method is described well in [19]. Firstly, rainflow counting is regard as a series of hysteresis loop extracted from load time history (x_1, y_1),…, (x_l, y_l),…, (x_n, y_n), and the generation of hysteresis loop is considered as a random process. If hysteresis loop is taken as the statistical sample, the frequency of (x_l, y_l) falling rainflow matrix i th rows, j th columns can be calculated by Eq. (1).

$$r_{ij} = \sum_{l=1}^{n} d_{i\times j}(x_l, y_l) \tag{1}$$

Where $d_{i\times j}(x_l, y_l)$ denotes whether (x_l, y_l) falls in interval $(i\times j)$ or not, that is, if (x_l, y_l) falls in interval $(i\times j)$, $d_{i\times j}(x_l, y_l) = 1$; otherwise $d_{i\times j}(x_l, y_l) = 0$. Therefore, the frequency of (x_l, y_l) falling in rainflow matrix i th row, j th column can be counted as:

$$H_{ij} = \frac{1}{n}\sum_{l=1}^{n} d_{i\times j}(x_l, y_l) \tag{2}$$

The probability of (x_l, y_l) falling in rainflow matrix i th row, j th column, expressed by p_{ij}, should be estimated. When it is estimated, not only H_{ij} but also the impact of sample points around it should be considered. And this impact can be described by kernel density function estimator $k(i, j)$. So the probability density of hysteresis loop (x_l, y_l) falling in rainflow i th row, j th column can be counted as

$$p_{ij} = \sum H_{ij} k(i, j) \tag{3}$$

Where $\sum k(i, j) = 1$. It also should be ensured that the impact of frequency of sample points closing to $(i\times j)$ is greater than the impact of the element away from the location on p_{ij}.

Such a kernel function can be denoted by

$$k(i, j) = \frac{1}{2\pi\sqrt{\det\Sigma}} e^{-\frac{1}{2}(\Delta_i, \Delta_j)\Sigma^{-1}\begin{pmatrix}\Delta_i \\ \Delta_j\end{pmatrix}} \tag{4}$$

Where (Δ_i, Δ_j) and $\Sigma^{-1}\begin{pmatrix}\Delta_i \\ \Delta_j\end{pmatrix}$ represent the mean value and covariance respectively.

The corresponding value of the kernel function for each element is $k(i, j)$ calculated by rainflow matrix. Then estimator of p_{ij} is obtained. So the probability density function of the whole rainflow matrix is obtained.

According to the probability density function and the extrapolation coefficient, the rainflow matrix corresponding to the measured load-time history can be extracted. Extrapolation coefficient can be calculated by the following methods.

1) Cumulative frequency of life cycle, expressed as N_i, is calculated by Eq. (5) is allocated.

$$N_i = 10^6 \times a_i \tag{5}$$

Where a_i represents the ratio that the i th working condition takes in all the working conditions.

2) Sum of load cumulative frequency of all the operating segments in each working condition is calculated. And in all the k working conditions the extrapolation coefficient of the i th working condition can be determined by Eq. (6), $i=1,2,\ldots,k$.

$$K_i = N_i \Big/ \sum_{j=1}^{k} n_j \tag{6}$$

Where, K_i is load extrapolation coefficient of i th working condition; n_j is cumulative frequency of j th working segment during i th working condition; i represents the i th working condition.

3) If the working condition and the channel are the same, extrapolation coefficient of load spectrum of each segment is equal.

Pretreatment of The Sample Load of The Spacerflange

The ZL50 wheel loader has major market occupancy and is studied as the representative in the test. The working conditions that the wheel loader works are always random and serious, so the working conditions should be typical.

In order to reflect the actual working condition of the wheel loader comprehensively and veritably, three kinds of working conditions, namely loose soil, small stonework and block stone were selected as working objects. Among them, the working condition of small stonework was a typical representation, whose measured load signal of transmission is shown in Figure.1. Therefore, this paper took it as an example to illustrate the method. In addition, the loading cycles were divided into six different operating segments according to its working characteristic.

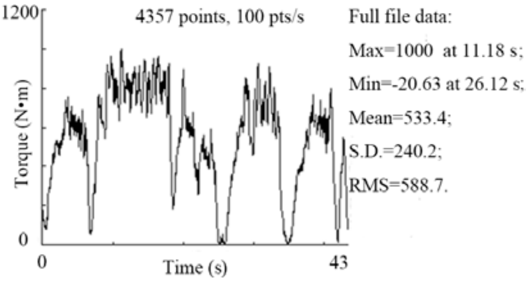

Figure.1. Load time history of the spacer flange of an operating cycle on the working condition of small stonework

Compiling Load Spectrum of Spacerflange Using NSEM

After the rainflow matrix extrapolation, the superposition can be considered as a synthesis of collected load spectrum on different working conditions. The operating load time histories of transmission system under five working conditions were collected. For simplicity, the loads under loose soil, small stonework and block stone were taken as an example.

Each working condition is divided into six operating segments including no-load forward, shoveling, heavy-load back, heavy-load forward, unloading and no-load back. In the extrapolation process of different operating segments extrapolation coefficient under different conditions are carried out according to the proportion of the working conditions. Then the load spectrum is extracted.

We superimpose the 12 load rainflow matrixes obtained by Eq. (7), then get the cumulative frequency curve of the load of transmission spacer flange for a wheel loader.

$$R = \sum_{i=1}^{2}\sum_{j=1}^{6} R_i^j \tag{7}$$

Where R represents the total cumulative frequency of the load spectrum.

Through the above method for data processing, automated processing of extrapolation is performed by the data processing module of nSoft. And different operating segments of load spectrum on different working conditions are obtained. The extrapolation result of spacer flange load spectrum during shoveling in stonework is shown in Figure.2. It can be seen that not only the frequency of load increases, but also the extreme of load spectrum increases.

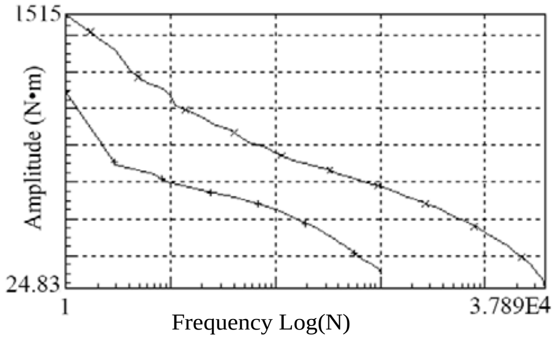

Figure.2. Extrapolation diagram of spacer flange load spectrum

The rainflow matrix (64×64) of synthetic conditions can be used to compile 8-level load spectrum. It also can be transformed to DAC format as load spectrum of fatigue analysis of transmission components.

Test Results

As shown in Figure.7, the amplitude spectrum, which is obtained using NSEM in the synthetic condition, is higher than the cycle amplitude of load spectrum of all other conditions. That is to say, after extrapolation, not only the cycle index of load spectrum but also the corresponding load amplitude increases, which conforms to actual working situation.

It also can be concluded that with the increase of sample size, the influence of the road surface planarization, non-uniformity of shoveling materials, etc. can be more and more obvious to the data, which fit into the actual operating conditions of engineering machinery.

Moreover, under the conditions that the curves are close to each other, it can be seen that amplitude contribution of synthesis working condition corresponding to the loose condition is greater than the contribution corresponding to small stonework, which is the result of interaction between the proportion of working conditions and the load amplitude.

Conclusion

The process of NSEM was illustrated using the load time history of the spacer flange of a wheel loader. Three typical working conditions were adopted in illustrating the extrapolating process. Based on load hysteresis loop, the principle of NSEM was analyzed. By analyzing the sample load, it is obtained that the kernel function shape of the spacer flange is range based ellipse. Finally, the load spectrum of the spacer flange is compiled. From the extrapolated load spectrum, we get that the extreme load and the cumulative frequence both increases. The result of extrapolation turned out well in estimating the whole-life load spectrum. Therefore, this method is feasibility and objectivity to process actual load time history.

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