Synchronous acceleration method of the load spectrum for tractor rotary tillage based on wavelet transform

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Abstract: The small load cycle dominates the load spectrum, resulting in inefficient laboratory-based accelerated reliability testing of tractors. While most traditional editing methods focus on accelerating single-type loading spectrum, few are suitable for multi-type loading spectra. This paper proposes a synchronization acceleration method for the rotary tillage load spectrum based on wavelet transform. The method decomposes the power take-off (PTO) torque load data and suspension load data using Daubechies wavelet basis functions, calculates the square sum of cumulative wavelet components at each scale, and identifies large damage segments through threshold setting and Hilbert envelope analysis. Acceleration of the rotary tillage load spectrum is then achieved based on time-domain synchronization. In addition, to measure the acceleration efficiency of load spectrum and find the optimal acceleration parameters suitable for tractor tillage load spectra, a pseudo-damage acceleration efficiency (PDAE) index is proposed to evaluate the acceleration effect. Ultimately, through data comparison, the optimal acceleration parameters suitable for tractor tillage operation load spectra are determined. After acceleration, the time retention ratio of the rotary tillage load spectrum is 85.27%, the damage retention ratio of the PTO torque load spectrum is 97.14%, and the damage retention ratio of the suspension load spectrum is 96.94%. Compared to the damage retention acceleration method, the wavelet acceleration method saves an additional 10.07% of time while maintaining the effectiveness of the load spectrum. This study can provide a reference for accelerating the load spectrum of agricultural machinery and has significant implications for the field of accelerated reliability testing applications.

Keywords: tractor, rotary tillage, load spectrum, wavelet transform, load acceleration
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1 Introduction

Tractors are a vital power source in agricultural production. The safety and reliability of tractor products are key to ensuring the efficiency of agricultural production[1]. The laboratory-based accelerated reliability test is an important method for improving the efficiency and accuracy of agricultural machinery product quality verification. As agricultural machinery prototypes move towards mass production, the accelerated reliability test is widely used due to its ability to save a lot of time and resources. The load spectrum is the link between the actual working conditions of tractors and reliability load tests. The compiled load spectrum includes the whole life cycle load spectrum of the tractor, enabling reliability tests to simulate actual working conditions[2,3]. However, since the whole life cycle load spectrum contains a large number of small load cycles that have little effect on the fatigue life, the direct use of it would lead to a waste of manpower, resources, and time. Therefore, it is necessary to accelerate the load spectrum to improve the efficiency of the reliability test. The complex working environment of tractors leads to variable working loads. Rotary tillage is a typical working condition commonly used with tractors, and its load spectrum includes PTO torque load and suspension load, which is more complex than other working conditions. It is necessary to consider time domain synchronization in the process of load spectrum compilation and acceleration; therefore, this paper selects the rotary tillage load spectrum for research purposes.

Research on the acceleration of load spectrum has mainly focused on single types of load spectrum, with little attention given to the synchronous acceleration of multi-type load spectrum. A commonly used method for accelerating single-type load spectrum is based on damage retention in the time domain, achieved by deleting small load cycles. Conle and Topper[4] first introduced the load editing technology and verified the effectiveness of the method by estimating the amount of fatigue damage generated by each amplitude level of the original history and comparing with the actual test result. Yan et al.[5] studied the small-load-omitting criterion by carrying out variable amplitude load fatigue tests on the notched elements of 45 steel with non-continuous hardening characteristics. The test results showed that when the amplitude of the load cycle was lower than or equal to the threshold of fatigue damage, it can be omitted, indicating that omitting small load cycles has little effect on fatigue damage. Paraforos et al.[6] proposed a methodology for accelerated structural durability tests on agricultural machinery. First, they used the rainflow cycle counting method to extract load cycles, and used the Palmgren-Miner method

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to determine the fatigue damage for each cycle and the total fatigue damage. Then, they combined road and field surface condition modeling analysis to assess cumulative fatigue damage at different operating conditions[7]. Finally, the number of laps required to reach the target damage values was optimized by calculating the average cumulative damage during each lap. The results showed that when average values were used for lap damages, the total testing time was 1228 h with an acceleration factor of 3.3[8]. Yu et al.[9] studied the acceleration method of the load spectrum of the front sub-frame and analyzed the acceleration effect of the load spectrum at pseudo-damage retention ratios of 90%, 95%, and 99%. The accelerated test results showed that the 90% retention accelerated spectrum had better acceleration effect. Pan et al.[10] applied the pseudo-damage reservation method for the first time to improve the efficiency of mature drive axle housing optimization. The test results indicated that the pseudo-damage reservation method could significantly reduce the duration of fatigue bench testing.

Since omitting small load cycles in the time domain will alter frequency components of the load spectrum[11], some scholars began to study the acceleration method based on frequency domain. Abdullah et al. transformed the load spectrum based on short-time Fourier transform, and then accumulated the decomposed frequency components. According to the distribution of cumulative values, the part with large damage contribution is extracted to accelerate the load spectrum[12,13]. Pratumnopharat et al., based on the research of Abdullah et al., introduced the method into the processing of wind turbine blades load. Finally, the load spectrum was accelerated by 84.62%, and the statistical parameter error before and after acceleration was less than 10%, which proves the effectiveness of the frequency acceleration method[14,15]. Putra et al. proposed an acceleration method based on wavelet transform. The Morlet wavelet basis function is used to process the load signal of the automotive coil spring[16,17]. According to the distribution of wavelet decomposition coefficients, large damage fragments were extracted. The acceleration of load spectrum is realized by using the multi-parameter evaluation method. This study proves that the Morlet wavelet basis function can better deal with automotive spring load. Zheng et al. used Db12 series wavelet basis function to decompose the load of automobile transmission shaft into 12 layers, and realized the identification and acceleration of load spectrum fragments based on wavelet components[18]. Shangguan et al. proposed a wavelet transform-based spectrum editing method for deriving effective load spectra for accelerated durability testing of mechanical components, and its validity was illustrated considering multi-axis load spectrums measured for the handling bushing a suspension control arm[19]. Wen et al. studied a fatigue analysis method based on power density and short-time Fourier transform. The accumulative power density was used to identify and extract high fatigue damage segments of original load signal, and the acceleration of the load signal of the 88-kW tractor front axle was achieved[20]. Then, they proposed a method for designing tractor accelerated structure tests suitable for a drum-type test, which realized the indoor condition simulation of accelerated load spectrum[21]. Li et al. used the acceleration method based on wavelet transform to accelerate the tractor PTO torque load spectrum[22]. The high-frequency wavelet coefficients and wavelet components obtained by wavelet transform were used to realize damage identification and omission.

In summary, current research on load spectrum acceleration methods tends to focus on accelerating a single type of load spectrum, and there are currently few methods for accelerating the load spectrum of tractor rotary tillage, which requires considering two types of loads simultaneously. Based on the characteristics of the load of tractor rotary tillage, this paper proposes a synchronization acceleration method for the rotary tillage load spectrum based on wavelet transform. The acceleration was achieved while maintaining the time domain synchronization of the rotary tillage load spectrum. The acceleration efficiency was quantified and the optimal parameters for accelerating the rotary tillage load spectrum were identified. Finally, the effectiveness of the proposed method is verified by comparing it with traditional damage preservation acceleration methods.

2 Materials and methods

2.1 Load collection and extrapolation of tractor rotary tillage

The load data acquisition test of rotary tillage was conducted using the TS404 tractor (manufactured by Shandong Wuzheng Group Co., Ltd.) as the prototype at the Shangzhuang Experimental Station of China Agricultural University in Haidian District, Beijing. The field test parameters are listed in Table 1.

Table 1 Field test parameters

Item	Parameters
Rotary tiller model	1GLN-0145
Tillage depth	120 mm
Tillage width	1800 mm
Operating speed	4.5-5.0 km·h^{-1}
Soil moisture content	18%-30%

The load of tractor rotary tillage mainly includes PTO torque load and suspension load. In order to collect load data accurately, a load acquisition system is developed. It consists of a wireless double flange torque sensor, shaft pin force sensor, wireless receiver, signal amplifier, NI-9203 acquisition card, and PC. The test site and the principle of the acquisition system are shown in Figure 1. The model of the wireless double flange torque sensor is CYB-807W, with a range of 0-2000 N-m. The model of the shaft pin force sensor is CYB-605S, with a range of 0-10 kN. The data acquisition system is developed based on NI Compact-DAQ, and the acquisition card is NI-9203. The software is developed based on the LabVIEW, which can realize the real-time acquisition and storage of load data.

Based on the actual situation of the field experiment, original data with the same operation parameters and stable operation process were selected for data preprocessing. Through time-frequency domain analysis and minimum sample size calculation of the load data, the minimum sample that can represent the characteristics of the overall load was finally obtained. Based on the peak over threshold model, the time-domain extrapolation of the rotary tillage load spectrum was realized[23], and the 1-time extrapolated load spectrum and the whole life cycle load spectrum were obtained, respectively. Among them, the cumulative frequency of the load in the whole life cycle load spectrum reaches 10^6, which can be considered to include all possible loading conditions. The extrapolated load spectrum is shown in Figure 2, where the time length of the 1-time extrapolated load spectrum is 140 s, and the time length of the whole life cycle load spectrum is 15 960 s.

2.2 Synchronous acceleration method of rotary tillage load spectrum

2.2.1 Wavelet transform

Generally speaking, damage to components tends to occur during large amplitude cycles, and the damage value is proportional to the amplitude. Wavelet transform is a useful tool for analyzing signals in both the time and frequency domains. The wavelet components obtained from its decomposition can represent the distribution of signal energy in the time and frequency domains. A larger wavelet component means that its time domain signal will have higher energy, meaning that it contains more damage, and vice versa. Therefore, the identification of damaged segments can be achieved by identifying the distribution of wavelet components.

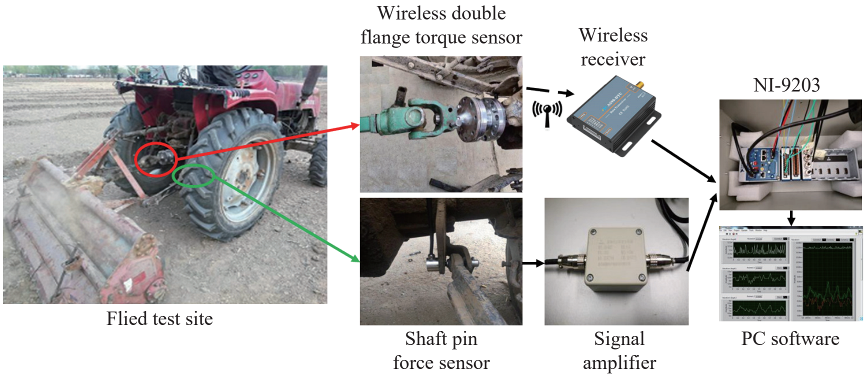
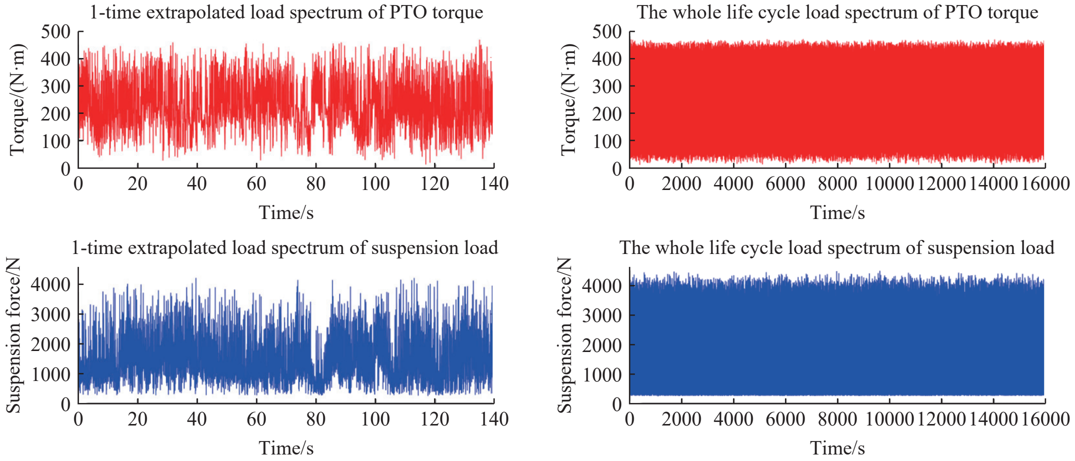


Figure 1 Field test site and test system



(a) 1-time extrapolated load spectrum (b) The whole life cycle load spectrum

Figure 2 Extrapolated load spectrum

The theory of wavelet transform is as follows:

The continuous wavelet transform for $f(t)\in L^2(R)$ is

$$W_f(a,b)=<f,\psi_{a,b}>=|a|^{-1/2}\int_{-\infty}^{+\infty}f(t)\psi\left(\frac{t-b}{a}\right)\mathrm{d}t \tag{1}$$

where, $\psi(t)$ is a wavelet basis function; a is a scaling parameter that controls the frequency by scaling the time t; b is a translation parameter that determines translation of $\psi(t)$ to a different position in the time axis; and $W_f(a,b)$ is the wavelet coefficient that can reflect the similarity between signal and wavelet basis function.

To accurately describe the characteristics of signal distribution at different scales, the selection of wavelet basis functions is crucial. However, with the wide range of wavelet basis functions and their diverse characteristics, it is necessary to choose the appropriate function based on the specific purpose[24]. The goal of this paper is to use wavelet transform to identify the damage concentration in the signal. Based on the principle of wavelet basis function selection and related literature on damage identification[17,18], the Daubechies wavelet is selected as the basis function for damage identification. Daubechies wavelets are abbreviated as Db*N*, where *N* represents the order of the wavelet. Db*N* series wavelets have compact support orthogonality, and their vanishing moment increases with the order. However, the vanishing moments and support lengths of Db*N* wavelet basis functions of different orders will affect the decomposition effect of the load signal. Therefore, it is necessary to select an appropriate wavelet basis function to decompose the rotary tillage load signal.

2.2.2 Hilbert envelope analysis

The identification of load damage fragments is realized by using Hilbert envelope analysis. This method is particularly effective for fault detection and damage identification due to its ability to extract the modulation signal from the original signal[25,26]. Hilbert envelope analysis is realized based on the Hilbert transform. Its principle is to make the signal have a 90° phase shift, thus transforming the actual signal into an analytic signal, whose real part is the signal itself; the imaginary part is the result of the Hilbert transform of the signal, and its amplitude is the envelope of the actual signal[27]. This envelope spectrum represents the distribution of the signal energy.

The principle of the Hilbert transform of signal $x(t)$ is as follows:

$$x_h(t)=H[x(t)]=\frac{1}{\pi}\int\frac{x(\tau)}{t-\tau}\mathrm{d}\tau=x(t)\frac{1}{\pi t} \tag{2}$$

Then the original signal $x(t)$ and the transformed signal $x_h(t)$ can form a new analytical signal $x_a(t)$:

$$x_a(t)=x(t)+jx_h(t) \tag{3}$$

Its amplitude is as follows:

$$A(t)=\sqrt{x^2(t)+x_h^2(t)} \tag{4}$$

2.2.3 Synchronous acceleration process of rotary tillage load spectrum

Combined with wavelet transform and envelope analysis, the synchronous acceleration process of rotary tillage load spectrum is proposed as follows:

1) Perform the wavelet decomposition of the load data using the Db*N* wavelet basis functions. The number of decomposition layers is set to *m*, so 1 approximate wavelet coefficient and *m* detailed wavelet coefficients of different scales are obtained.

2) Reconstruct the detailed wavelet coefficients to obtain *m* groups of detailed wavelet components $D_j(t_i)$ at each scale. Where, $j=1,2,3\ldots,m$ represents the decomposition scale, and $t_i=1,2,3\ldots,n$ represents the time point corresponding to the current wavelet component.

3) At each time point t_i, the accumulated sum of squares of detailed wavelet components (AccSSDWC) at various scales is calculated according to Equation (5) to represent the fatigue damage energy of the load signal.

$$A(t_i)=\sum_{j=1}^{m}D_j^2(t_i) \tag{5}$$

where, $D_j(t_i)$ is the detailed wavelet components at each scale, and $A(t_i)$ is the calculation result of AccSSDWC.

Figure 3 shows the distribution of the PTO torque load spectrum and the AccSSDWC of all 12 scales.

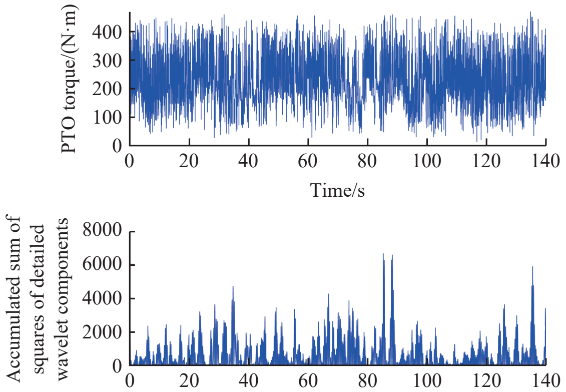


Figure 3 PTO torque load and its AccSSDWC

4) Establish a threshold for the identification of signal segments with substantial damage contributions within the load signal. Utilize half of the extremum range of the AccSSDWC as the base value of the threshold, and enable the gradient recognition of load damage by configuring a varying threshold level.

The base value of the threshold can be calculated using Equation (6).

$$T=\frac{\max(A(t_i))-\min(A(t_i))}{2} \tag{6}$$

Then the calculation formula for the *k*-th threshold level is:

$$T_k=T-\frac{p}{s}T \tag{7}$$

where, s is the total number of threshold levels that have been set, and p $(0<\frac{p}{s}<1)$ is the current threshold level. As shown in Figure 4, it represents the corresponding threshold value when $s=20$ and $p=2,4,6,8,10$, respectively.

5) According to the current threshold T_k, the candidate sequence of the damaged segment can be obtained by locating the time series $(t_i=1,2,3\ldots,N)$ with AccSSDWC greater than T_k.

6) Extract damage fragments from load signals based on Hilbert envelope analysis. The extraction principle is shown in Figure 5. First, calculate the Hilbert envelope of AccSSDWC. Then, use the candidate points obtained in step 5 as the center to find the position where the monotonicity of the front and rear envelopes changes. Finally, find the corresponding time point and extract the load data, which is the damage fragment. In Figure 5, the time point corresponding to candidate b is t_b ; a, c are the time points of the monotonic change of the Hilbert envelope, and their corresponding time points are t_a and t_c, respectively. Thus, the time axis (t_a,t_c) in the original load spectrum is the damage fragment which needs to be extracted.

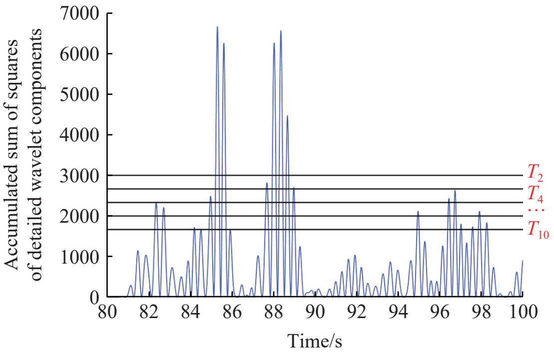


Figure 4 Thresholds corresponding to different threshold steps

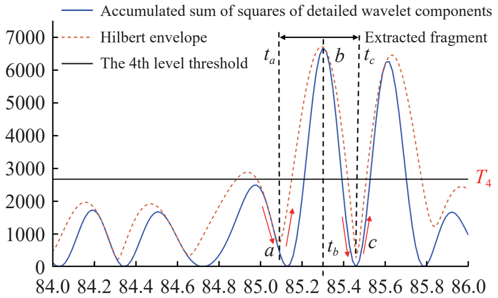


Figure 5 Schematic diagram of damage fragment extraction

7) Accelerate the rotary tillage load spectrum synchronously. Since the damage fragment obtained in step 6 is discontinuous, the signal fragments need to be spliced. The splicing of load spectrum is achieved based on the time domain synchronization of load spectrum of rotary tillage. As illustrated in Figure 6, the damage fragments of PTO torque ($T_{\text{PTO}}=(t_a,t_c)$) and suspension load ($T_{\text{suspension}}=(t_d,t_f)$) are obtained through the above steps. These fragments are then combined in the time domain to obtain $T_{\text{union}}=(t_a,t_e)$ according to the time domain synchronization, which represents the damage fragment for this period. Finally, all the load segments are processed using this method and connected using Sine

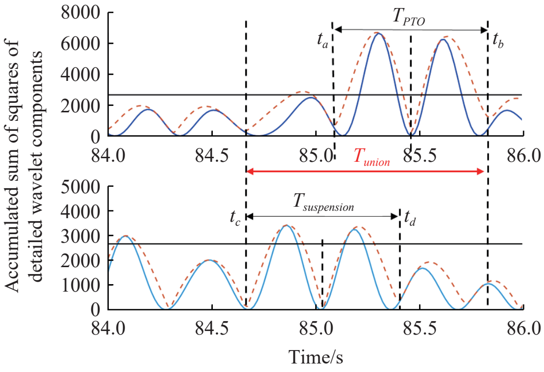


Figure 6 Schematic diagram of synchronous acceleration of load spectrum

curve to complete the synchronous acceleration of the rotary tillage load spectrum.

2.3 Pseudo-damage acceleration efficiency

In the acceleration process of load spectrum, the order N of wavelet basis function and threshold level p will affect the acceleration efficiency of load spectrum. Generally speaking, the indices to evaluate the effect of single acceleration are retention time ratio (RT) and retention damage ratio (RD), and the calculation methods are shown in Equation (8) and Equation (9), respectively.

Retention time ratio:

$$\mathrm{RT}_N^p = \frac{T_N^p}{T_0} \times 100\% \tag{8}$$

where, RT_N^p represents the retention time ratio of the accelerated load spectrum corresponding to the load signal decomposed using the N order Db wavelet basis function at threshold level of p ; T_N^p represents the retention time length of the accelerated load spectrum corresponding to the load signal decomposed using the N order Db wavelet basis function at threshold level of p ; T_0 represents the time length of the original load spectrum. The smaller the RT_N^p, the greater the compression of the load spectrum.

Retention damage ratio:

$$\mathrm{RD}_N^p = \frac{D_N^p}{D_0} \times 100\% \tag{9}$$

where, RD_N^p represents the retention damage ratio of the accelerated load spectrum corresponding to the load signal decomposed using the N order Db wavelet basis function at threshold level of p ; D_N^p represents the retention damage of the accelerated load spectrum corresponding to the load signal decomposed using the N order Db wavelet basis function at threshold level of p ; D_0 represents the pseudo-damage of the original load spectrum. A greater D_N^p indicates a smaller effect on the pseudo-damage of the load spectrum.

As can be seen from Equations (8) and (9), RT_N^p and RD_N^p only consider a single influencing factor, which may lead to biases in the evaluation of the acceleration results. For example, if RD_N^p is very large but RT_N^p is also large, it means that the acceleration effect is not obvious; or if RT_N^p is small but RD_N^p is also small, it can cause signal distortion. Therefore, it is necessary to consider the interrelationship between RT_N^p and RD_N^p comprehensively in the acceleration process. Based on this, the pseudo-damage acceleration efficiency (PDAE) is proposed to evaluate the acceleration effect and select the optimal acceleration parameters. This metric denotes the ratio of the accelerated time of the load spectrum to the induced fatigue damage, that is, the extent of time saved per unit of damage accelerated. A greater value indicates that more time can be saved for each unit of damage accelerated. The calculation formula for PDAE is as follows:

$$\mathrm{PDAE}_N^p = \frac{1-\mathrm{RT}_N^p}{1-\mathrm{RD}_N^p} \tag{10}$$

where, PDAE_N^p represents the pseudo-damage acceleration efficiency of the accelerated load spectrum corresponding to the load signal decomposed using the N order Db wavelet basis function at threshold level of p.

3 Results and discussion

Based on the acceleration method proposed in this paper, the extrapolated load spectrum of rotary tillage is accelerated. However, due to the large amount of data in the whole life cycle load spectrum, it is not practical to display it here. Instead, the 1-time extrapolation load spectrum is used as an example to illustrate the acceleration process. The acceleration results for the whole life cycle load spectrum will be provided at the end of the paper.

3.1 Synchronous acceleration results of load spectrum of rotary tillage

3.1.1 Determination of optimal acceleration parameters

In order to determine the optimal acceleration parameters for the load spectrum of rotary tillage operation, the selection process is illustrated by taking the 1-time extrapolated load spectrum of PTO torque as an example. First, the PTO torque load signal is decomposed using Db1-Db15 as the basis function in turn, and the number of wavelet decomposition scales is set to 12; then, the load spectrum is accelerated, where the total threshold level is set to 20 in each damage identification process. However, when the threshold level is less than 10, the RD of the load spectrum is less than 60%, leading to significant loss of detail in the load spectrum. Therefore, the threshold level of $p = 10, 11, \ldots, 19$ is selected for damage identification. The PTO torque load spectrum is processed according to the above process, and a total of 150 acceleration load spectra are obtained. Finally, the pseudo-damage corresponding to each accelerated load spectrum is calculated by using Ncode software, and the PDAE of 150 accelerated load spectra are calculated. The results are shown in Figure 7. It can be seen from Figure 7 that the optimal acceleration of PTO torque load spectrum can be achieved with Db1 decomposition at a threshold level of 16, with $\mathrm{PDAE}_1^{16} = 28.37$, $\mathrm{RD}_1^{16} = 98.72\%$, and $\mathrm{RT}_1^{16} = 63.68\%$.

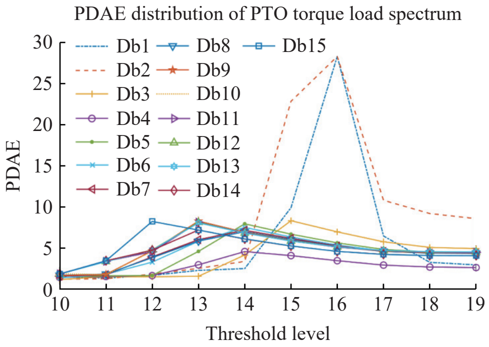


Figure 7 PDAE distribution of PTO torque load spectrum under different acceleration parameters

The PDAE diagram of the accelerated suspension load spectrum is obtained by using the same procedure as described above. The results are shown in Figure 8. As can be seen, the optimal acceleration is achieved with Db7 decomposition at a threshold level of 18, with $\mathrm{PDAE}_7^{18} = 7.73$, $\mathrm{RD}_7^{18} = 96.40\%$, and $\mathrm{RT}_7^{18} = 72.19\%$.

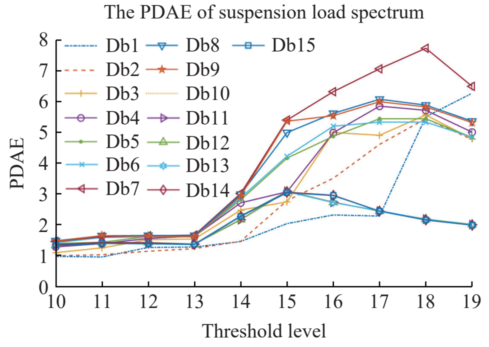


Figure 8 PDAE distribution of suspension load spectrum under different acceleration parameters

3.1.2 Synchronous acceleration of extrapolated rotary tillage load spectrum

The 1-time extrapolation rotary tillage load spectrum is accelerated synchronously using the determined acceleration parameters. The time length of the load spectrum after synchronous acceleration is 113.84 s, the RT is 81.32%, the RD of PTO torque load is 98.99%, and the RD of suspension load spectrum is 97.56%. The diagram of the acceleration process is shown in Figure 9.

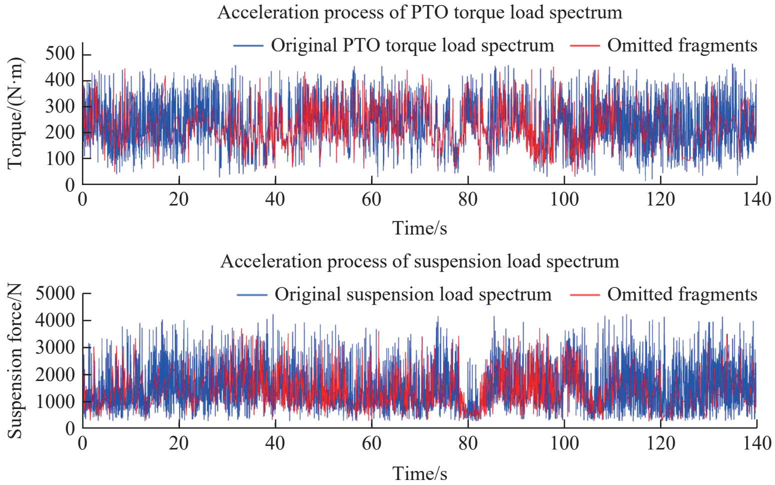


Figure 9 Acceleration process of 1-time extrapolated load spectrum

3.2 Rationality analysis of PDAE

Taking the 1-time extrapolated PTO torque load spectrum as an example, the distribution of RD and RT of the accelerated load spectrum under different wavelet orders and different threshold steps are plotted respectively, as shown in Figure 10 and Figure 11.

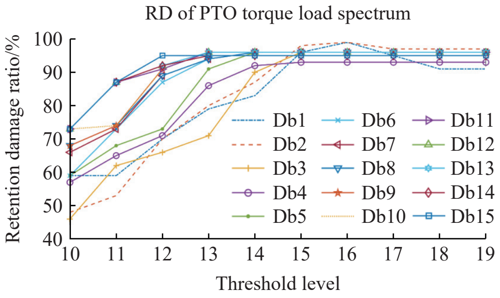


Figure 10 RD of PTO torque load spectrum under different acceleration parameters

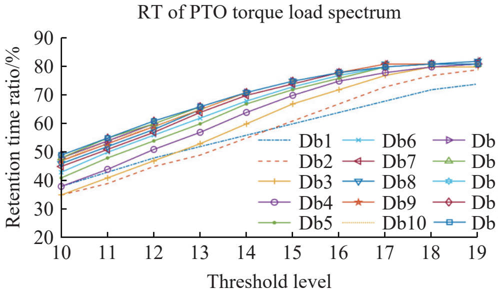


Figure 11 RT of PTO torque load spectrum under different acceleration parameters

It can be seen from Figure 10 that different acceleration parameters exert varying impacts on the RD. As the threshold level increases, the RD gradually increases and tends towards stability. When the threshold level exceeds 15, the RD of the accelerated load spectrum for all wavelet basic functions except Db4 and Db1 is greater than 95%. Among these, Db2 wavelet basic function at level 16 exhibits the highest RD value of 98.84%. It is evident that, if the maximum RD is taken into consideration, the accelerated load spectrum produced by Db2 wavelet basic function at level 16 should be chosen. However, it can be seen from Figure 11 that $\mathrm{RT}_2^{16} = 67.10\% > \mathrm{RT}_1^{16} = 63.68\%$, indicating that the acceleration effect of the load spectrum is not optimal under these parameters.

Similarly, Figure 11 illustrates that different acceleration parameters have various impacts on the RT. As the threshold level increases, the RT increases, meaning that the duration of the accelerated load spectrum increases. Results show that Db2 wavelet basic function exhibits the best acceleration effect when the threshold level is below 15, while Db1 wavelet basic function exhibits the best acceleration effect when the threshold level exceeds 15. It is also clear that if the RT is selected as the evaluation index, the accelerated load spectrum produced by Db2 wavelet basic function at level 10 ($\mathrm{RT}_2^{10} = 34.74\%$) or Db1 wavelet basic function at level 15 ($\mathrm{RT}_1^{15} = 60.10\%$) should be chosen. However, Figure 10 demonstrates that $\mathrm{RD}_2^{10} = 47.91\%$, indicating that the accelerated load spectrum has a large error, while $\mathrm{RD}_1^{15} = 96.98\% < \mathrm{RD}_1^{16} = 98.72\%$ indicates that the acceleration efficiency under this parameter is not optimal.

In conclusion, different wavelet basis functions and threshold levels have varying effects on the acceleration of the load spectrum. On one hand, this is attributed to the differing degrees of compatibility between various wavelet basis functions and the load signal. Specifically, for DBN wavelets, a higher order corresponds to larger vanishing moments and longer support lengths, indicating that such wavelet basis functions are better suited for processing signals with longer durations and higher frequencies. Consequently, employing high-order wavelet basis functions can lead to more precise outcomes; on the other hand, as the threshold level rises, the number of preserved damage segments also increases. However, excessively raising the threshold level can compromise acceleration efficiency. Therefore, it is essential to take into account the interplay between these two factors to determine more optimal acceleration parameters.

3.3 Comparison and verification of accelerated results

In order to verify the effectiveness of the acceleration method proposed in this paper, the damage retention acceleration method is also used to accelerate the 1-time extrapolated load spectrum of rotary tillage, and the accelerated load spectra obtained by both methods are compared. In order to facilitate the description, the acceleration method based on wavelet transform is referred to as wavelet method, and the damage retention acceleration method is referred to as damage retention method.

3.3.1 Accelerated results based on damage retention method

Damage retention method is realized by using Ncode software. Taking the RD obtained from wavelet method as a reference, the RD of the PTO torque load spectrum is set to 98.72%, and the RD of the suspension load is set to 96.40% for acceleration, respectively. The actual RD for the PTO torque load spectrum accelerated is 98.75% with the RT = 60.60%, and for the suspension load spectrum, the actual RD is 96.70%, and the RT is 78.49%. The acceleration results are then processed based on time domain synchronization to obtain the final accelerated spectrum. The time length of the accelerated load spectrum is 127.95 s; the RT is 91.39%; the RD of the PTO torque load spectrum is 99.89%; the RD of the suspension load spectrum is 99.12%. The final results of the two acceleration methods are shown in Figure 12.

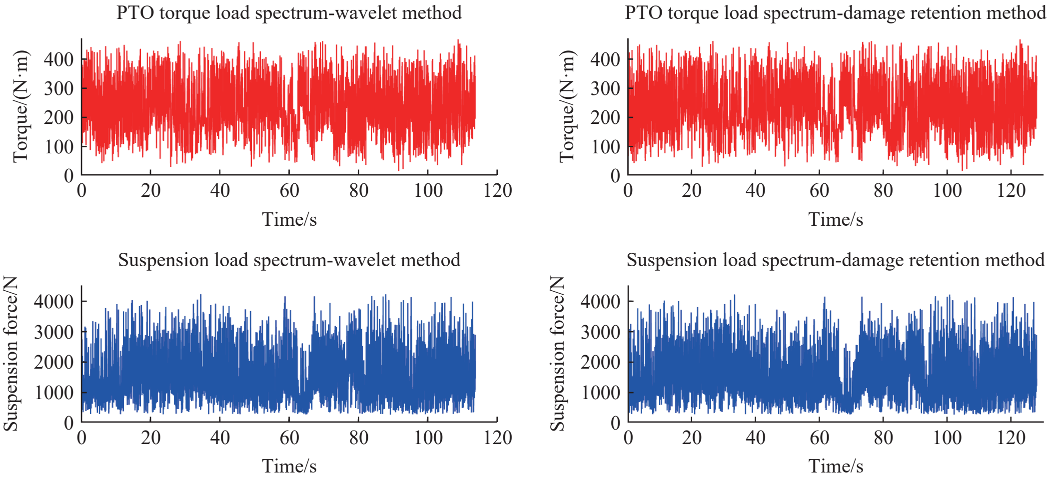


Figure 12 Acceleration results of the two methods

3.3.2 Comparison of acceleration results

The acceleration results of the two methods are summarized in Table 2. As the table shows, both methods performed well in terms of single acceleration under the same retention damage ratio. For PTO torque load, the RT of the damage retention method was 3.08% lower than that of the wavelet method, while for suspension load, the RT of the wavelet method was 10.25% lower than that of the damage retention method. In a word, both methods demonstrated high acceleration efficiency for a single type of load spectrum. However, for the results of synchronous acceleration, the RT of accelerated spectrum obtained by the wavelet method is 10.07% lower than that obtained by the damage retention method. It is generally considered that the load spectrum is equivalent when the retention damage ratio exceeds 95%. Therefore, it can be concluded that compared to the damage retention method, the wavelet method is able to save more time and is more suitable for acceleration of multiple types of load spectra.

Table 2 Comparison of acceleration results

Acceleration method	Load signal	Single acceleration			Synchronous acceleration		
		RD/%	RT/%	PDAE	RD/%	RT/%	PDAE
Wavelet method	PTO torque	98.72	63.68	28.38	98.99	81.32	18.50
Damage retention method	PTO torque	98.75	60.60	31.52	99.39	91.39	14.11
Wavelet method	Suspension load	96.40	72.19	7.73	97.56	81.32	7.66
Damage retention method	Suspension load	96.70	78.49	6.52	99.12	91.39	9.78

3.3.3 Comparison of statistical characteristics

Calculating the statistical characteristic parameters of the load spectrum before and after acceleration, as well as the errors, can directly reflect the changes in its load characteristics. The mean load is a key indicator affecting fatigue life; the root mean square (RMS) represents the energy distribution of the load spectrum; and kurtosis reflects the distribution of extreme load values. The results are listed in Table 3.

Table 3 Statistical characteristic parameters of load spectrum

Load type	Acceleration method	Mean	Error of mean/%	RMS	Error of RMS/%	Kurtosis	Error of kurtosis/%
PTO torque load spectrum	Original data	223.05	/	236.17	/	2.75	/
	Wavelet method	223.86	0.36	237.23	0.45	2.69	–2.18
	Damage retention method	221.34	–0.77	234.65	–0.64	2.76	0.36
Suspension load spectrum	Original data	1445.13	/	1616.20	/	3.42	/
	Wavelet method	1452.05	0.48	1625.02	0.55	3.49	2.05
	Damage retention method	1454.91	0.68	1626.45	0.63	3.37	–1.46

As is evident from Table 3, the statistical characteristic parameters of the accelerated load spectrum derived from both methodologies are largely consistent with those of the original load. Furthermore, the relative errors of all statistical parameters are below 5%, which indicates that both acceleration techniques can adequately preserve the distribution features of the load signal, thereby fulfilling the error criteria for accelerated editing of the load spectrum.

3.3.4 Comparison of the power spectral density

By comparing the distribution of the load spectrum power spectrum density (PSD) before and after acceleration, the changes of the load signal in the frequency domain are analyzed, as shown in Figure 13. As illustrated, the PSD of the load spectrum accelerated by these two methods is basically consistent with that before acceleration, for both PTO torque load and suspension load. Generally, the small load cycles tend to appear as high-frequency signals. Therefore, when small load cycles are omitted, the PSD of the accelerated load spectrum shifts at 23.4 Hz. However, the effect of this shift on the load spectrum can be negligible.

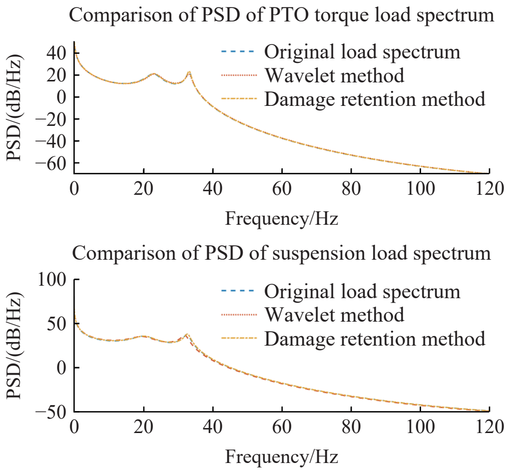


Figure 13 PSD comparison of load spectrum

3.4 Acceleration of the whole life cycle load spectrum

The above process verifies the effectiveness of the synchronous acceleration method based on wavelet transform. As a result, the whole life cycle of rotary tillage load spectrum is accelerated using this method, as shown in Figure14. The time length of the accelerated load spectrum is 13 609.40 s; the RT of the load spectrum is 85.27%; the RD of the PTO torque load spectrum is 97.14%; and the RD of the suspension load spectrum is 96.94%.

To verify the acceleration effect of the whole life cycle load spectrum, the rainflow counting method is employed to separately plot the amplitude-frequency distribution diagram and the mean-frequency distribution diagram for both the original and accelerated load spectra. The comparative results for the PTO torque load spectrum and the suspension load spectrum are illustrated in Figures 15 and 16, respectively.

As can be seen from Figure 15a, for the PTO torque load spectrum, the accelerated load spectrum removes more small-amplitude cycles and retains more large-load cycles, therefore the accelerated load spectrum can preserve more extreme loads. From Figure 15b, it is observed that the mean-frequency distribution characteristics of the two load spectra are basically consistent, indicating that the overall damage retention effect of the load spectrum is relatively good. Likewise, from Figure 16, it can be seen that for the suspension load spectrum, the accelerated load spectrum obtained by wavelet method retains the distribution characteristics of the original load spectrum in terms of mean-frequency and amplitude-frequency, and other distribution situations are similar to those of the PTO torque load spectrum. Therefore, it can be concluded that the acceleration method proposed in this paper can efficiently shorten the time of the load spectrum while preserving the damage characteristics of the load spectrum, thereby providing a reference for the indoor accelerated reliability test of tractors.

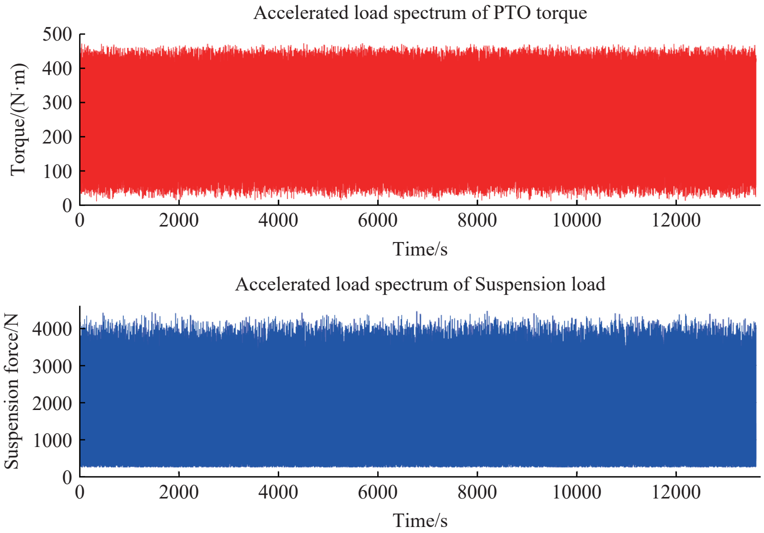
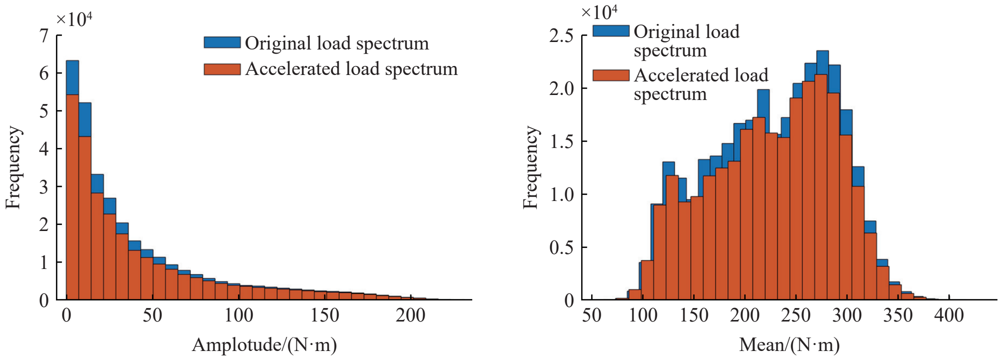


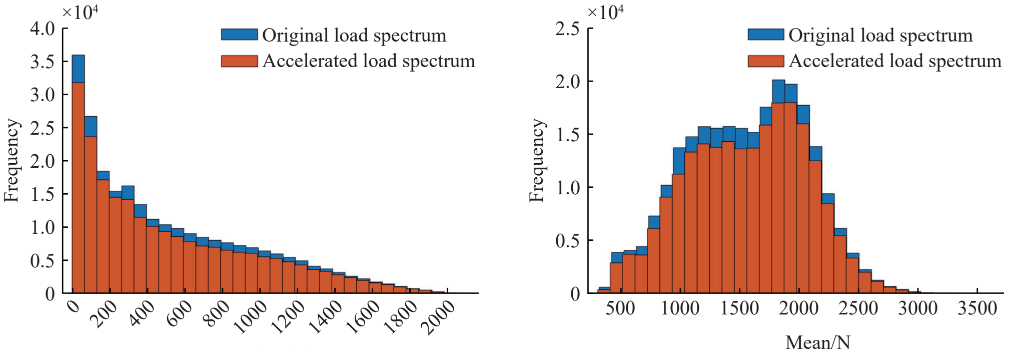
Figure 14 Accelerated results of the whole life cycle of rotary tillage load spectrum



a. Amplotude-frequency comparison

b. Mean-frequency comparison

Figure 15 Comparison of rainflow counting for PTO torque load spectra



a. Amplotude-frequency comparison

b. Mean-frequency comparison

Figure 16 Comparison of rainflow counting for suspension load spectra

4 Conclusions

This paper proposes a new synchronization acceleration method for rotary tillage load spectrum based on wavelet transform. Db*N* series wavelet basic functions are used to perform wavelet decomposition on PTO torque and suspension load, respectively, to obtain detailed wavelet components at each scale. The identification of damaged segments is achieved by calculating the accumulative sum of squares of wavelet components and setting the threshold. The extraction of large damaged segments in load spectrum is performed by using the Hilbert envelope analysis method, and the acceleration of the rotary tillage load spectrum is realized according to the time domain synchronization. Finally, this method is applied to accelerate the 1-time extrapolated rotary tillage load spectrum and the whole life cycle rotary tillage load spectrum.

This paper presents a new indicator to evaluate the acceleration effect of the load spectrum, that is pseudo-damage acceleration efficiency, and the optimal acceleration parameters of the rotary tillage load spectrum are determined. For the PTO torque load spectrum, the acceleration should be performed using the Db1 wavelet basic function at a threshold level of 16. For the suspension load spectrum, the acceleration should be performed using the Db7 wavelet basic function at a threshold level of 18. Finally, the validity of the acceleration parameters is verified, providing a reference for the selection of acceleration parameters for agricultural machinery load spectrum.

The effectiveness of the acceleration method proposed in this paper is verified through comparison with the damage retention acceleration method. The results showed that the acceleration method based on wavelet transform has advantages in acceleration efficiency, statistical characteristics, and frequency domain distribution. In particular, when considering time domain synchronization, the acceleration method based on wavelet transformation saves 10.07% more time compared to the damage retention method, which has important significance in the field of agricultural reliability testing applications.

This paper has investigated a wavelet transform-based method for synchronously accelerating the rotary tillage load spectrum and has achieved acceleration of the whole life cycle load spectrum. However, there are still some limitations that need to be addressed in future research. For instance, the current calculation of load spectrum fatigue damage is realized through simulation calculations, and experimental validation on actual tractors has not been carried out; the acceleration effect of this method on different types of load spectra has not been compared and validated; and the damage contribution weights of different operation processes are not considered in the acceleration process. In-depth research will continue to be conducted to provide more references for the accelerated fatigue testing of tractor reliability.

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