Loading method for tractor rotary tillage load spectrum based on extreme load retention resampling

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Abstract: Conducting bench tests for tractors according to the load spectrum is essential for assessing their reliability and fatigue durability. However, achieving an accurate replication of field operating conditions poses challenges due to the disparity in response characteristics between the tractor bench loading system and the frequency data of the load spectrum. Consequently, discrepancies in test results arise. To mitigate this challenge, this study proposes a loading method for the tractor rotary tillage load spectrum based on extreme load retention resampling. Firstly, a tractor rotary tillage load acquisition test was conducted, and a one-time-extrapolated load spectrum was compiled based on the Peak Over Threshold model. Considering the characteristics of rotary tillage operations, the tractor rotary tillage load spectrum loading bench was developed, which primarily includes the Power Take-Off (PTO) loading system and the suspension loading system. On this basis, a rotary tillage load spectrum loading system based on a Fuzzy-PID controller was proposed to realize the dynamic loading of the rotary tillage load spectrum. The dynamic response characteristics of the loading bench were analyzed based on a simulation model, and the results showed that the loading bench can achieve dynamic loading of load spectra with frequencies below 25 Hz. To match this characteristic, a load spectrum resampling method based on extreme load retention was proposed to resample the rotary tillage load spectrum. Based on the retention of the load spectrum fatigue damage, a resampled rotary tillage load spectrum with a resampling ratio of 3 was obtained, with a loading frequency of 20.98 Hz. Finally, the tractor rotary tillage loading test was conducted based on the resampled rotary tillage load spectrum. The test results demonstrated that the loading bench effectively replicated the resampled rotary tillage load spectrum. For the PTO torque load spectrum, the average error is –7.53%, with a delay of 30 ms, and for the suspension load spectrum, the average error is –2.48%, with a delay of 22 ms. The result indicated that the resampled load spectrum can well match the dynamic characteristics of the loading bench. This research can serve as a practical reference for implementing tractor bench tests grounded in load spectra.

Keywords: spectrum, Power Take-Off, Fuzzy-PID controller, extreme load retention resampling, bench test

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1 Introduction

Tractors serve as indispensable tools in agricultural production, with their reliability exerting a direct influence on agricultural productivity and economic benefits[1]. As a typical operation for tractors, rotary tillage primarily relies on the tractor's Power Take-Off (PTO) and suspension system to provide power to the rotary tiller. The tractor PTO and suspension system bears complex and variable loads during operation, which have a significant impact on their fatigue reliability. Therefore, conducting tractor reliability tests is essential[2].

Traditional tractor reliability tests typically necessitated long-term field trials conducted under actual operating conditions; therefore, they are both resource intensive and inefficient. However, recent years have witnessed a significant advancement in tractor load spectrum compilation technology. This progress has laid the groundwork for indoor bench reliability tests of tractors, thereby enabling the execution of reliability assessments through indoor bench methodologies[3,4]. Central to this approach is the load spectrum, which delineates the temporal evolution of loads sustained by the tractor during real-world operations. Such spectra represent a crucial avenue for investigating the reliability of the tractor.

The utilization of load spectra in bench testing serves the purpose of replicating the loads encountered during field operations, thereby substituting traditional field reliability tests, enhancing test efficiency, and reducing testing costs[5]. Yang et al. conducted load collection experiments for a three-point suspension under plowing conditions and employed a genetic algorithm to select extrapolation thresholds. Subsequently, they compiled the plowing three-point

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suspension traction resistance load spectrum based on time-domain extrapolation[6]. Addressing the limitations of traditional time-domain extrapolation methods, Yang et al. proposed a tractor drive shaft load time-domain extrapolation method based on the Markov chain Monte Carlo-peak over threshold (MCMC-POT) technique. This method effectively captured the load spectrum over the entire life cycle under plowing conditions. Additionally, they introduced a time-domain extrapolation method based on EMD-POT to enhance the adaptability of traditional POT extrapolation methods to nonstationary loads and to provide further insights into extrapolation reconstruction[7]. Yu et al. compiled the load spectrum of a tractor PTO under rotary tillage operations using the peak over threshold (POT) model and refined the method for selecting time-domain extrapolation thresholds[8]. Meanwhile, Wen et al. investigated the load spectrum acceleration method based on power spectrum density. Their study involved identifying and extracting large load segments in the load spectrum by computing the cumulative power density of the load spectrum, thereby expediting the load spectrum to enhance the efficiency of the tractor bench tests[9]. However, while these studies primarily focused on the collection and compilation methods for load spectra, there remains a paucity of in-depth research concerning the application of load spectra for indoor bench tests.

To effectively conduct indoor bench tests utilizing a load spectrum, it is imperative to develop compatible loading equipment and devise appropriate loading control methods. In order to simulate the load conditions of a tractor during rotary tillage, it is necessary to simultaneously load both the tractor's PTO and suspension system[10]. However, currently, there is a scarcity of testing equipment that can perform this task, as most available equipment only has a single function. Siddique et al. utilized a PTO dynamometer to measure engine load and fuel consumption across different load levels, aiming to construct a fuel consumption simulation model for the tractor powertrain and to optimize load characteristics[11]. Roeber et al. utilized a PTO loading test bench dynamometer from the Nebraska Tracker Test Lab to calibrate a tractor torque measurement system[12]. Meanwhile, Wang et al.[13] and Sumer et al.[14] constructed PTO loading test benches equipped with an alternating current (AC) dynamometer and an eddy current dynamometer, respectively. Dai et al. developed an indoor calibration device for tractor three-point hitch and proposed a new spatial force measurement device to guide calibration and testing[15]. These setups were primarily employed to evaluate the performance of the tractor and ascertain its load characteristics. However, it is noteworthy that most loading benches are limited to facilitating static torque loading according to predefined procedures, thereby lacking the capability to achieve dynamic loading based on the load spectrum.

Loading control methods play a pivotal role in conducting bench tests based on load spectra; however, research in this domain remains relatively limited. Wang et al. proposed a tractor PTO torque dynamic loading method grounded in the load spectrum and devised a torque dynamic loading control algorithm utilizing a fuzzy proportional-integral-derivative (PID) controller, achieving dynamic loading at a frequency of 20 Hz. Although this study introduced a specific method for utilizing load spectra in bench testing, it did not explore the relationship between high-frequency load spectra and loading equipment performance[16]. Wang et al. compiled the load spectrum for a tractor's three-point suspension system based on the optimal distribution fitting method, and developed a suspension loading system to achieve dynamic loading of the programmed load spectrum[17]. Wen et al. proposed a method for designing tractor accelerated structure tests suitable for a drum type test bench, employing optimization matrix construction, time-domain extrapolation, augmented Lagrangian multiplier, and Monte Carlo methods. This approach facilitated an indoor simulation of the accelerated load spectrum[4]. Meanwhile, Yan et al. compiled a dynamic torque load spectrum for the PTO and conducted durability tests on the tractor PTO using a dynamic loading test bench for tractor transmission; however, they did not elaborate on the development process of the loading bench[18]. Mattetti et al. proposed a method for accelerating durability tests of tractor prototypes. Their approach involved calculating displacements on the wheel hub from acceleration measurements, applying fatigue editing techniques to load signals, and utilizing a four-post bench to simulate structural damage. Ultimately, this methodology achieved an acceleration factor of 5.3 for fatigue testing[19]. Additionally, Cutini and Bisaglia conducted a twelve-hour test on all tractors using a four-poster test bench, simulating transport conditions by inputting acceleration signals acquired during terrain transportation[20]. In summary, research on the load simulation of tractor rotary tillage conditions is still in its early stages, as it requires not only specialized rotary tillage loading equipment but also the ability to simultaneously control both PTO torque load spectrum and suspension load spectrum loading.

Not only that, to accurately depict the load characteristics of field operations within a compiled load spectrum, it is also imperative to employ a high sampling frequency for operational load collection[21]. Consequently, a high-frequency compiled load spectrum ensues. However, employing such a high-frequency load spectrum directly for bench loading tests necessitates loading equipment with sufficiently high dynamic response characteristics. Failure to meet this requirement would result in the inaccurate reproduction of actual field conditions, thereby compromising the fidelity of test results.

In response to this challenge, this study proposes a tractor rotary tillage load spectrum loading method grounded in extreme load retention resampling. The objective is to reconcile the discrepancy between the load spectrum's high frequency and the dynamic response characteristics of the loading bench, thereby offering insights for tractor bench tests. The primary contributions of this study are outlined below:

1) A tractor rotary tillage load spectrum loading bench was developed. Combining the characteristics of rotary tillage operations, a PTO loading system and a suspension loading system were designed to simulate the rotary tillage conditions.

2) A load spectrum resampling method based on extreme load retention was proposed to reduce the loading frequency of the load spectrum while ensuring the effectiveness of the spectrum in terms of fatigue damage.

3) A dynamic loading control method for rotary tillage load spectrum based on a Fuzzy-PID controller was proposed, and the loading test based on resampled rotary tillage load spectrum was conducted.

2 Materials and methods

2.1 Time-domain extrapolation of rotary tillage load spectrum based on POT model

2.1.1 Collection of tractor rotary tillage load spectrum

The load during tractor rotary tillage operations includes both the PTO torque load and the suspension load. A rotary tillage load acquisition system was developed to collect the PTO torque load and the suspended load of the tractor, and the field test site and the collection system are shown in Figure 1. In this investigation, the TS404 tractor (Manufacturer: Shandong Wuzheng Group Co., Ltd.) was utilized as the experimental prototype, equipped with a 1GLN-0145 rotary tiller for the PTO load collection test conducted at the Shangzhuang test station in Haidian district, Beijing, China. The tillage depth and width are 200 mm and 1800 mm, respectively; the operating speed is in the range of 4.0-4.5 km/h, and the torque sampling frequency is 1000 Hz.

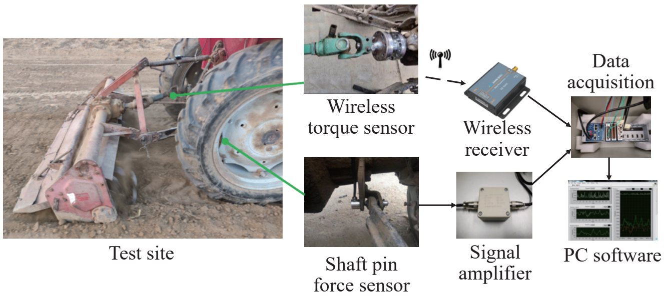

Figure 1 Field test site and collection system

2.1.2 Extrapolation of rotary tillage load spectrum

The extrapolation of the tractor rotary tillage load spectrum is achieved based on the Peak Over Threshold (POT) model. This approach utilizes the Generalized Pareto Distribution (GPD) to fit the distribution law of the data exceeding the threshold, thereby predicting the extreme loads. The extrapolation process is illustrated in Figure 2.

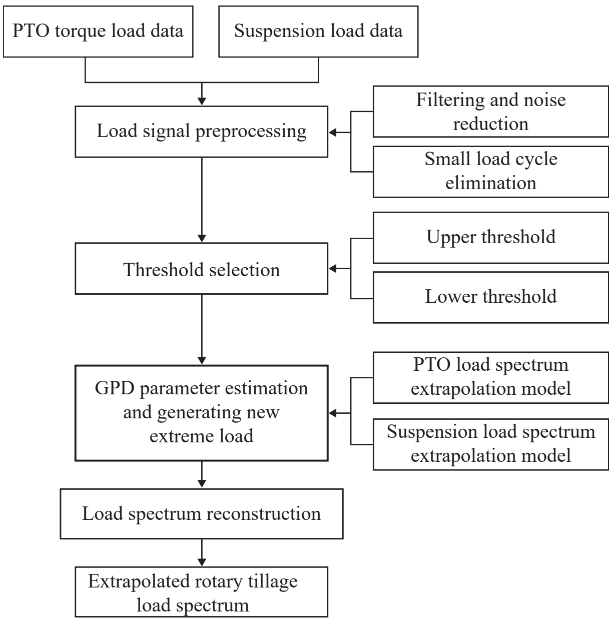

Figure 2 Extrapolation process based on POT model

The GPD is the basis for the extrapolation of excess. The cumulative distribution function (CDF) of GPD is as follows:

$$G(x;u,\sigma,\xi)=\begin{cases}1-\left(1+\xi\dfrac{x-u}{\sigma}\right)^{-\frac{1}{\xi}}, & \xi\neq 0, x\geq u\\ 1-\exp\left(-\dfrac{x-u}{\sigma}\right), & \xi=0, x\geq u\end{cases} \tag{1}$$

The probability density function (PDF) of GPD is as follows:

$$g(x;u,\sigma,\xi)=\begin{cases}\dfrac{1}{\sigma}\left(1+\xi\dfrac{x-u}{\sigma}\right)^{-\frac{1}{\xi-1}}, & \xi\neq 0, x\geq u\\ \dfrac{1}{\sigma}\exp\left(-\dfrac{x-u}{\sigma}\right), & \xi=0, x\geq u\end{cases} \tag{2}$$

where, u means the threshold; $x-u$ means the excess; ξ means shape parameter; and σ means scale parameter.

A threshold selection method based on False Discovery Rate (FDR) control was used to calculate the extrapolation thresholds, which resulted in the extrapolation thresholds for PTO torque load spectrum and suspension load spectrum, respectively. Based on these thresholds, the data exceeding the thresholds were extracted for GPD fitting. The estimated GPD parameters corresponding to the upper and lower thresholds of the PTO torque load spectrum and suspension load spectrum are listed in Table 1.

Table 1 GPD fitting results of rotary tillage load spectrum

Spectrum	Threshold		Shape parameter	Scale parameter
PTO spectrum	Upper threshold	234.50	–0.3760	89.9660
	Lower threshold	146.00	–0.2856	39.8230
Suspension load spectrum	Upper threshold	1615.60	–0.2927	852.5101
	Lower threshold	611.79	–0.7211	254.8103

Therefore, the POT models corresponding to the upper and lower thresholds of the PTO torque load spectrum are as follows:

$$G(x,u,\sigma,\xi)=1-\left(1-0.3760\frac{x-234.50}{89.9660}\right)^{2.6596} \tag{3}$$

$$G(x,u,\sigma,\xi)=1-\left(1-0.2856\frac{x-146.00}{39.8230}\right)^{3.5014} \tag{4}$$

The POT models corresponding to the upper and lower thresholds of the suspension load spectrum are as follows:

$$G(x,u,\sigma,\xi)=1-\left(1-0.2927\frac{x-1615.60}{852.5101}\right)^{3.4164} \tag{5}$$

$$G(x,u,\sigma,\xi)=1-\left(1-0.7211\frac{x-611.79}{254.8103}\right)^{1.3868} \tag{6}$$

Furthermore, the load spectrum with an extrapolation factor of 1 is obtained by replacing the excess of the original load with the random data from Eq.(1)-Eq.(4). The compiled one-time-extrapolated rotary tillage load spectrum is illustrated in Figure 3. The one-time-extrapolated load spectrum contains 7164 data points and spans 113.84 seconds, indicating that the load data frequency is 62.93 Hz.

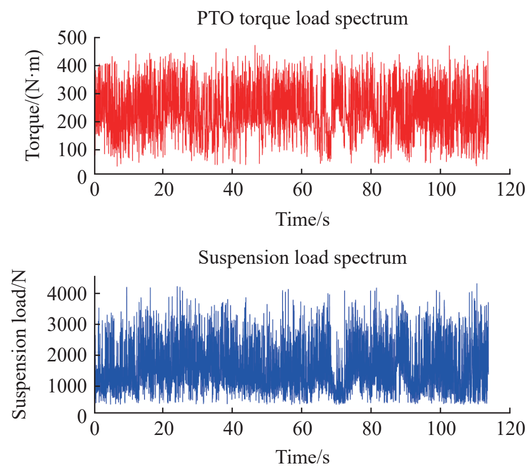

Figure 3 One-time-extrapolated rotary tillage load spectrum

2.2 Load spectrum resampling method based on extreme load retention

The data frequency of the load spectrum is defined as the number of load sampling points per second. A higher data frequency corresponds to a larger volume of data. Consequently, during bench tests, it becomes imperative for the dynamic response characteristics of the loading equipment to match this high data frequency. To address this challenge, the present study proposes a resampling method grounded in extreme load retention. This method aims to strike a balance between data frequency and loading equipment performance.

The integer-multiple decimation in traditional resampling methods refers to taking a value from the target signal every $M-1$ data, where M is an integer called the decimation factor[22]. While the traditional resampling method preserves the frequency-domain information of the original signal by extracting loads at fixed intervals, it may overlook extreme load signals[23]. Given the significance of extreme loads in applying the load spectrum to reliability analysis and fatigue damage calculation of components, this study advocates for a novel resampling method centered on retaining extreme loads. The proposed process is as follows:

(1) Given the sampling period T_1 of the input load spectrum $x(n_1T_1)$, the corresponding sampling rate is $F_1 = 1/T_1$, and n_1 is the number of sampling points.

(2) Determine the resampling ratio M based on the target load spectrum $y(n_2T_2)$, calculated as:

$$M = \frac{F_1}{F_2} \tag{7}$$

where, n_2 is the sampling point index sequence of the input load spectrum; T_2 is the sampling time interval; and $F_2 = 1/T_2$ is the corresponding sampling frequency.

(3) The resampled load spectrum $y(n_2T_2)$ is expressed as: $y(n_2T_2) = \lambda(n_1T_1)\cdot x(n_1T_1)$,

where, $\lambda(n_1T_1)$ is the resampling period sequence,

$$\lambda(n_1T_1) = \begin{cases} 1, & n_1 = 0, \pm M, \pm 2M \\ 0, & \text{other} \end{cases}.$$

(4) Calculate the mean value A of the input load spectrum $x(n_1T_1)$:

$$A = \frac{\sum x(n_1T_1)}{n} \tag{8}$$

where, n is the total number of sampling points, and $\sum x(n_1T_1)$ represents the sum of all load data in $x(n_1T_1)$.

(5) Extract M load data points from $x(n_1T_1)$ as candidate sequences according to the resampling ratio M, where $n_1 = Mn_2$, and n_2 corresponds to the sampling points of the target load spectrum.

(6) Identify the extremum load in the candidate sequences using the following criterion to select new sampling points:

$$y(n_2T_2) = \begin{cases} \max(\lambda(kT_1)x(kT_1)), \\ \left(\dfrac{x((n_1-M)T_1)+x((n_1-M+1)T_1)+\ldots+x(n_1T_1)}{M} \geq A\right), \\ n_1 = Mn_2 \\ \min(\lambda(kT_1)x(kT_1)), \\ \left(\dfrac{x((n_1-M)T_1)+x((n_1-M+1)T_1)+\ldots+x(n_1T_1)}{M} < A\right), \\ n_1 = Mn_2 \end{cases} \tag{9}$$

where, $k = n_1 - M, n_1 - M + 1, \ldots, n_1$.

(7) Iteratively repeat Steps (5) and (6) until all data in the input load spectrum are processed, and the output $y(n_2T_2)$ is the resampled load spectrum.

The main principle of this approach is to detect the relationship between the average value of the extracted M load data points and the average value A of the original signal, to identify and preserve the extreme values in the M load data, thereby ensuring that the resampled signal contains the extreme load points, further ensuring that overall damage remains as unchanged as possible.

2.3 Development of dynamic loading bench for rotary tillage load spectrum

The scheme of the dynamic loading bench is illustrated in Figure 4, consisting of a PTO loading system, a suspension loading system, an electrical control cabinet, a monitor for PC software, and a movable chassis.

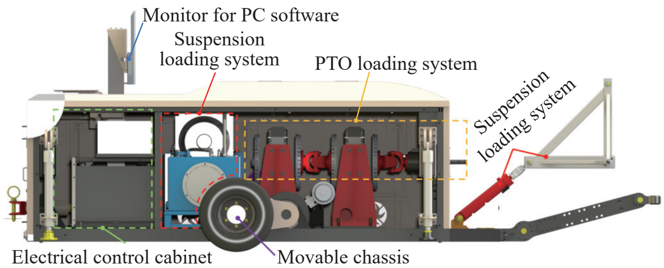

Figure 4 Scheme of the dynamic loading bench

The structure of the loading system and suspension loading system is shown in Figure 5. The PTO loading system comprises two eddy current dynamometers, a dynamometer controller, a torque sensor, coupling, and a torque output shaft. By virtue of series installation, the system can furnish a maximum torque load of 3000 N·m. A dynamometer is employed for controlling PTO torque loading. The torque sensor plays a pivotal role in measuring torque and rotation speed, with its data fed back to the dynamometer controller to facilitate torque loading control.

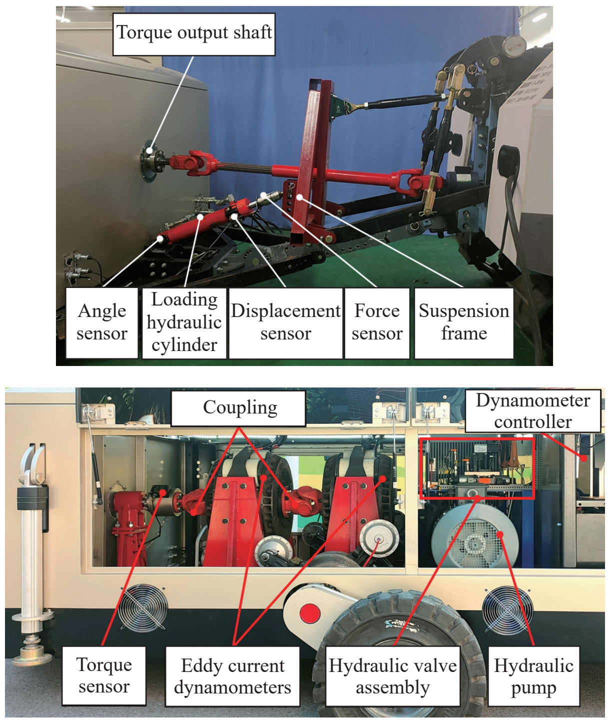

Figure 5 Structure of loading system

The suspension loading system consists of a loading hydraulic cylinder, a force sensor, a displacement sensor, an angle sensor, a suspension frame, a hydraulic valve assembly, and a hydraulic pump. The loading hydraulic cylinder is utilized to simulate soil resistance, with a maximum loading force capacity of 50 kN. The force sensor is employed to measure the loading force. The displacement sensor and angle sensor are respectively used to detect the displacement and orientation of the loading force. The suspension frame is designed according to testing standards, serving to connect the loading bench to the tractor's three-point linkage system. The hydraulic valve assembly consists of electro-hydraulic servo proportional relief valves and electro-hydraulic proportional directional control valves, which, in conjunction with the hydraulic pump, enable dynamic control over the loading force and direction exerted by the hydraulic cylinder. The specific parameters of sensors and hydraulic valves used in the loading bench are listed Table 2.

The electrical control cabinet serves as the repository for a range of instruments, including a loading control instrument, a bench control instrument, a monitor, and a power controller. The loading control instrument was constructed atop the NI-Compact RIO embedded system, primarily tasked with data acquisition and dynamic loading control. Concurrently, a bench control instrument was employed to adjust the test parameters to meet the diverse horsepower tractor test requirements. Developed using LabVIEW, the PC software facilitated data management and user interaction while the monitor enabled data display. The principle of the loading control system is shown in Figure 6.

Table 2 Loading system equipment parameters and functions

Equipment name	Model	Range	Function
Eddy current dynamometers	KM-2400	0-2400 N·m	Implement PTO torque loading
Torque sensor	MH816	0-3000 N·m	Detect PTO torque and speed
Loading hydraulic cylinder	/	0-50 kN	Implement traction force loading
Traction sensor	DHJL-4	0-50 kN	Detect traction force magnitude
Displacement sensor	MNH-40	0-400 mm	Detect loading position
Angle sensor	MCJSV05 A-2-B	0-180°	Detect traction force angle
Electro-hydraulic proportional relief valve	AGMZO-A-10/210	0-21 MPa	Control traction force magnitude
Electro-hydraulic proportional reverse valve	PRM6-10-3Z11/80-24	0-80 L·min^{-1}	Control traction force direction

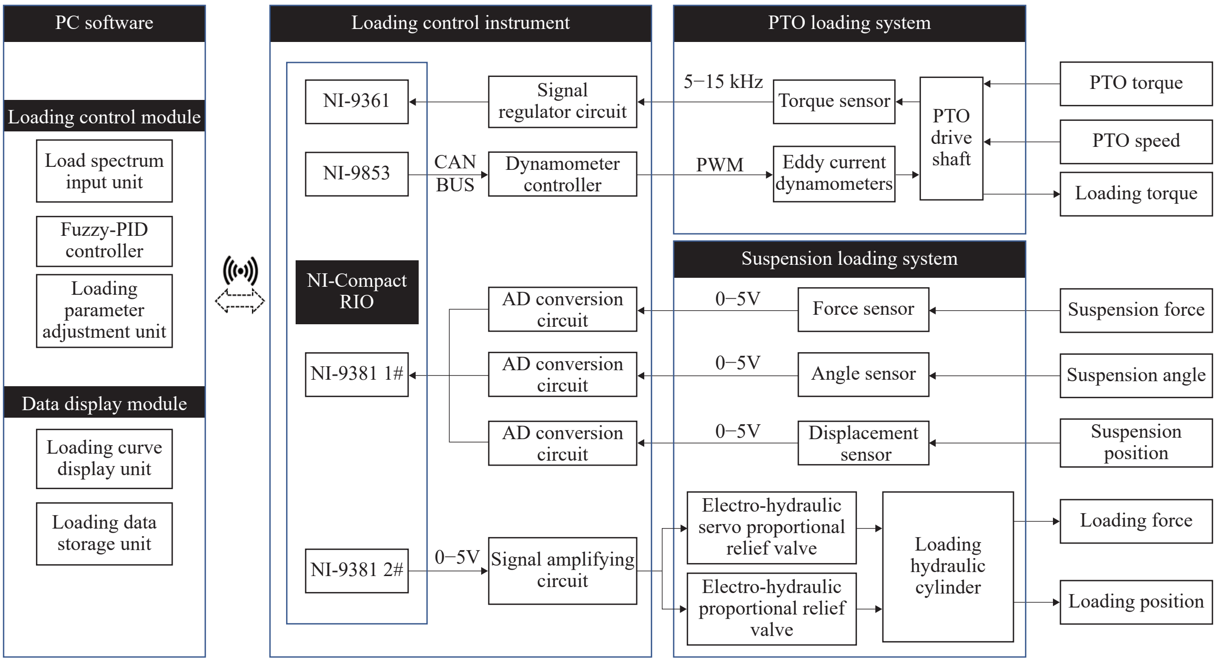

Figure 6 Principle of the loading system

2.4 Loading control system based on Fuzzy-PID controller

In pursuit of achieving precise loading in accordance with the load spectrum, a loading algorithm based on a Fuzzy-PID controller is developed. The principle of Fuzzy-PID controller is shown in Figure 7. This controller is divided into the PTO torque loading controller and the suspension loading controller. These two components are designed to carry out the dynamic loading of the PTO torque load spectrum and the suspension load spectrum, respectively.

2.4.1 Design of PTO torque loading controller

Regarding the PTO torque loading controller, the input of fuzzy controller is torque deviation (E) and deviation change rate (EC), and the output is the correction values of the three PID parameters ΔK_p, ΔK_i, and ΔK_d. The input of PID controller is torque deviation (E) and parameter correction value, and the output is the eddy current dynamometer control signal.

Based on the torque loading range, the domains for the fuzzy controller's input variables E and EC are set within [–600, 600], and the output universes for ΔK_p, ΔK_i, and ΔK_d are established as (–2, 2), (–0.5, 0.5), and (–0.1, 0.1), respectively. Both input and output variables are quantized into seven levels, with corresponding fuzzy subsets {NB, NM, NS, ZO, PS, PM, PB}, signifying negative big, negative middle, negative small, zero, positive small, positive middle, and positive big, respectively. The Gaussian function serves as the membership function for each fuzzy subset.

The fuzzy control rules are established based on the impact of PID parameters on the eddy current dynamometer's torque control and practical operational experience. These rules are listed in Table 3. The fuzzy controller utilizes a two-dimensional Mamdani reasoning approach, where the max-min method is employed for making control decisions, and defuzzification is accomplished using the Centroid method.

2.4.2 Design of suspension loading controller

The development process of the suspension loading controller is similar to that of the PTO torque loading controller, with the following distinctions:

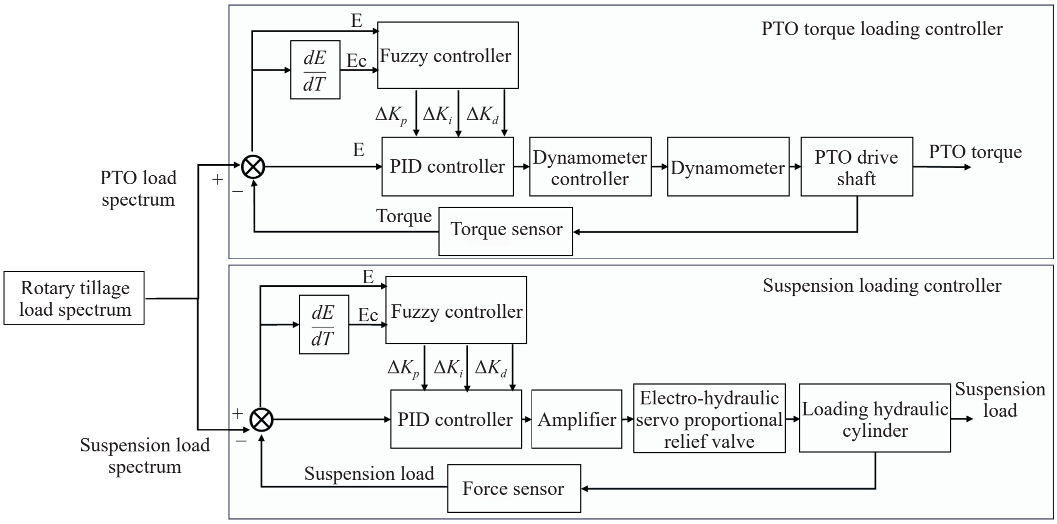

Figure 7 Principle of Fuzzy-PID controller

Table 3 Fuzzy rules of ΔK_p, ΔK_i, and ΔK_d

$\Delta K_p/\Delta K_i/\Delta K_d$		EC						
		NB	NM	NS	ZO	PS	PM	PB
E	NB	PB/NB/PS	PB/NB/NS	PM/NM/NB	PM/NM/NB	PS/NS/NB	ZO/ZO/ZO	ZO/ZO/PS
	NM	PB/NB/PS	PB/NB/NS	PM/NM/NB	PS/NS/NM	PS/NS/NM	ZO/ZO/NS	NS/ZO/ZO
	NS	PM/NB/ZO	PM/NM/NS	PM/NS/NM	PS/NS/NM	ZO/ZO/NS	NS/PS/PS	NS/PS/ZO
	ZO	PM/NM/ZO	PM/NM/NS	PS/NS/NS	ZO/ZO/NS	NS/PS/NS	NM/PM/NS	NM/PM/ZO
	PS	PS/NM/ZO	PS/NS/ZO	ZO/ZO/ZO	NS/PS/ZO	NS/PS/ZO	NM/PM/ZO	NM/PS/ZO
	PM	PS/ZO/PB	ZO/ZO/NS	NS/PS/PS	NM/PS/PS	NM/PM/PS	NM/PB/PS	NB/PB/PB
	PB	ZO/ZO/PB	ZO/ZO/PM	NM/PS/PM	NM/PM/PM	NM/PM/PS	NB/PB/PS	NB/PB/PB

(1) Input and output variables: The input variables for the fuzzy controller of the suspension loading system are the suspension force deviation (E) and the deviation change rate (EC). The outputs are the correction values of the three PID parameters ΔK_p, ΔK_i, and ΔK_d. For the PID controller, the input variable is the suspension load deviation (E), and the output variable is the control voltage for the electro-hydraulic proportional relief valve.

(2) Domain: According to the loading range of the suspension loading system, the basic domains of input variables E and EC of the fuzzy controller are determined as (–5000,5000), and the domains of output variables ΔK_p, ΔK_i, ΔK_d are determined as (–3,3), (–1,1), and (–0.1 0.1), respectively.

(3) Membership functions: The Triangular function is selected as the membership function for each fuzzy subset.

2.4.3 Step response system identification of the loading system

To achieve the simulation of the dynamic characteristics of the loading system, step response system identification was used to obtain the transfer function of the loading system. During the step response test of the PTO loading system, the PTO speed was set to 1000 r/min. When the speed was stabilized, a loading command was sent through the software, causing the eddy current dynamometer to generate a braking torque. The step response curve of the PTO loading system is shown in Figure 8. At T=1 s, a step control signal PWM=24 was applied, and the dynamometer began to respond approximately 0.011 s later. The torque reached a stable state at T=2.27 s. Using the MATLAB system identification module to analyze the step response curve, the transfer function of the PTO loading system was obtained as shown in Equation (10):

$$G(s)=\frac{T(s)}{U(s)}=\frac{0.9425s^2+598.5s+2857}{s^2+38.74s+154.2}e^{-0.011s} \tag{10}$$

Similarly, the identification was performed on the suspension loading system, and the results are shown in Figure 9. The transfer function of the suspension loading system is given as:

$$G(s)=\frac{T(s)}{U(s)}=\frac{-1.026s^3+29.19s^2+34.09s+27.54}{s^3+8.663s^2+10.01s+5.858}e^{-0.015s} \tag{11}$$

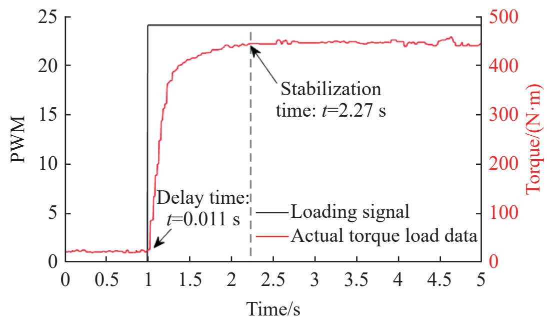

Figure 8 Step response curve of PTO loading system

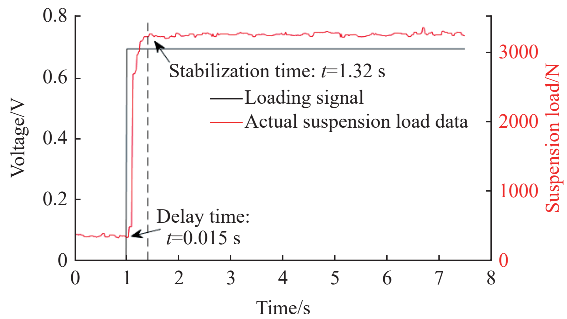

Figure 9 Step response curve of suspension loading system

2.4.4 Simulation model of Fuzzy-PID controller

To ascertain the dynamic response characteristics of the loading bench utilizing the Fuzzy-PID controller, a simulation model is built using Simulink, as shown in Figure 10. The initial parameters of the PID controller in the PTO torque loading controller are 0.7850, 0.2117, and 0.0148, while for the suspension loading controller, they are 0.3875, 0.5551, and 0.0031.

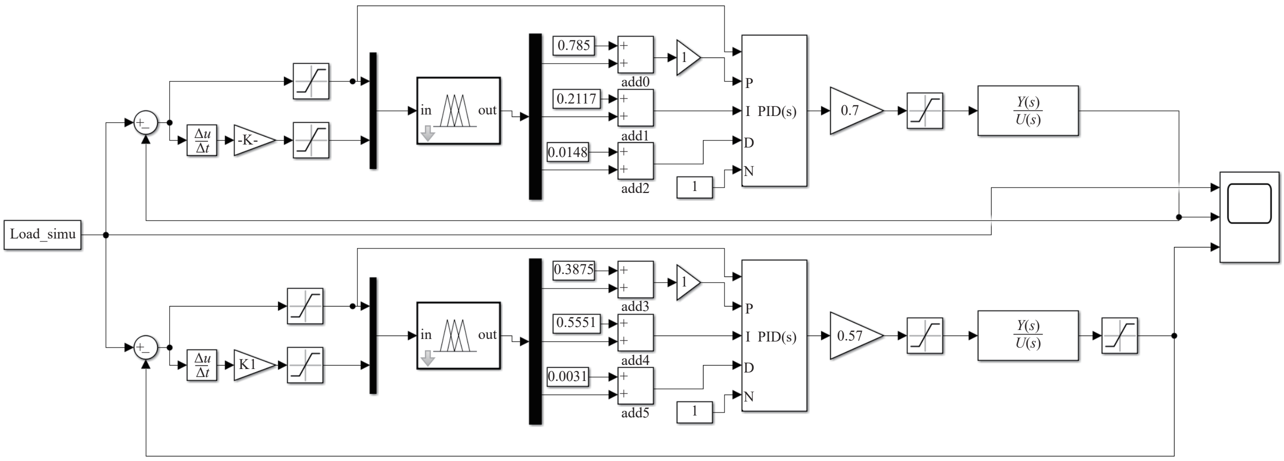

Figure 10 Simulation model

3 Results and discussion

3.1 Resampling results and validation of the rotary tilling load spectrum

3.1.1 Analysis of dynamic response characteristics of loading bench

The precision of the load spectrum loading hinges significantly on the dynamic response characteristics of the loading bench. To scrutinize the dynamic response characteristics of the loading bench, sinusoidal signals with frequencies of 1, 5, 10, 20, 25, and 30 Hz were chosen as inputs for the Simulink simulation model. For the PTO torque loading controller, the amplitude of the sinusoidal signal was set to 200, with an offset of 200 and a phase shift of 270°. The simulation results of PTO torque loading controller are shown in Figure 11.

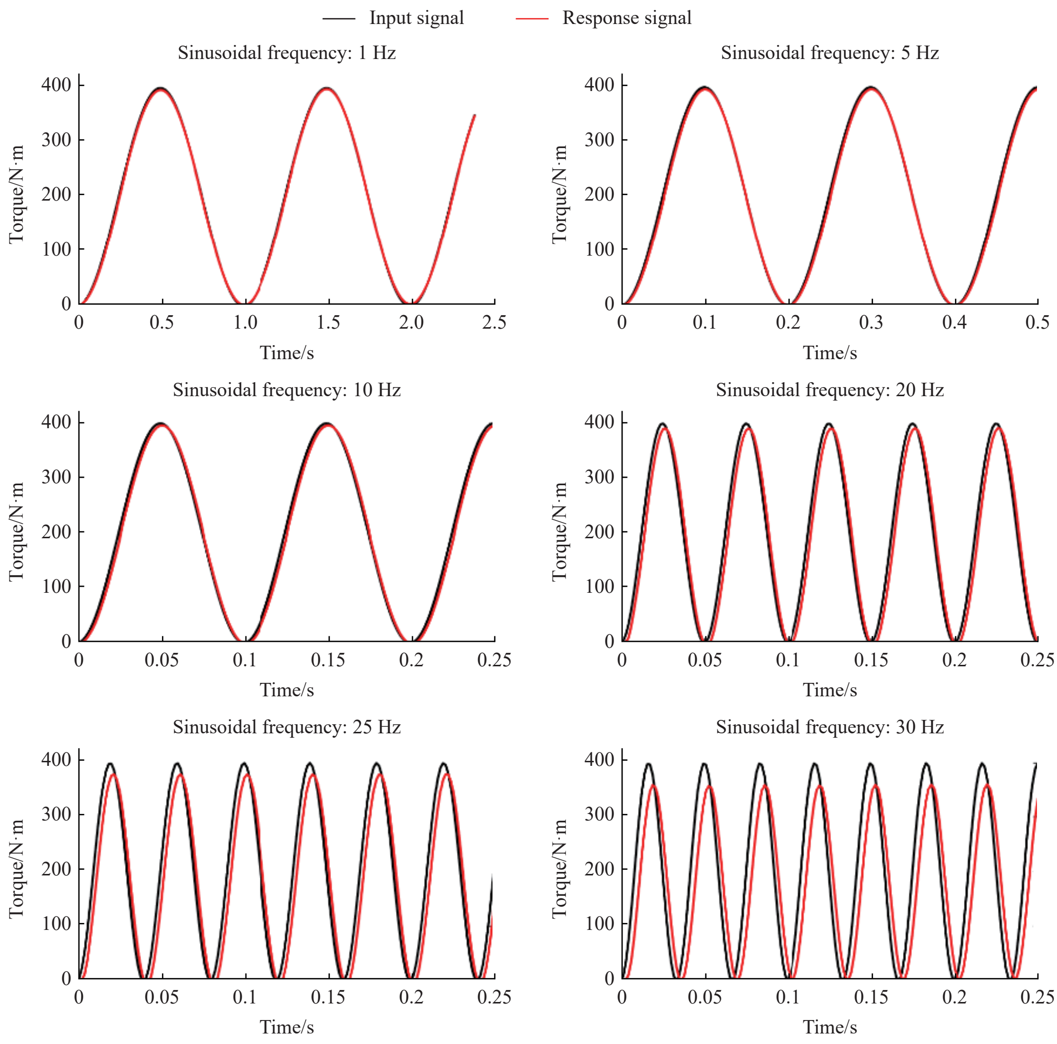

Figure 11 Dynamic response characteristics of PTO torque loading controller

The findings revealed that the PTO torque loading controller demonstrated effective responses to sinusoidal signals below 10 Hz. At a frequency of 10 Hz, the loading controller exhibited a lag of 0.001 s and a maximum error of 0.89%. However, as the frequency of the sinusoidal signal increased, the system's response began to manifest errors and lags. Specifically, for sinusoidal signals at 25 Hz, the loading system exhibited a lag of 0.003 s and a maximum error of 5.09%. Notably, for sinusoidal signals at 30 Hz, the loading system ceased to respond accurately, with a lag of 0.005 s and a maximum error of 9.34%. Consequently, based on the analysis, it can be deduced that the proposed PTO torque loading controller can attain satisfactory response effects below 25 Hz.

Similarly, the dynamic response results of the suspension loading controller to 25 Hz and 30 Hz sinusoidal signals are shown in Figure 12. For the suspension loading controller, the amplitude of the sinusoidal signal was set to 2000. The results indicate that when the sinusoidal frequency is 30 Hz, the loading system begins to exhibit a significant lag of 0.005 s and a maximum error of 6.99%. Therefore, it can be concluded that the suspension loading control system can also achieve good tracking performance at frequencies below 25 Hz. The lag is 0.003 s and the maximum error is 4.60%.

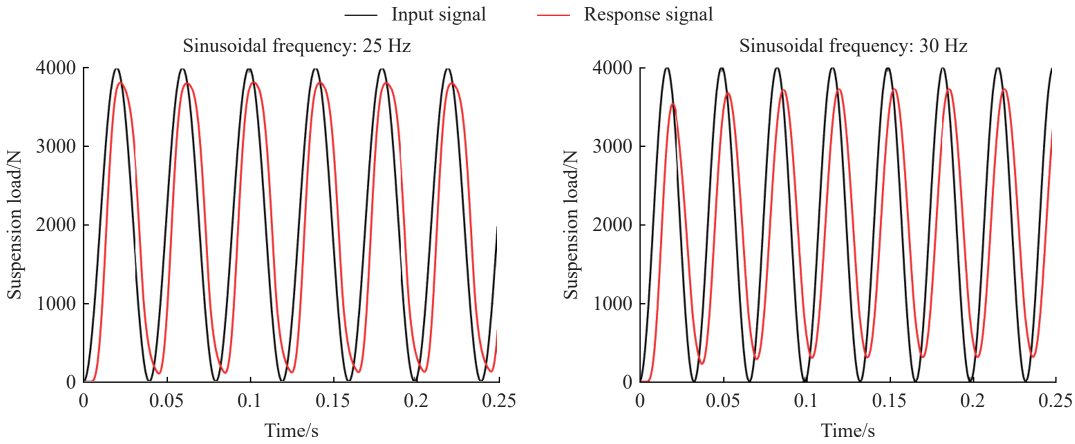

Figure 12 Dynamic response characteristics of suspension loading controller

3.1.2 Comparison validation of the resampled load spectrum

To assess the viability of the resampling method proposed in this study, the comparison was conducted using the PTO torque load spectrum as an example. Both traditional and extreme load retention resampling techniques were utilized to resample the compiled PTO torque load spectrum. Consequently, resampled load spectra were generated with resampling ratios of M=2, 3, 4, and 5.

Computing the statistical characteristic parameters of the resampled load spectrum facilitates a clear depiction of the alterations in the load characteristics. Concurrently, the pseudo-damage retention ratio served as an indicator to evaluate the extent to which the original load damage was preserved following resampling. Ncode GlyphWorks was utilized to determine the pseudo-damage retention ratio for each resampled load spectrum individually, with the outcomes detailed in Table 4.

Table 4 Statistical characteristic of the resampled PTO torque load spectrum

Load type	M	Data frequency/Hz	Maximum/ N·m	Minimum/ N·m	Mean/ N·m	Pseudo-damage retention ratio
Original load	/	62.93	470.00	15.10	223.86	100%
Extreme load retention resampled load spectrum	2	31.47	470.00	15.10	231.48	99.81%
	3	20.98	470.00	15.10	236.52	99.19%
	4	15.73	470.00	15.10	240.26	97.78%
	5	12.59	470.00	15.10	243.01	96.05%
Traditional resampled load spectrum	2	31.47	406.18	39.42	221.30	52.05%
	3	20.98	391.16	55.30	221.31	35.04%
	4	15.73	380.97	71.17	221.33	24.39%
	5	12.59	368.71	73.20	221.34	21.96%

Table 4 indicates that as the resampling ratio increases, the data frequency proportionally decreases. The proposed extreme load retention resampling method effectively retains both maximum and minimum values in the original load spectrum, whereas traditional resampling methods fail to preserve these critical extremum load features, thus losing essential extreme load data. Furthermore, the reduced data volume during resampling, combined with preserved extremum loads, induces an increased mean value in the resampled spectrum obtained through the extreme load retention method compared to the original load spectrum. Regarding pseudo-damage retention, an increase in the resampling ratio correlates with a decrease in the pseudo-damage retention ratio, signifying an augmented retained damage error within the load spectrum. However, the extreme load retention resampling method retained more than 95% of the damage in the original load, indicating that it was closer to the original load. Hence, the extreme load retention resampling method proposed in this study effectively preserves its essential characteristics while retaining damage.

As shown in Figure 13, the power spectral density (PSD) curves of the resampled load spectra generated by both methods demonstrate high consistency with the original load spectrum. This spectral congruence confirms that the resampling process preserves the energy distribution characteristics of the load spectrum. These results collectively validate the fidelity of the proposed resampling methodology.

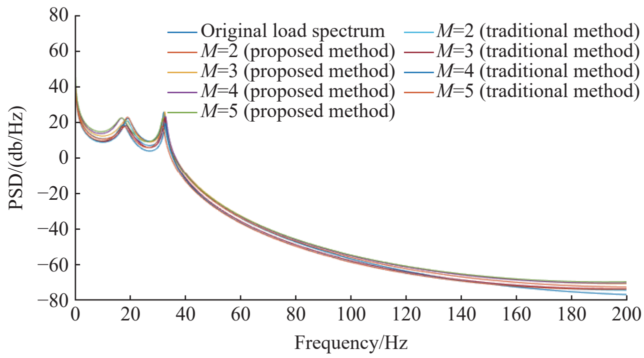

Figure 13 PSD comparison between original and resampled load spectrum

Figure 14 illustrates a comparison between the PTO load spectrum, at a resampling ratio of 3, acquired through both methods. Both methods resampled the original loads; however, the extreme load retention resampling method exhibited a capacity to preserve more extreme load points. Conversely, the traditional resampling method omitted numerous extreme load points, resulting in a disturbance of the load cycles.

3.1.3 Resampling results of rotary tillage load spectrum

Based on the aforementioned analysis and considering the dynamic response characteristics of the loading controller, a load spectrum with a resampling ratio of 3 was ultimately chosen as the input signal for the loading bench test, as depicted in Figure 15. This decision was based on the fact that, with a resampling ratio of 3, the frequency of the resampled load spectrum data amounted to 20.98 Hz, thereby meeting the dynamic response requirements of the loading controller (20.98 Hz < 25 Hz). Moreover, to prevent a shock impact on the system due to the non-zero load at the starting point of the compiled load spectrum, a sinusoidal curve was employed for a smooth transition during the initial stage of the load spectrum.

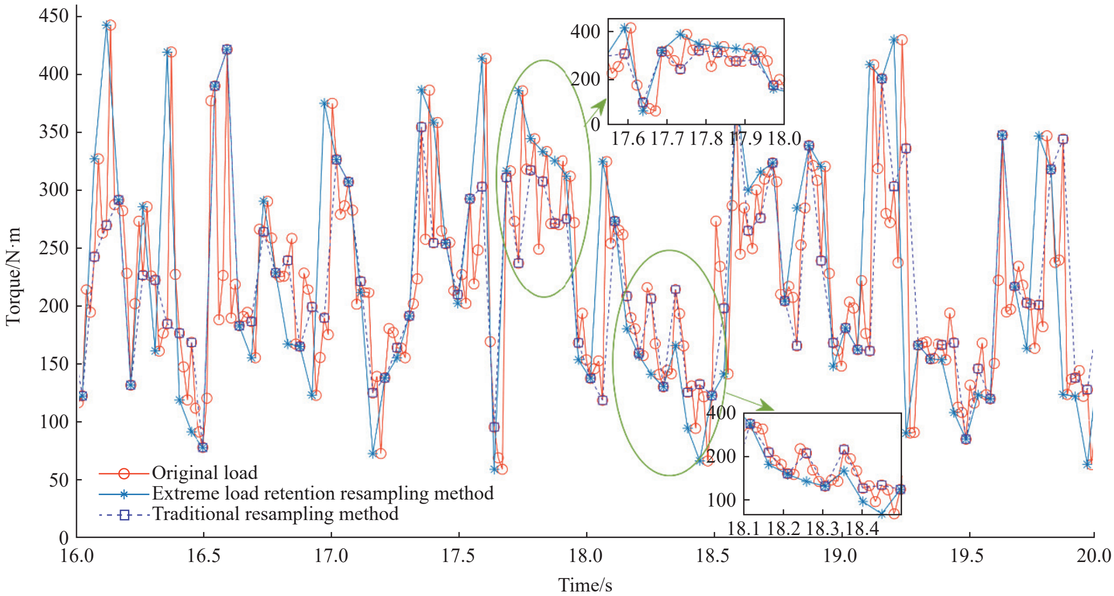

Figure 14 Comparison of resampling results (M=3)

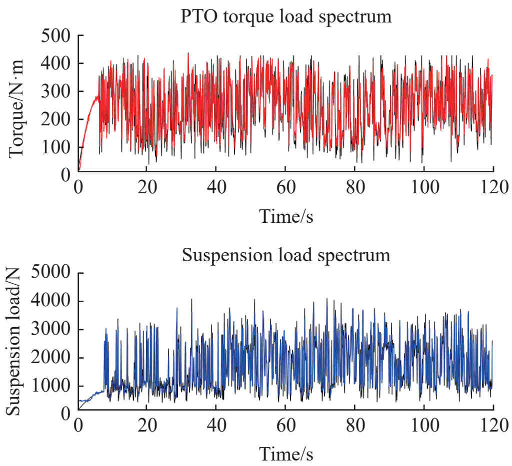

Figure 15 Resampled rotary tillage load spectrum

3.2 Loading test based on resampled rotary tillage load spectrum

3.2.1 Simulation loading test of resampled load spectrum

Based on the simulation model, the dynamic response of the loading system to the resampled load spectrum is verified. The resampled load spectrum is used as the input for the simulation model, with the loading frequency set to 20.98 Hz. The simulation result for the first 30 seconds is shown in Figure 16.

As can be seen from Figure 16, the load spectrum loading algorithm based on the Fuzzy-PID controller has achieved dynamic loading of the resampled load spectrum. For the PTO load spectrum, the goodness of fit between the simulation results and the resampled load spectrum is 30.03 N·m, with a maximum error of 5.08%, and R^2=0.9998. For the suspension load spectrum, the goodness of fit between the simulation results and the resampled load spectrum is 186.56 N, with a maximum error of 2.63%, and R^2=0.9996. The simulation test results indicate that the dynamic response characteristics of the loading platform can meet the requirements of the resampled load spectrum loading frequency.

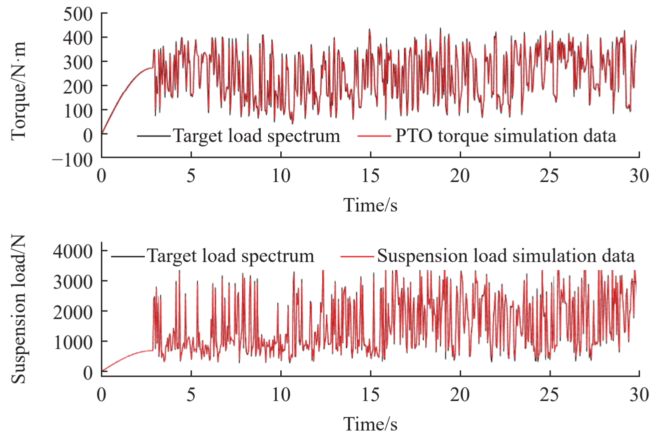

Figure 16 Simulation result

3.2.2 Bench test of resampled load spectrum

The loading test based on the resampled rotary tillage load spectrum was carried out to verify the actual performance of the loading test bench and the Fuzzy-PID controller. The test site is shown in Figure 17. The loading test was conducted using a suspension lift and PTO dynamometer test platform to simulate the tractor. The loading bench is connected to the test platform via the

PTO drive shaft and the suspension frame, linking to the test platform's PTO and three-point hitch, respectively. During the loading test, the PTO output speed was set to 1000 r/min, and the suspension frame was positioned 200 mm above the ground. Subsequently, the rotary tillage load spectrum, which includes the PTO torque load spectrum and the suspension load spectrum, is simultaneously fed into the loading system, with the loading frequency set to 20.98 Hz, thereby enabling the simulation of the rotary tillage working conditions within a controlled testing environment.

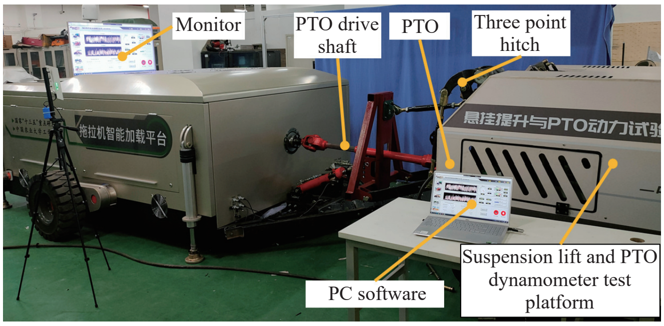

Figure 17 Tractor rotary tillage load spectrum bench test scheme

The actual loading curve for the initial 60 s is illustrated in Figure 18. It can be seen from that the actual load trend closely matches the input load spectrum, suggesting that the dynamic loading bench for tractor rotary tillage adeptly reproduces the rotary tillage load spectrum.

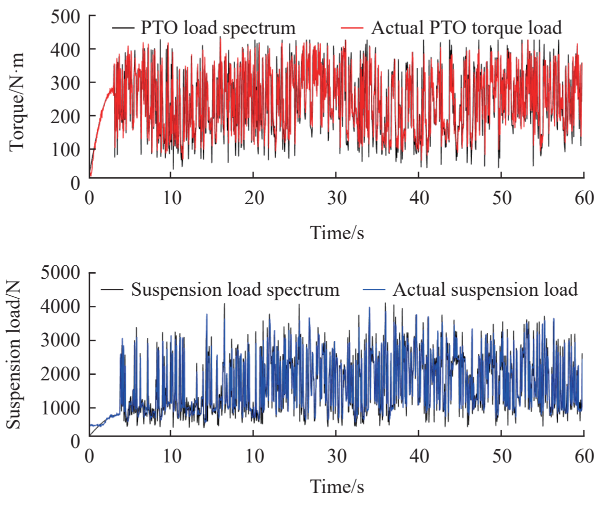

Figure 18 Actual loading result

For the PTO loading system, the goodness of fit between the actual load data and the target load spectrum is 48.10 N·m, with R^2=0.9988, and the average error is –7.53%; for the suspension loading system, the goodness of fit between the actual load data and the target load spectrum is 561.74 N, with R^2=0.9975, and the average error is –2.48%. This demonstrates that the tractor rotary tillage load spectrum loading bench and the Fuzzy-PID controller proposed in this paper can effectively reproduce the rotary tillage load spectrum.

Figure 19 presents a magnified comparison of the loading curves spanning the 20-30 s period. It illustrates a minor delay in the loading bench's tracking of the rotary tillage load spectrum. For the PTO loading system, the delay is approximately 30 ms; for the suspension loading system, the delay is approximately 22 ms. This means that the loading frequency of the resampled load spectrum matches the dynamic response characteristics of the loading bench. However, the loading bench exhibits reproduction errors for spike loads. This is because spike loads exhibit large short-term fluctuations while the loading system contains time delay links, leading to poor peak-valley reproduction capability in the load spectrum. In future research, studies will focus on the reproduction of sudden load changes.

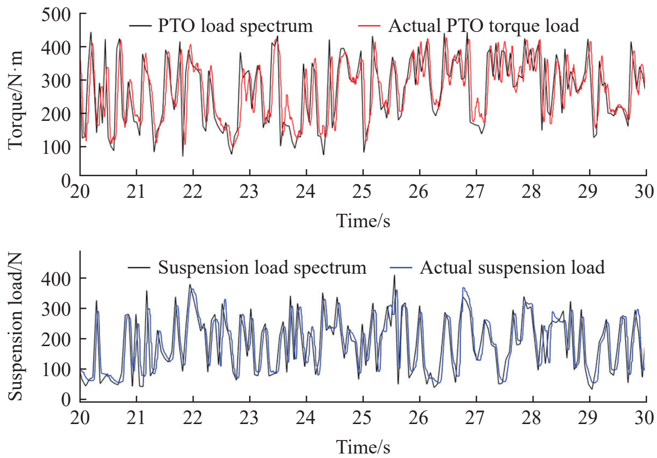

Figure 19 Comparison of loading curves in the time period 20-30 s

4 Conclusions

In response to the challenge posed by the inability of tractor bench tests to faithfully replicate actual operating conditions due to the high frequency of the load spectrum, this study advocates for a tractor rotary tillage load spectrum loading method founded on extreme load retention resampling. With the objective of facilitating tractor rotary tillage bench tests predicated on the load spectrum, this investigation delved into four key areas: the development of the loading bench and control system, resampling of the load spectrum, and experimental validation. The contributions of this study are as follows:

1) The tractor rotary tillage load spectrum loading bench and control system were developed. The loading bench includes a PTO torque loading system and a suspension loading system, capable of simultaneous loading on the tractor's PTO and three-point hitch to simulate rotary tillage conditions. The Fuzzy-PID controller is used to achieve dynamic loading control of the rotary tillage load spectrum. The dynamic response characteristics test shows that the loading bench can achieve dynamic loading of load spectra with frequencies below 25 Hz.

2) A load spectrum resampling method grounded in extreme load retention is introduced. Departing from conventional resampling techniques, this method endeavors to diminish the loading frequency of the load spectrum while ensuring damage efficacy through the preservation of extreme loads. Ultimately, the rotary tillage load spectrum, acquired with a resampling ratio of 3, is designated as the input signal for bench testing. This resampled load spectrum effectively maintains the data characteristics of the original load, with the frequency decreasing from 62.93 Hz to 20.98 Hz.

3) The loading test based on the resampled rotary tillage load spectrum was conducted. The results show that the loading bench and the Fuzzy-PID controller proposed in this paper can effectively reproduce the rotary tillage load spectrum. For the PTO loading system, the average error is –7.53%, with a delay of 30 ms, and for the suspension load spectrum, the average error is –2.48%, with a

delay of 22 ms. This indicates that the loading frequency of the resampled load spectrum matches the dynamic response characteristics of the loading bench and can meet the dynamic loading test demands of the tractor.

This study investigates the application of high-frequency load spectrum in the tractor rotary tillage bench test, which can serve as a reference for load spectrum-based indoor reliability testing of tractors. The study primarily accomplished the compilation and resampling of load spectra under tractor rotary tillage conditions, along with analytical validation of the resampling method's effectiveness. However, load spectrum characterization under other operational conditions remains unexplored. Critical working parameters, including field environment, operational procedures, and implementation configurations, may significantly influence load spectrum characteristics, potentially affecting resampling outcomes. Therefore, future research should incorporate more comprehensive load spectrum testing and fatigue analysis to achieve a complete understanding of operational scenarios. Based on bench test results, future work must optimize both the dynamic response characteristics and hardware configuration of the loading bench to accurately reproduce high-frequency load components. While this study has successfully simulated dynamic loading for rotary tillage conditions, the fatigue reliability impact on tractor tillage systems has not yet been investigated. Subsequent research will focus on developing fatigue reliability assessment protocols based on the established load spectrum, thereby providing theoretical support for structural optimization of agricultural machinery.

Acknowledgements

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