Design and performance analysis of indoor calibration device for the force-measuring system of the tractor three-point hitch

Dong Dai[1,2], Du Chen[1], Xu Mao[1*], Yawei Zhang[1,2], Yutong Li[3], Shumao Wang[1], Bin Zhang[2*]

(1. *Department of Mechanical and Electrical Engineering, College of Engineering, China Agricultural University, Beijing 100083, China*;
2. *Department of Mechanical Design and Manufacturing, College of Engineering, China Agricultural University, Beijing 100083, China*;
3. *Beidahuang Agricultural Service Group Heilongjiang Agricultural Machinery Service Co., Ltd, Harbin 150090, China*)

Abstract: The real-time monitoring of the load in farming by the sensor installed on the tractor's three-point hitch can effectively improve the farming efficiency and force-position combined control, reduce the compaction risk of the wheel on the soil and reduce the fuel consumption in farming process. However, the measurement and quantification of the loads on the three-point hitch have some problems remaining unresolved: testing the accuracy and reliability of a load measuring system is hard when the tractor works in a field, the mathematical model of spatial forces usually lacks a practical and effective validation, and the calibration process of the measurement system is inconvenient and incomplete while easily causing a low accuracy. Specifically, this paper builds a new spatial-force mathematical model based on the geometry of a three-point hitch. To eliminate the discrepancy of the geometric model with the actual structure and to refine the mathematical model, a calibration process is conducted by developing a calibration bench, which is equipped with a data acquisition system and a multi-parameter monitoring interface. The three-point hitch installed on this calibration bench is subject to steady-state loading. The loading force, angle of the lower drawbar, and three-component forces (three shaft pin sensors' forces) of the three-point hitch are well measured. With applying for the measured data to calibrate the theoretical mathematic model eventually derives the resultant force from all the three-component forces, a dynamical loading bench was developed to test the calculated resultant force for the three-point hitch during the sinusoidal and randomly variant dynamical loadings tests. A hitch force measurement system is also developed to collect real-time data and calculate the resultant force of measured three-component forces through the calibrated mathematical model. The results of the dynamical loading tests show that the average relative error MRE = 1.09% with an average force measurement time delay being Δt = 0.5 s, the root mean square error RMSE = 59.3 N, and the coefficient of determination R^2 = 0.9903. As observed, the shape and the trend of the generated resultant force curve are basically the dynamical loading force. The dynamical loading test proves the high efficacy and reliability of the proposed indoor calibration method for calculating the load based on the three-component forces as measured on the three-point hitch. Besides, the preliminary study of the proposed method on the hitch load provides great potential to improve the indoor six-component measurement and quantification of both the force and momentum acting on the three-point hitch.

Keywords: tractor, three-point hitch, hitch force calibration bench, hitch force measurement system, dynamic loading verification method

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1 Introduction

Tractor has significant role in agricultural production because of its excellent capability of power output. Typically, its technological development represents to a large extent the development level of agricultural mechanization in the country[1,2]. The introduction and promotion of intelligence will also improve farming production efficiency and reduce energy consumption and environmental pollution[3-5]. With the introduction of a series of measures and standards by the country and the agricultural machinery industry to standardize agricultural machinery testing, more and more attention has been paid to the testing of tractors' operating efficiency and status parameters under different working conditions[6,7].

Tractor field plowing, harrowing, sowing, and harvesting operations are mainly completed by rear hitch hooking and towing various supporting agricultural machinery. The main factor that affects tractor energy consumption and efficiency is the resistance from the force between soil and tillage tools[8,9]. Therefore, it is particularly important to install sensors in the three-point hitch mechanism and establish a tillage resistance measurement system that can effectively optimize farming power and reduce the risk of soil compaction by wheels[10-12], and fuel consumption during farming.

The development of hitch force measurement system has been explored from two aspects: direct methods using force sensors or

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Biographies: Dong Dai, Postgraduate, research interest: agricultural intelligent equipment, Email: daidong_zb@cau.edu.cn; **Du Chen**, Professor of Engineering, research interest: agricultural intelligent equipment, Email: tchendu@cau.edu.cn; **Yawei Zhang**, Lecturer, research interest: agricultural intelligent equipment, Email: zywcau@cau.edu.cn; **Yutong Li**, General Manager, research interest: agricultural machinery and equipment, Email: liyutong17777@163.com; **Shumao Wang**, Professor, research interest: agricultural intelligent equipment, Email: wangshumao@cau.edu.cn.

***Corresponding author: Xu Mao**, Associate Professor, research interest: agricultural intelligent equipment. College of Engineering, China Agricultural University, Beijing 100083, China. Tel: +86-13716076675, Email: maoxu@cau.edu.cn; **Bin Zhang**, Professor, research interest: agricultural robot technology. College of Engineering, China Agricultural University, Beijing 100083, China. Tel: +86-13611393882, Email: zhangbin64@cau.edu.cn.

strain gauges, and indirect methods using hitch frame structures. The force sensor or strain gauge detection method is to measure the hitch force by the five-drawbar force measurement method[11-13], the three-pin summation force measurement method[14,15], or the sticking strain gauge method[16,17] without the aid of the external frame structure. According to Bauer et al.[12], five pulling sensors installed respectively at the upper-lower drawbars and the lifting drawbar to obtain the force on each drawbar and the total hitch force could be calculated, so as to analyze the soil compaction problem caused by the different loads on the rear wheel of the tractor tilting during furrow farming. Furthermore, three-pin force measurement device combined with the three-point hitch mechanism were used by Xu et al.[15], replaced the five-drawbar force measuring method and conveniently realized the measurement of the horizontal traction force. Recently, Keen et al.[16] applied the strain gauges attached to the side of the tie drawbar to measure the force of the hanging tie drawbar during plowing which could provide a reference for fatigue life prediction by the finite element analysis method.

The indirect force measurement of the hitch frame structure needs to connect the hitch frame between the tractor and the farm implement[18-21], design a multi-sensor space six-component force measuring mechanism, through analysis to calculate the horizontal force, vertical force, lateral force and moment of the soil resistance on the agricultural implement or hitch. According to Roca et al.[18], a three-point hitch double-frame structure was devised to measure the synthetic longitudinal force between the agricultural implement and the soil by analyzing the forces and moments at different couplings between the frame and the implement, which reduce the influence of the dead weight of the measuring frame and the terrain slope on the force of the tractor. Chen et al.[19] designed a three-dimensional force measurement array device based on a multi-dimensional force sensing unit, which was installed on the hitch force measurement frame to measure and calculate the three spatial resultant forces and three spatial moments of the three-point hitch force. Reduce the coupling error between sensors, and the interference of torque and component force, thereby improving the detection accuracy of dynamic load.

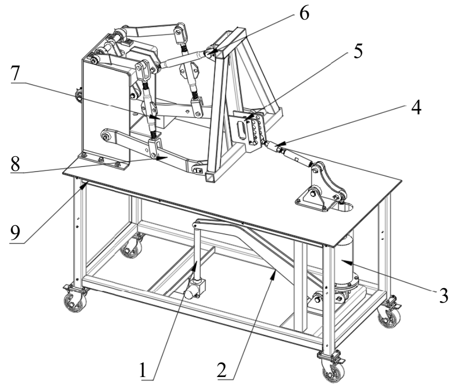
Although previous studies have made in-depth discussions on the design and application of force measuring mechanisms, they have failed to consider the verification of the static and dynamic calibration and detection accuracy of the measuring system. At this stage, most of the detection of the accuracy of the three-point hitch mechanism is based on the standards and measures promulgated by the country and the agricultural machinery industry[22,23], mainly carrying out indoor static test[24,25]. However, these tests lack the function of calibration test, cannot truly simulate the dynamic loading situation in the field, and lack the dynamic response analysis of the hitch force measurement system. Therefore, this detection method lacks complete and accurate verification of the hitch force measurement system and the solution of the space force. At the same time, it affects the calibration accuracy and reduces the accuracy and reliability of the system's hitch force detection in the field.

The main contributions of this paper are an analytical method that can provide accurate verification and calibration for the hitch force measurement system and the solution of the spatial six-component force; designed a three-point hitch space force calibration bench and a hitch dynamic loading bench according to the tractor hitch structure and farming conditions; developed a vehicle-mounted detector and a visual software for data collection and monitor. Finally, in order to verify the superiority of the proposed method and bench, a measurement method of three-pin summation force sensors was selected to conduct an indoor calibration and verification test.

2 Materials and methods

2.1 Design of hitch force calibration bench

According to the tractor's three-point hitch structure, the force value, and the operating angle of agricultural machinery, this research designed a loading mechanism that can adjust the height of the hitch and the load of different agricultural machinery, and built a three-point hitch space force calibration bench, as shown in Figure 1. The system consists of a hitch mechanism, a loading mechanism, and a detection and control system. By controlling the electric cylinder to load the pulling force, the lever is used to amplify the loading force, and the static stress is generated by the compression double spring in the spring cylinder, which acts on the fixed plate of the pulling rod to achieve the stable load of the calibration bench force on the three-point hitch. In order to simulate the angle of the force of the farm implement (such as the change of tillage depth, and the change of the traction force direction), the hitch frame of the hitch calibration bench is set with multiple holes to realize the loading of multi-angle force.



1. Electric cylinder 2. Lever bracket 3. Spring cylinder 4. Pulling rod 5. Hitch auxiliary frame 6. Shaft pin sensor 7. Loading control box 8. Three-point hitch structure 9. Calibration bench bracket

Figure 1 Structure design of hitch force calibration bench

The characteristic loading force range of the calibration bench is 0-20 kN, and the load angle range is –15°-30°. The system uses a high-precision sensor to detect the loading force, the detection range is 0-20 kN, and the accuracy is 0.02% FS.

2.2 Schematic analysis of structural force

Analyze the force of the three-point hitch structure and farm implements, and derive the geometric relationship of the force of each link of the hitch mechanism. In order to simplify the analysis of farm implements and hitch drawbars, the weight of each drawbar and the tilting movement of the hitch calibration bench are ignored[26-28]. Simplify hitch and agricultural machinery to the linkage motion projected on the central longitudinal plane of the calibration bench, which is approximately simplified to a two-dimensional plane motion[29-32], as shown in Figure 2.

Figure 3 shows the simplified plane geometric relationship diagram of the hitch calibration bench mechanism. The following hinge point C of the lower drawbar and the fixed frame is set as the coordinate origin to establish a rectangular coordinate system, A, B, and G are the hinge points between the upper drawbar, left lower drawbar, right lower drawbar and the suspension auxiliary frame respectively, D is the hinge point of the upper drawbar and the fixed

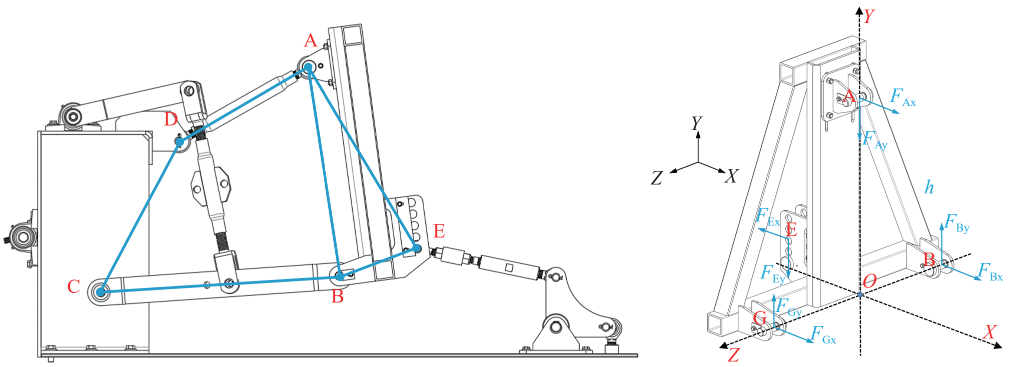


Figure 2 Schematic diagram of the hitch structure of the calibration bench

frame of the calibration bench. E is the hinge point of the loading tension rod and the hitch auxiliary frame, AD is the upper drawbar, and BC is the lower drawbar.

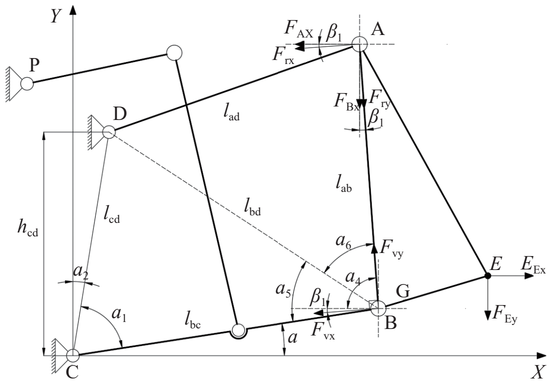


Figure 3 Plane force analysis of upper and lower drawbars and suspension auxiliary frame

In Figure 3, α represents the inclination angle of the hitch lower drawbar, the force sensor's F_{ix}, F_{iy} (i=r,v,w. unit: N) directions are perpendicular and coplanar respectively on the projection surface of the hitch frame ABG, derive the horizontal tension F_{jx} and vertical tension F_{jy} (j= A, B, G. unit: N) at the hinge points of hitch A, B, G. According to the geometric relationship, the angle β_1(°) between the F_{ix} of the sensor and the horizontal direction is obtained as:

$$\beta_1 = \frac{\pi}{2} - \alpha + \arccos\frac{l_{bd}^2 + l_{bc}^2 + l_{cd}^2}{2l_{bd} \cdot l_{bc}} + \arccos\frac{l_{bd}^2 + l_{ab}^2 + l_{ad}^2}{2l_{bd} \cdot l_{ab}} \tag{1}$$

where, α is the angle of the lower drawbar, (°); l_{bc} is the length of the lower drawbars, m; l_{bd} is the plane projection distance of two hinge points B and D, m; l_{cd} is the plane projection distance of two hinge points C and D, m; l_{ab} is the plane projection distance of hinge point between the upper-lower drawbars and farm implements, m; l_{ad} is the length of the upper drawbar, m.

The length of the plane projection between the two connecting points B and D in the equation $l_{bd} = (l_{cd}^2 + l_{bc}^2 - 2l_{cd}l_{bc}\cos\alpha_1)^{1/2}$; where, α_1 is the angle between the CD drawbar and the lower drawbar CB on the horizontal projection surface, (°); h_{cd} is the vertical distance between hinge point C and hinge point D, m. $\alpha_1 = \pi/2 - \alpha - \arccos(h_{cd}/l_{cd})$.

Calculated by Equation (1), the horizontal tensile force F_{jx} and vertical tensile force F_{jy} at hinge points A, B, and G are respectively:

$$F_{jx} = F_{ix}\cos\beta_1 + F_{jy}\sin\beta_1 \tag{2}$$

$$F_{jy} = F_{ix}\sin\beta_1 + F_{iy}\cos\beta_1 \tag{3}$$

Ignoring the force in the lateral direction, according to the analysis in Figure 3, the horizontal tensile force F_{Ex} and the vertical tensile force F_{Ey} on the pulling force at point E of the hitch auxiliary frame are:

$$F_{Ex} = \sum F_{jx} \tag{4}$$

$$F_{Ey} = \sum F_{jy} \tag{5}$$

Then the traction force at the hinge point E of the three-point hitch F_E (N) can be obtained. Additionally, a comparative analysis of the hitch force F_E and the loading force will be conducted to enable the detection, calibration, and verification of the hitch force measurement system.

The relevant parameters of the three-point hitch mechanism of the calibration bench, such as the size of each drawbar and the distance of the hinge points, are listed in Table 1.

Table 1 Hitch mechanism related parameters

Technical parameter	Drawbar length/mm				
	h_{cd}	l_{ab}	l_{ad}	l_{bc}	l_{cd}
Value	455	635	510	720	512

3 Acquisition system of hitch force

3.1 Data acquisition system

Combined with the hitch force acquisition function and requirements, the data acquisition system for the hitch device is designed, including sensors, a data acquisition box, software monitoring platform, and mobile battery box. The data acquisition system is equipped with a special data acquisition unit, which can be easily and quickly connected to the hitch force calibration bench or dynamic loading test bench and realizes the simultaneous acquisition of multiple data such as hitch force, angle, and pulling force, software data display, analysis and processing, and storage functions.

Sensors include shaft pin sensors, pulling force sensors, and angle sensors. The collected voltage signal and pulse signal are transferred to the filter circuit and signal conditioning circuit through the circuit conversion board to realize signal preprocessing, and improve signal stability and acquisition accuracy. The signal is collected and processed by the acquisition board, then it is transmitted to the monitoring computer and software platform. The system is powered by the mobile battery box and outputs 12 V and 24 V voltages. The physical block diagram of the acquisition system hardware is shown in Figure 4.

The signal of the data acquisition system has been calibrated by a professional metrological institution[7,33], and its acquisition

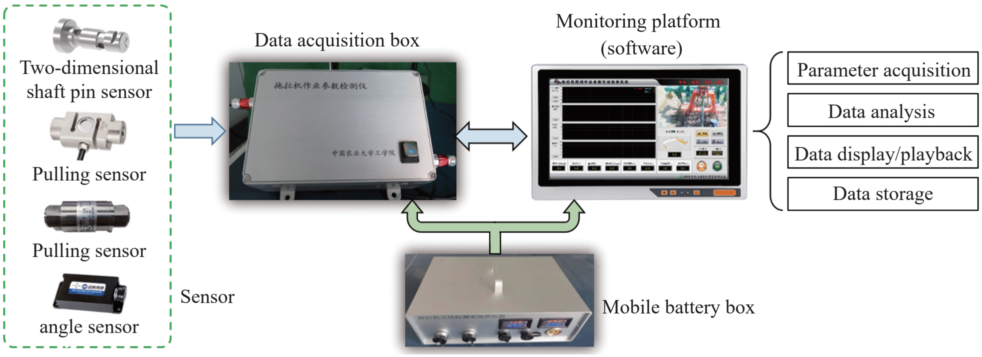


Figure 4 Physical block diagram of data acquisition system

accuracy fully meets the requirements for the measurement accuracy of the hitch force.

3.2 Software detection platform

The system software platform adopts the virtual instrument LabVIEW development environment, which can quickly develop the human-computer interaction interface, realize the data acquisition of multi-sensor signals, and provide a variety of data analysis module[7]. The software program flowchart is shown in Figure 5.

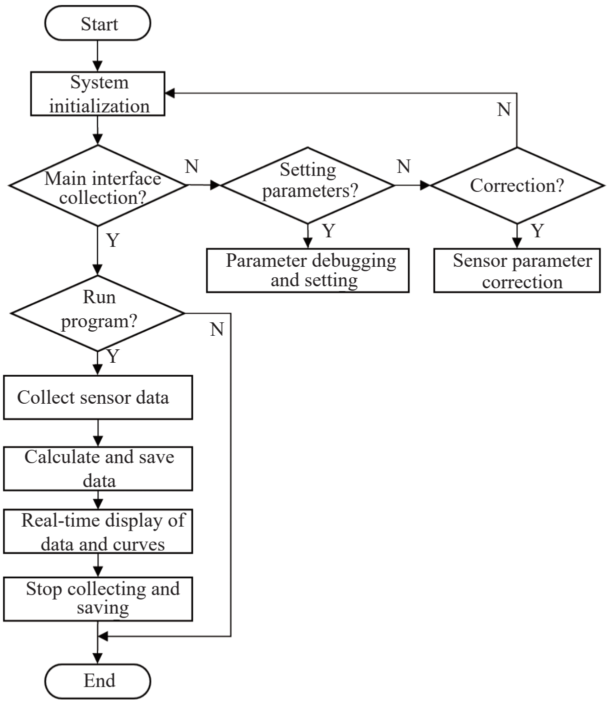


Figure 5 Flowchart of software detection program

The functional design of the detection software includes 1) Interface interaction, design of equal-scale device diagrams to realize intuitive interface data observation, data parameter input, and control; 2) Software control, complete functions such as data reading, save data, and data playback analysis of the capture card; 3) Data calibration, realize the original signal test of each channel, sensor parameter correction, and test calibration. The calibration interface of the software detection platform is shown in Figure 6.

4 Test and analysis

In order to verify whether the development of the hitch force calibration bench system can achieve the verification and calibration effect of the hitch force measurement system, conducted multiple tests and verifications in the College of Engineering of China

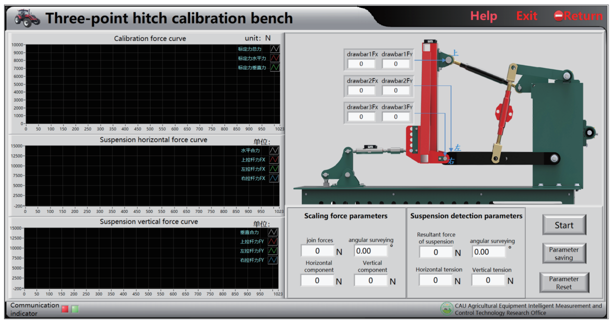


Figure 6 Calibration interface of software detection platform

Agricultural University. Including the hitch force acquisition and calibration test of the hitch force calibration bench, and the indoor dynamic loading verification test.

Select the hitch force measurement system with three-pin summation force measurement method for verification and calibration test, the measurement method of three shaft pin sensors, and install the three two-dimensional shaft pin sensors to the three hanging points of three-point hitch and farm implements respectively. This method does not require a complicated multi-sensor suspension frame structure, and connects the farm implements with the hitch upper and lower drawbars by means of shaft pins, measures the force in the X and Y directions of the three-point hitch longitudinal plane, the working principle is shown in Figure 7. Each sensor outputs two independent voltage signals, the resultant force and direction are calculated by the positive and negative values of the X and Y axis signals. The inclination sensor measures the angle of the upper and lower drawbars and the pulling rod, and the angle sensor measures the angle of the upper drawbar, and the angle of the dynamic loading bench cylinder.

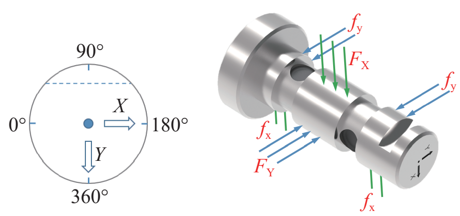


Figure 7 Force diagram of two-dimensional shaft pin sensor

In order to measure the calibration and verification effect of the hitch force measurement system, this paper selects the root mean square error (RMSE) and the coefficient of determination (R^2) as evaluation indicators[23]. These equations are as follows:

$$\mathrm{RMSE}=\sqrt{\frac{\sum_{i=1}^{N}(X_i-x_i)^2}{N}} \tag{6}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(x_i - \widehat{x}_i)^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad (7)$$

where, n is the number of samples collected by parameters; X_i is the measured value of hitch force, and x_i is the loading force value. The smaller the RMSE, the R^2 value is closer to 1, indicating that the calibration and verification effect of the hitch force measurement system is better.

4.1 Hitch force calibration bench test

Operate the three-point hitch force calibration bench to carry out the steady-state gradual loading of the hitch force measurement system. The two-dimensional shaft pin sensors are respectively installed at the hinge joints of the upper and lower drawbars and the farm implement, fix the sensors with snap-fit; connect the shaft pin sensors, pulling sensors, and angle sensors to the data acquisition system. Adjust the three-point hitch so that the lower drawbar is at a horizontal or downward angle, and the loading pulling rod is fixed on the hitch auxiliary frame and is horizontally inclined upward, pulling force gradually through the loading control box, hitch force calibration bench test as shown in Figure 8.

The range of loading force by controlling the calibration bench is 2300-6700 N. The test includes loading process (the process of increasing pulling force) and unloading process (the process of reducing pulling force) and carried out at an interval of 500 N, the measured resultant force of hitch is obtained according to the measured value of shaft pin sensors and the above equations, as shown in Figures 9a and 9b. Compare and analyze the measured hitch force and loading force (Figure 9c), analysis and calculation of the gradually loading fitting equation is y=1.0173x+354.75, R^2=0.9998; the gradually unloading fitting equation is y=1.0052x+447.74, R^2=0.9997, the test data and fitting curve are shown in Figure 10. According to the measurement results after calibration fitted by the equations in Table 2, the relative error is about 1%, which meets the measurement error requirement of 5%, indicating that the acquisition effect of the hitch force measuring system after calibration is satisfactory.

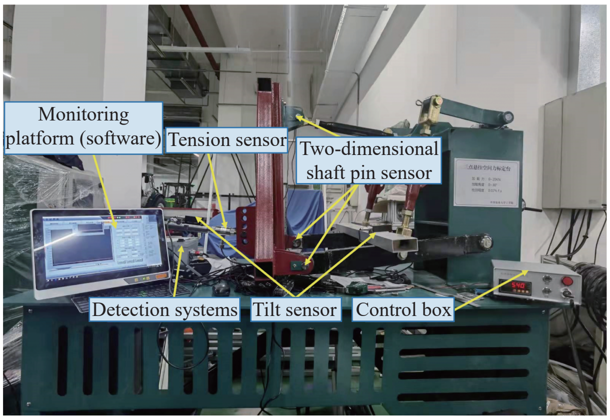
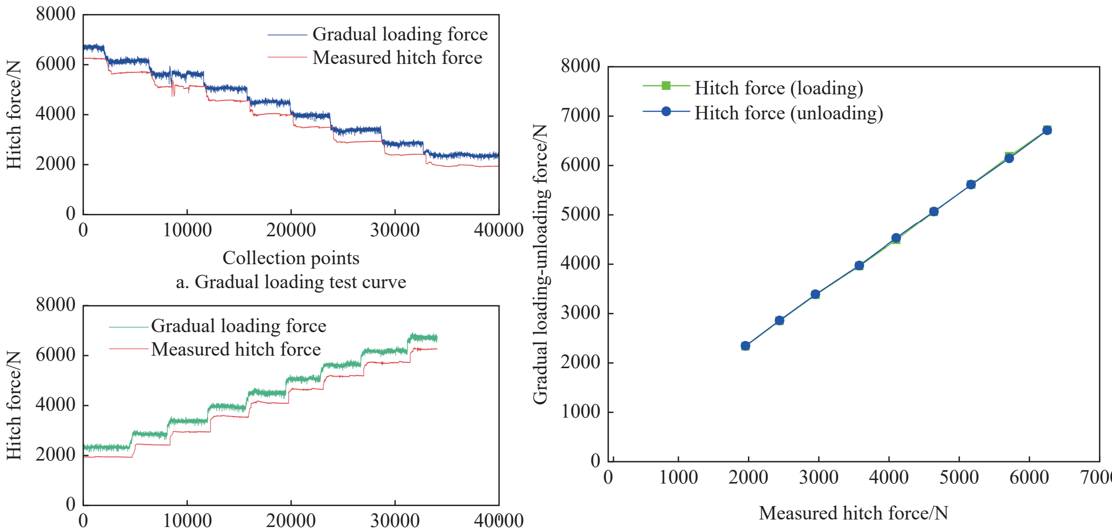


Figure 8 Hitch force calibration bench test

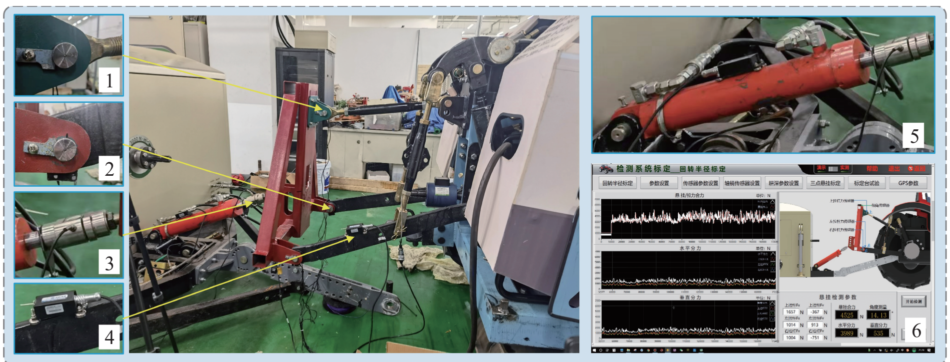


a. Gradual loading test curve

b. Gradual unloading test curve

c. Linear fitting curve between measured values and loading-unloading values

Figure 9 Fitting curve of measured value and loading value of hitch force



1. Upper drawbar sensor 2. Lower drawbars 3. Pulling sensor 4. Angle sensor 5. Loading cylinder 6. Software interface for dynamic signal loading verification

Figure 10 Three-point hitch dynamic loading bench test

Table 2 Measurement results after equation fitting

Calibration mode	Group No.	Load value/N	Measured value/N	relative error/%
Loading process (increasing pulling force)	1	2345.2	2384.7	1.69
	2	2857.9	2874.2	0.57
	3	3383.2	3390.1	0.20
	4	3960.4	4015.5	1.39
	5	4493.3	4552.8	1.32
	6	5066.9	5093.1	0.52
	7	5621.6	5625.0	0.06
	8	6188.2	6171.0	0.28
	9	6722.7	6715.7	0.10
Unloading process (reducing pulling force)	1	6713.2	6721.9	0.13
	2	6149.3	6144.0	0.08
	3	5617.4	5595.4	0.39
	4	5074.6	5027.5	0.93
	5	4531.1	4479.1	1.15
	6	3974.6	3940.2	0.86
	7	3392.9	3348.6	1.31
	8	2867.0	2827.2	1.39
	9	2351.5	2378.0	1.12

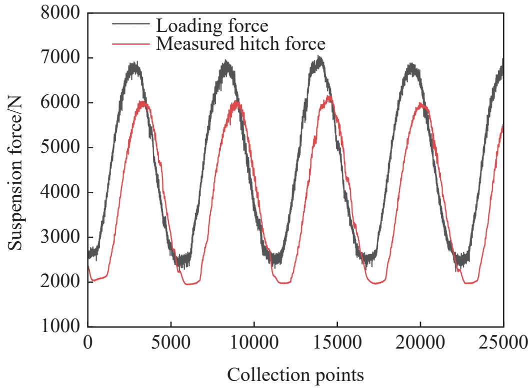
4.2 Hitch dynamic loading verification test

When the tractor is actually farming in the field, the hitch force is an irregular continuous signal. In order to verify the dynamic force acquisition effect of the calibrated hitch force measurement system, and to approximate the force of the hitch in the actual field farming process, this paper adopts the self-designed indoor hitch loading test bench for testing. The indoor hitch loading test bench is specially designed for the indoor loading test of the tractor three-point hitch, it can be used for accurate calibration and dynamic response verification of tractor-mounted agricultural implement measurement system (sensor and acquisition instrument).

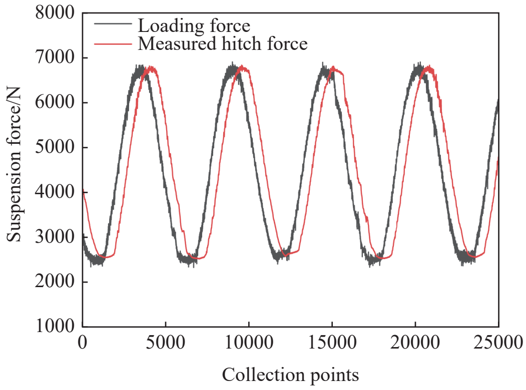
Install the hitch auxiliary frame and the calibrated hitch force measurement system on the three-point hitch frame of the dynamic loading bench, control the loading cylinder through the measurement and control system of the dynamic loading bench, carry out sinusoidal loading verification test and random loading verification test, as shown in Figure 10.

4.2.1 Sinusoidal curve loading verification test

The loading cylinder loads the hitch force measurement system with sinusoidal signal[34], to test and verify the following effect and fitting calibration effect of the hitch force measurement system on dynamic periodic loads. The amplitude of the input sinusoidal signal is 2150 N, and the overall offset is 4650 N. The experimental verification results are shown in Figure 11.



a. Sinusoidal loading results without equationfitting



b. Sinusoidal loading results after equationfitting

Figure 11 Sinusoidal loading verification test

According to the sinusoidal loading test results, due to the characteristics of the sensor and hardware system, the hitch force measuring system has a small delay relative to the pulling force signal of the loading cylinder, the delay is about $\Delta t = 0.5$ s. After the fit calibration of the equation, the actual hitch the curve value of force and loading force $R^2 = 0.9985$, and the root mean square error RMSE=51.53 N. It shows that after the calibration and fitting of the hitch force measured by the hitch force measurement system on the calibration bench, the dynamic sinusoidal load acquisition can basically follow the sinusoidal curve loading force signal of the loading cylinder. The verification test shows that the acquisition effect of the hitch force measurement system is better after the calibration of the calibration bench and the correction of the fitting equation.

4.2.2 Random curve loading verification test

In order to verify the dynamic random load acquisition effect of the hitch force measurement system, a random load signal is input to control the loading cylinder to carry out a loading verification test, as shown in Figure 10.

Figure 12 shows the comparison result curve of random loading force and measured hitch force, set the random loading force range from 2500 to 6000 N, the sampling frequency of the data acquisition system is set to 1000 Hz, and take the first 360 k sampling data points for data analysis and comparison. Figure 13 is a partially enlarged view of the data curve of the rectangular box in Figure 12. It can be seen from the figure that after fitting and calibrating the hitch force measurement system through the hitch calibration bench, the measured hitch force value is basically consistent with the magnitude and trend of the loading force value, and the time delay is Δt=0.5 s.

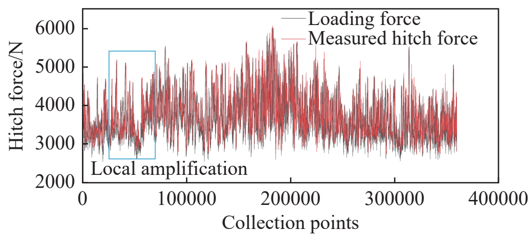


Figure 12 Verification results of dynamic random loading and acquisition

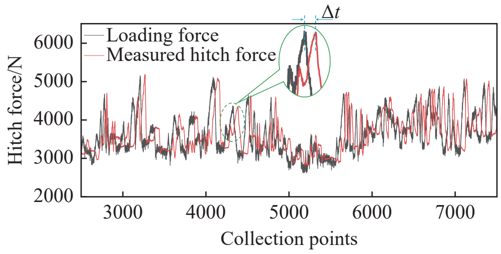


Figure 13 Enlarged view of dynamic random loading and acquisition curve

As shown in Table 3, after verifying and calibrating the suspension force measurement system, comparative analysis results of the curves of the measured hitch force and the loading force. The average relative error MRE=1.09%, the root mean square error RMSE=59.3 N, and the coefficient of determination R^2=0.9903. It can be shown from data analysis and curve, the error between the measured hitch force and the random loading force is small under the dynamic loading signal, the calibrated hitch force measurement system can meet the accurate collection requirements of the field hitch dynamic force. Therefore, it can be considered that the three-point hitch force calibration bench and the dynamic loading bench can realize the verification and calibration of the hitch force measurement system, and it can provide indoor high-precision calibration and verification methods for the research of tractor hitch force measurement system at the present stage.

Table 3 Analysis of relevant parameters of hitch loading and measured force

Item	Max/N	Min/N	Average value/N	Average relative error/%	R_{RMSE}/N
Loading force	5157	2756	3604	1.09	59.3
Measured force	5186	2824	3635		
Error/%	0.56	2.46	0.86	/	/

5 Conclusions

1) A device and method for indoor high-precision calibration and static and dynamic verification of the tractor suspension force measurement system were proposed. According to the tractor's rear hitch structure and field farming status, a three-point hitch space force calibration device and a tractor parameter detection system were designed, which can realize the calibration and fitting correction of the hitch force measurement system in the indoor static and dynamic loading test.

2) Taking the force measurement method of three two-dimensional shaft pin sensors as a case study, this paper calculated the geometric relationship of the calibration bench structure and conduct a gradual signal loading test to validate the results. Based on the comparative analysis of the load setting force and the actual measurement value of the hitch force measurement system, further, modify the calculation equation of the geometric relationship by the fitting equation, and obtain a more accurate expression of the measured hitch force.

3) In order to verify the detection effect of dynamic load, simulate the loading condition of tractor hitch field work, carry out indoor sine signal and random load signal loading test verification for the modified and fitted hitch force measurement system: comparative analysis of the measured value of the hitch force measurement system compared with the dynamic load setting force, detection delay is about Δt=0.5 s, the average relative error MRE=1.09%, the root mean square error RMSE=59.3 N, the coefficient of determination R^2=0.9903. The changing trend and amplitude of the measured suspension force curve are basically the same as the loading force.

The indoor calibration and verification methods and devices for the tractor hitch force measurement system were investigated, which can simulate actual field conditions, and improve the accuracy and credibility of the field hitch data. The research can provide experimental verification and research foundation for the calibration of hitch force measurement system and the calculation of spatial six component force.

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