Design and modelling of the full-feed peanut picking device with self-adaptive adjustable working clearance and feeding rate

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Abstract: To improve the declining performance of a full-feed peanut picking device or solve the mechanical failures that occur due to fluctuations in the feeding rate during operation, the 4HLJI-3000 peanut intelligent picking combine harvester, which is a picking device with a self-adaptive adjustment of the working clearance, was developed as the research object in this study. Moreover, the key components, such as the picking roller, concave plate sieve and clearance adjustment mechanism of the concave plate sieve, were designed and analysed. Through the force analysis of the concave plate sieve of the picking device, the mathematical model of the concave plate sieve displacement of the picking device and feeding rate was obtained. The software system for monitoring, storing and analysing the concave plate sieve displacement of the picking device based on EasyBuilder Pro was designed, and the road monitoring test of displacement variation of concave plate sieve of the picking device and feeding rate was carried out. The linear function, power function, exponential function, quadratic function, compound function, logarithmic function and cubic function fitting were used to perform regression analysis of the test results by using IBM SPSS software. The results showed that the cubic function model had a higher fitting precision, and its determination coefficient was 0.992. Model verification experiments were proposed, and the results showed that the established cubic function model had a good accuracy. The absolute deviation rate ranged from 0 to 4.83%, and the average deviation rate was 2.22%. The deviation rate increased with an increasing feeding rate. The field experiments also proved that there was a cubic function relationship between the feeding rate and concave plate sieve displacement, the measured concave plate sieve displacement deviation rate ranged from 0 to 6.19%, and the average deviation rate was 2.73% compared with the calculated results. This study can provide a reference for the optimization design of the structure of full-feeding picking devices for peanuts and other crops and the intelligent measurement and control of the feeding rates.

Keywords: agricultural machinery, peanut, picking device, feeding rate, concave plate sieve displacement, EasyBuilder
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1 Introduction

The peanut is an important oil and cash crop in world oil production and trade and is second only to the soybean[1-3]. According to the statistics of the World Food and Agriculture Organization (FAO), in 2020, China's peanut planting area was 4.62×10^6 hm^2, and the output was 1.80×10^7 t, ranking among the highest in the world. However, compared with American countries, the mechanization level of peanut harvesting in China is relatively outdated, and most peanut planting areas are still dominated by semi-mechanized and segmented harvesting[4-7]. In 2020, the mechanization level of peanut harvesting in China was only 49.61%[8]. The design of the existing peanut pickup combine harvester mostly refers to foreign technologies or the relevant technologies of rice and wheat combine harvesters. Regarding harvesting, there is relatively little professional research, especially in the pod picking process. The operation performance and quality are still not ideal, and they significantly restrict the development of the peanut industry.

The design of the picking device and the feeding rate directly affect the operation performance of the picking device. During harvesting, if the feeding amount of the fruit picking device is less than the designed feeding amount, the operation efficiency of the harvester will be reduced, and the harvesting cost will be increased. If it is larger than the designed feeding amount, it will cause an unpicked loss, entrainment loss increase, congestion and even mechanical failure.

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Research on the threshing device and feeding rate of crop combine harvesters abroad started early, but most of them focused on rice and wheat combine harvesters[9-13]. Research on the feeding rate of peanut harvesters is limited because most foreign peanut varieties are sprawled, peanut seedlings are interwoven together similar to carpets during harvesting, and the feeding rate is relatively uniform and stable. Robert[14] changed the working speed of the rice and wheat harvester through a certain control algorithm to stabilize the roller load to obtain a stable feeding rate. Waree et al.[15] studied an axial flow maize threshing device and established a model of the threshing loss and power consumption. Gomez-Gil et al.[16] used GPS technology, particle weight sensors and field experiments to establish a mathematical model of the feeding rate and working speed of grain combine harvesters.

At present, there are few academic reports on the picking device and its feeding rate of a peanut pickup combine harvester in China[17,18], and the related research on the picking device and its feeding amount is mostly focused on the combined harvester of rice, wheat and maize[19-23]. Li et al.[24] studied the relationship between the feeding rate and the pressure of the cylinder behind the concave plate sieve of the threshing roller of the grain combine harvester and the total loss of threshing and separation. Tang et al.[25] studied the influence of prestress on the unbalanced vibration of the threshing device caused by straw winding using the finite element method and pointed out that a reasonably designed prestressed support beam structure could effectively suppress the dynamic characteristics of the threshing machine during the threshing process. Wang et al.[26,27] studied the influence of factors such as the rotational speed of the threshing roller, the feeding rate, and the threshing clearance of the cross axial flow threshing separation device on the threshing and separation performance, optimized the device structure, and established mathematical models of the non-threshing rate and entrained the loss rate of the cross axial flow threshing and separation device using probability theory. A threshing separation device with an adjustable threshing clearance was designed by changing the diameter of the threshing roller through the clearance adjusting mechanism. To reduce the breakage rate and entrained loss rate in a high-moisture maize harvesting process, Zhu et al.[28] studied the correlation between key factors such as the threshing roller speed, concave clearance, feed speed and threshing rate. Fan et al.[29] developed an electrohydraulic automatic control system for the threshing clearance to improve the reduced threshing performance of the maize harvester when the threshing roller is blocked due to the complex field environment, different crop conditions and different feeding rates. Liu et al.[30] used the DEM method to analyse the distribution of the threshed mixture under the conditions of a single threshing clearance and multiple threshing clearance of the rice combine harvester. Tian et al.[31] designed a rice combine harvester with a double threshing roller speed and double threshing clearance and conducted experiments to analyse the effects of different speeds and clearances on the damage rate and impurity content rate. Li et al.[32] designed a high moisture maize threshing device with a T-shaped file rod and analysed the influence of different factors on the separation performance by the DEM method. To develop a highly adaptive threshing device that can adjust the working parameters of the threshing device in real time according to different operating objects and environmental changes, Su[33] carried out research on the adaptive control method of the variable diameter roller and threshing device of the rice combine harvester. Zhao[34] designed a threshing roller feeding rate measurement system using thin film sensors to solve the problem of blockage and inaccurate blockage warnings of rice harvesters. You and You et al.[35] designed a fuzzy control system for the feeding rate based on the oil pressure of the continuously variable speed hydraulic cylinder of the threshing roller of the grain combine harvester.

The above studies show that the operating effect of threshing device is affected by factors such as threshing clearance and feeding rate. Timely adjustment of operating clearance and control of feeding rate become important technical ways to improve operating effect. The above research on adjusting mechanism and feeding rate monitoring method can provide ideas and technical reference for this work.

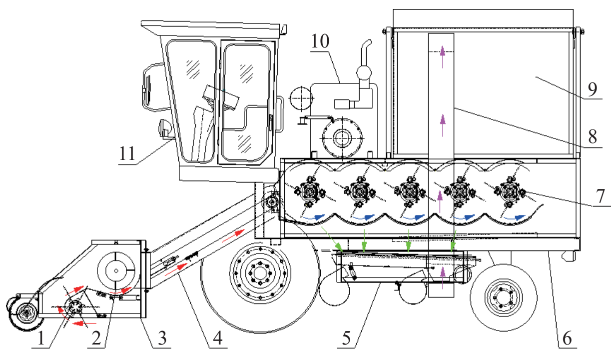
The purpose of this study was to develop a kind of peanut picking device with an adjustable working clearance for the peanut pickup combine harvester and establish a mathematical model of the concave plate sieve displacement and feeding rate of the picking device to provide a theoretical basis and technical reference for the automatic control research of the peanut picking harvester. The main research contents include the following: 1) developing a picking device with an adjustable clearance between the picking roller and concave plate sieve; 2) developing and analysing the mathematical model between the displacement of the concave plate sieve and the feeding rate of the full feeding peanut pickup combined harvester; 3) designing a working load monitoring system and method for the picking device of the full feeding peanut pickup combined harvester; 4) analysing the specific functional relationship between the feeding rate and the displacement of the concave plate sieve through experiments.

2 Design of the picking device with an adjustable working clearance

2.1 Overall structure and working principle

2.1.1 Pickup combine harvestor

In the early stage, the author developed a full-feed peanut pickup combine harvester, whose structure is shown in Figure 1. It is mainly composed of a pickup platform, conveying trough, cleaning device, chassis, picking device, pneumatic lifting device, granary, engine, cab, etc. During operation, the pickup platform picks up and gathers the peanut seedlings, and sends the peanut seedlings to the picking device through the conveying trough; Peanut pods and some seedlings picked by the picking device fall into the cleaning device for cleaning and separation. The pods are sent to the granary through the pneumatic lifting device, and the seedlings are discharged out of the machine body by the cleaning device.

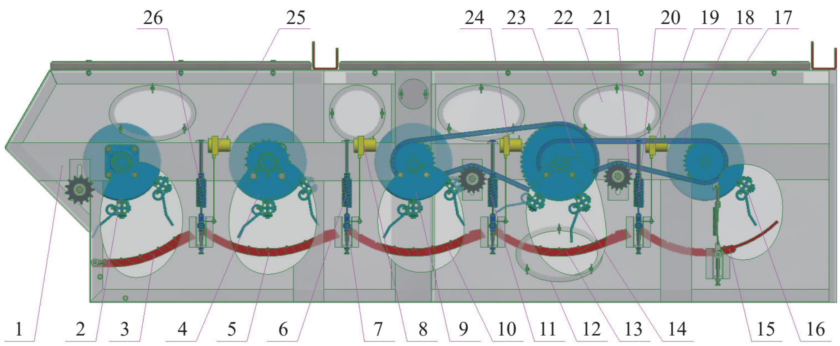


1. Pickup roller 2. Screw conveyor 3. Pickup platform 4. Conveying trough 5. Cleaning device 6. Chassis 7. Picking device 8. Pneumatic lifting device 9. Granary 10. Engine 11. Cab

Figure 1 Structure diagram of pickup combine harvestor

2.1.2 Picking device

The developed picking device structure of the full-feeding peanut pickup combine harvester with an adjustable clearance between the picking roller and the concave plate sieve is shown in Figure 2. It is mainly composed of a frame, picking rollers, concave plate sieves, suspension springs, concave plate sieve installation mechanisms, pull rope displacement sensors, and sprockets. The picking device is mainly used to transport the peanut seedlings transported from the previous working link (conveying device) through Picking Rollers Ⅰ, Ⅱ, Ⅲ, Ⅳ, and Ⅴ in turn for picking, seedling separation, and miscellaneous seedling throwing. The picked peanut pods, smaller branches and broken seedlings, soil and other impurities fall through the concave plate sieve to the cleaning device under the picking device, and most of the peanut seedlings are thrown to the subsequent seedling collection device by Picking Roller Ⅴ. The main parameters of the picking device are listed in Table 1.



1. Frame 2. Picking Roller Ⅰ 3. Concave Plate Sieve I 4. Picking Roller Ⅱ 5. Concave Plate Sieve Ⅱ 6. Suspension Spring Ⅱ 7. Concave plate sieve installation mechanism 8. Pull Rope Displacement sensor Ⅱ 9. Picking Roller Ⅲ 10. Concave Plate Sieve Ⅲ 11. Suspension Spring Ⅲ 12. Lower observation port 13. Concave Plate Sieve Ⅳ 14. Picking Roller Ⅳ 15. Concave Plate Sieve Ⅴ 16. Picking Roller Ⅴ 17. Top plate 18. Transmission chain 19. Pull Rope Displacement Sensor Ⅳ 20. Suspension Spring Ⅳ 21. Tensioning sprocket 22. Upper view inspection port 23. Drive sprocket 24. Pull Rope Displacement Sensor Ⅲ 25. Pull Rope Displacement Sensor I 26. Suspension Spring I

Figure 2 Diagram of the picking device structure

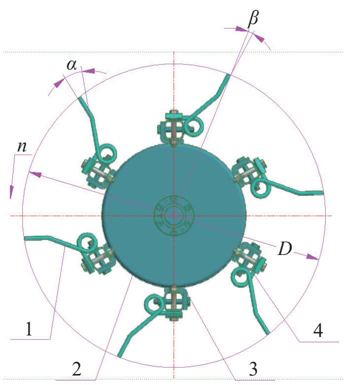
Table 1 Pickup conveyor main parameters

Parameters	Values
Picking device size (length×width×height)/mm×mm×mm	3252×1200×940
Concave plate sieve up and down movement range/mm	15-75
Supporting power/kW	7.5
Rated speed of picking roller Ⅰ, Ⅱ, Ⅲ/r·min^{-1}	300
Rated speed of picking roller Ⅳ, Ⅴ/r·min^{-1}	165 (27/49)

2.2 Design of key components

2.2.1 Picking roller

The picking roller is the core part of the picking device, which is mainly used to grab and drive the peanut seedling movement to separate the peanut pod from the seedling vine. The structure of the picking roller is shown in Figure 3, which is mainly composed of the picking spring teeth, supporting discs, spring teeth installation square tubes, etc.



1. Picking spring teeth 2. Supporting disc 3. L-shaped mounting plate 4. Spring teeth installation square tube

Figure 3 Diagram of the picking roller structure

The picking roller diameter D is determined by the feeding rate and physical properties of the peanut plants. If D is too small, it is easy to jam the picking roller, and it is difficult to meet the requirements of pod picking with a large feeding rate. If D is too large, then the peanut plants occupy a large space, are heavy, and increase the cost. The overall consideration is to have an ideal design of D=640 mm.

To reduce the impact of the picking spring teeth on peanut seedlings, reduce the damage rate of peanut pods, ensure the smooth transmission of peanut seedlings between the two picking rollers, and prevent the picking roller return-taking phenomenon (return-taking phenomenon refers to the phenomenon in which the peanut seedling rotates repeatedly around the same picking roller driven by the picking spring tooth so that the peanut seedling cannot smoothly enter the next picking roller; return taking will lead to winding of the picking roller around the peanut seedling, causing congestion), the external linear section of the picking spring tooth is designed to tilt backwards at an angle β, as shown in Figure 3. However, if β is too large, the grasping ability of the picking teeth will be reduced, so it is necessary to bend the picking teeth at a certain angle α. After a preliminary experimental study, they were designed as α=22° and β=6°.

The number of picking teeth rows N directly affects the frequency of the picking teeth grasping the peanut seedlings. If N is too small, the grasping interval of the picking teeth on the peanut seedlings is too long, each row of picking teeth grabs too many peanut seedlings, and the material layer is too thick, which affects the fruit picking effect. Therefore, to ensure that the peanut seedlings are grabbed by the picking teeth in time, the following conditions should be met:

$$L \le L_1 + L_2 \tag{1}$$

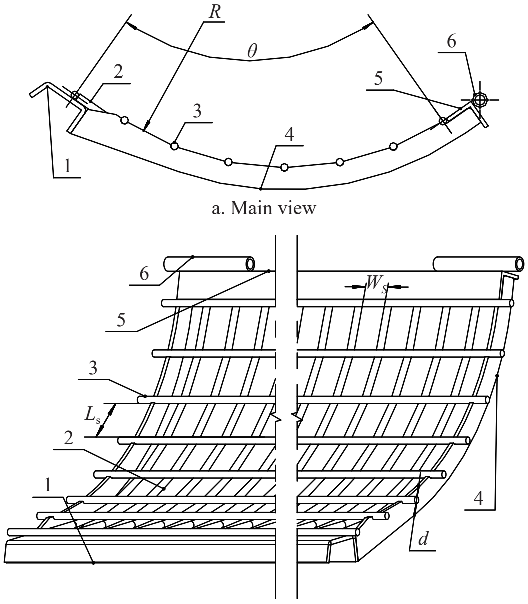
$$L = \pi D / N \tag{2}$$

where, L is the arc length between the outer ends of two adjacent picking teeth, mm; L_1 is the plant length of the peanut seedlings at the harvest time, mm; L_2 is the taproot length of the peanut seedlings at the harvest time, mm.

According to the field survey and literature [36], L_1=310-510 mm, and L_2=70-140 mm. Substituting the above data into Equations (1) and (2), it can be obtained that N≥5.29 mm. The larger N is, the better. However, excessive N will increase the quality, power consumption and manufacturing cost of the picking roller and will increase the rotary inertia of the picking roller, affecting the performance of the whole machine. Comprehensively considering and referring to the design experience of rice and wheat combine harvesters, N=6 was taken.

2.2.2 Concave plate sieve

The concave plate sieve, which is mainly used to form a “dynamic and static” joint action with the picking roller to complete the picking of peanut pods and cause the peanut pods to pass through the concave plate sieve holes and fall onto the subsequent cleaning device to complete the separation of pods and seedlings, is another core part of the picking device. At the same time, the concave plate sieve plays a role in supporting the peanut seedlings to be transported between the picking rollers and to finally be thrown out of the machine body. The concave plate sieve is mainly composed of a connecting lap slot, sieve body, supporting arc plate, connecting angle steel, suspension round pipe, etc. The structure is shown in Figure 4.



a. Main view

b. Axial side view

1. Connecting lap slot 2. Circumferential sieve rod 3. Axial sieve rod 4. Supporting arc plate 5. Connecting angle steel 6. Suspension round pipe

Note: W_S is the width of the sieve hole, mm; d is the sieve rod diameter, mm.

Figure 4 Diagram of the concave plate sieve structure

As shown in Figure 4a, if the effective wrap angle of the concave plate sieve θ is too large, the return-taking phenomenon easily occurs, causing poor transmission between the picking rollers. If θ is too small, the effective picking area of the concave plate sieve is too small, the picking efficiency is low, and the number of concave plate sieves and picking rollers need to be increased. Regarding the design with comprehensive consideration, θ=70° was chosen.

As the sieve body plays a major role in picking pods and supporting peanut seedlings, the sieve body should have a certain stiffness. If the sieve rod diameter d is too small, the sieve rod is similar to fine steel wire relative to the size of the peanut seedling, the shearing effect on the peanut seedling is increased, and the short miscellaneous, such as broken branches and seedlings, are increased, which increases the operation difficulty of the subsequent cleaning device. Therefore, the larger d is, the better. However, if d is too large, it will increase the quality of the sieve body and increase the manufacturing cost. Based on comprehensive consideration, d=10 mm was chosen for the design.

The size of the sieve hole directly affects the picking and separating function of the concave sieve. If the sieve hole size is too small, the damage to the peanut pods will increase; at the same time, the passing ability of the peanut pods through the sieve body will be poor. If the sieve hole size is too large, the picking performance will decline, and at the same time, the broken branches and seedlings passing through the sieve body will increase, which will increase the workload of the subsequent cleaning device. In addition, it is mainly the circumferential sieve rod that acts as a friction barrier for peanut seedlings to pick pods, and the peanut seedlings mainly move along the circumferential direction of the sieve body under the drive of the picking roller. The peanut pods mostly move along the circumferential direction of the sieve body, and there may be two pods moving side by side. Therefore, the sieve hole size should meet the following conditions:

$$L_S \geq L_0 \tag{3}$$

$$W_S \geq 2d_0 \tag{4}$$

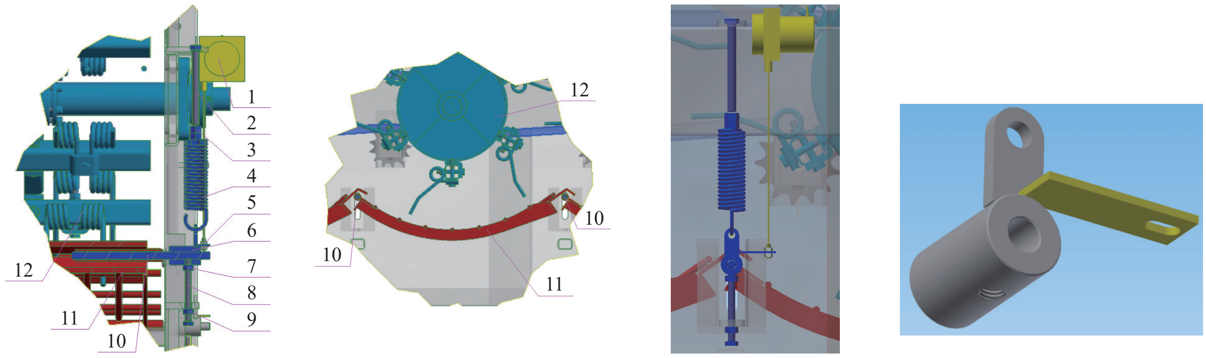
where, L_S is the length of the sieve hole, mm; L_0 is the length of the peanut pod at harvesting time, mm; W_S is the width of the sieve hole, mm; d_0 is the diameter of the peanut pod at the harvest stage, mm.

According to field research and the literature [37], L_0=15-62 mm, and d_0=10.0-19.9 mm. The above data was substituted into Equations (3) and (4), and the design margin was appropriately increased. It is designed as L_S=65 mm, W_S=40 mm.

2.2.3 Concave plate sieve clearance adjustment mechanism

The concave plate sieve clearance refers to the distance between the top of the picking spring teeth and the upper end of the concave plate sieve axial rod. The concave plate sieve clearance is an important parameter affecting the quality of the picking operations. The smaller the concave plate sieve clearance is, the tighter the peanut seedlings in the clearance is, the stronger the picking capacity is, and the higher the picking rate is. However, it is easy to increase the damage rate. The larger the concave plate sieve clearance is, the fluffier the peanut seedlings in the clearance are, and the weaker the interaction between the picking spring teeth is. Moreover, the picking rate and damage rate will all decrease. Therefore, the concave plate sieve clearance should be adjusted according to the quantity of the feeding peanut seedlings in real time to ensure the best working performance.

In this study, a suspension concave plate sieve clearance adaptive adjustment mechanism was designed, as shown in Figure 5. It is mainly composed of pre-tightening the force adjusting bolts, lock nuts, suspension springs, connectors, limit bolts, concave plate sieve suspension rods, etc. One end of the concave plate sieve suspension rod is inserted into the suspension tube on the concave plate sieve, and the other end other end is passed through the connector. The limit bolt is screwed into the connector, and the concave plate sieve suspension rod is pushed and locked with Locking Nut Ⅱ to prevent loosening. The initial clearance can be adjusted by adjusting the limit nut on the limit bolt. The lower end of the suspension spring suspends the connector, and the upper end is connected to the pre-tightening force adjusting bolt. The concave plate sieve can be suspended by rotating the pre-tightening force adjusting the bolt, and the concave plate sieve clearance can reach the initial clearance. At the same time, the pre-tightening force of the suspension spring can be adjusted to change the difficulty of adaptive adjustment of the concave plate sieve clearance with the feeding amount.



a. Structure diagram b. Partial schematic diagram c. 3D schematic diagram d. Connector schematic diagram

1. Pull rope sensor 2. Pre-tightening force adjusting bolt 3. Lock Nut I 4. Suspension spring 5. Sensor pull-rope lock nut 6. Connector 7. Lock Nut II 8. Limit bolt 9. Limit nut 10. Concave plate sieve suspension rod 11. Concave plate sieve 12. Picking roller

Figure 5 Concave plate sieve clearance adjustment mechanism

3 Monitoring method for the working load of the picking device

3.1 Force analysis of the concave sieve of the picking device

During the harvest operation, the picking spring tooth carries the peanut seedlings to move backwards along the concave plate sieve radian direction. The concave plate sieve is affected not only by the gravity of the peanut seedlings but also by the friction force of the peanut seedlings and the extrusion pressure between the peanut seedlings and the concave plate sieve. The force analysis of the concave plate sieve is shown in Figure 6.

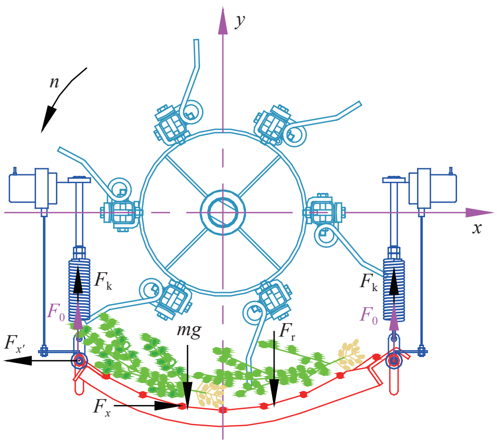


Figure 6 Force analysis of the concave plate sieve

In the x-axis direction, the component force of the friction force, extrusion force and other forces on the concave sieve in the x-axis direction counteracts the force exerted by the frame on the concave plate sieve suspension tube, and the force is balanced in the x-axis direction, namely:

$$F_x + F_{x'} = 0 \tag{5}$$

where, F_x is the component of the friction force, extrusion force and other forces on the concave plate sieve in the x-axis direction, N; $F_{x'}$ is the force exerted by the frame on the suspension tube, N.

In y-axis direction, regarding the gravity of the peanut seedlings, the component of the extrusion force of the peanut seedlings on the concave plate sieve in the y-axis direction counteracts the tension force of the suspension spring on the concave plate sieve and the pre-tightening force exerted on the concave plate sieve. By assuming that the force exerted on the suspension springs on the four corners of the concave plate sieve is approximately equal and assuming that the friction force exerted by the peanut seedlings on the concave plate sieve is symmetrically and evenly distributed along the y-axis, then the components of the friction force on the positive and negative sides of the x-axis in the y-axis direction are offset. Moreover, the force exerted on the y-axis is balanced. When the sum of the gravity of the peanut seedlings, the gravity of the concave plate sieve itself, and the component force of the extrusion force of peanut seedlings on the concave plate sieve in the y-axis direction is less than or equal to the pre-tightening force, the concave plate sieve does not move. Only when it is greater than the pre-tightening force will the concave plate sieve move, that is

$$\begin{cases} F_k = F_0, & mg + Mg + F_r \leq 4F_0 \\ F_k = mg + Mg + F_r = 4k(y + y_0), & mg + Mg + F_r > 4F_0 \end{cases} \tag{6}$$

where, F_r is the component of the extrusion force of the peanut seedlings on the concave plate sieve in the y-axis direction, N; F_k is the tension force of the suspension spring on the concave plate sieve, N; F_0 is the pre-tightening force of the suspension spring on the concave plate sieve, N; m is the mass of the peanut seedling in the concave plate sieve, kg; M is the mass of the concave screen itself, kg; g is the gravitational acceleration constant, g=9.8 m/s^2; k is the elastic coefficient of the suspension spring, N/mm; y is the displacement of the suspension spring, mm; y_0 is the displacement of the suspension spring when the pre-tightening force is F_0, mm.

It is assumed that all the peanut seedlings picked up by the front picking device are transported to the picking device, and the loss in the middle is ignored.

$$m = q \tag{7}$$

where, q is the feeding rate, kg/s.

According to References [24] and [38], the extrusion force F_r is related to the degree of the extrusion of the peanut seedlings and can be calculated as follows:

$$F_r = K_p(C_{\max}/\delta)^N \tag{8}$$

$$C_{\max} = q\lambda/[(1+\lambda)\rho v_s w] \tag{9}$$

where, K_p is the coefficient; $C_{\max}$ is the natural laying thickness of nongrain materials, mm; δ is the clearance between the picking spring teeth and concave plate sieve, mm; N is a real number; λ is the mass ratio of the pods and seedlings; ρ is the natural laying density of nongrain materials, kg/m^3; v_s is the average linear velocity of peanut seedlings in concave plate sieve, m/s; w is the width of concave plate sieve, m.

According to Equations (6)-(9), when $mg + Mg + F_r > 4F_0$,

$$y = \frac{1}{4k}Mg - y_0 + \frac{1}{4k}gq + \frac{1}{4k}K_p\left[\frac{\lambda}{\rho\delta v_s w(1+\lambda)}\right]^N q^N \tag{10}$$

As seen from the above equation, when other parameters (density of the peanut seedlings and ratio of the pod seedlings) are fixed, the stiffness of the suspension spring is selected, and the harvester is fed stably and evenly, the displacement of the suspension spring is mainly affected by the feeding rate. The above equation can be simplified as:

$$y = K_0 + K_1 q + K_2 q^N \tag{11}$$

where, K_0, K_1, and K_2 are the constant coefficients.

3.2 Monitoring system design

3.2.1 Overall structure

To measure the test data in real time, a working condition monitoring system for a peanut picking device was designed in this paper, which mainly monitors the change in the concave plate seven sieve clearance with the working load, that is, the change in the concave plate sieve displacement. The structure diagram of the monitoring system is shown in Figure 7. The system is mainly composed of three parts: sensor unit, data acquisition and data storage analysis. The sensor unit converts the displacement of the concave plate sieve into an electrical signal, and the data acquisition module converts the electrical signal into a displacement value and displays it, transmitting it to the touch screen for storage through the RS485 bus.

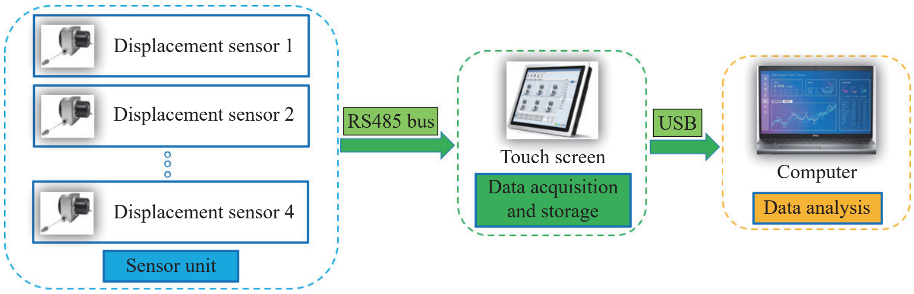


Figure 7 Monitoring system structure diagram

3.2.2 Hardware design

1) Displacement sensor

The displacement sensor adopts the MPS-S series pull rope displacement sensor produced by Shenzhen MILONT Technology Co., Ltd., which is mainly used to monitor the displacement change of the concave plate sieve in the y-axis direction (as shown in Figure 7). The main parameters are listed in Table 2.

2) Touch screen

The touch screen adopts the cMT2109X2 type touch screen produced by Artrich Technology Co., LTD., which is mainly used to collect, display and store the real-time data of the pull rope displacement sensor. The main parameters are listed in Table 3.

Table 2 Sensor main parameters

Parameters	Values
Range/mm	500
Output signal	RS485 digital signal
Linear accuracy/%	±0.1
Resolution/bit	32
Maximum working speed/m·s^{-1}	1.0
Supply voltage/V DC	6-30

Table 3 Touch screen main parameters

Parameters	Values
Touchscreen type	Four wire resistance type
Processor	Quad-core RISC
RAM/GB	1
Flash/GB	4
Supply voltage/VDC	(24±20)%

3.2.3 Software design

A data acquisition and storage system is designed using EasyBuilder Pro V6.07.01S software. The "Data sampling" module was used to read the address and data of the pull rope displacement sensor and establish the "Concave plate sieve displacement" database. The "Historical data display" and "Trend chart" components under the "Data/History" directory were used to index the data in the "Concave plate sieve displacement" database, record the data in different periods and display the change trend of the data. As the picking device has multistage concave plate sieves, the picking device blockage phenomenon mainly occurs at the first and second stage concave plate sieve, and the loss of the peanut seedlings here is small. Moreover, the feeding rate is closest to the actual feeding rate; thus, this system mainly monitors the displacement of the first and second stage concave plate sieves. That is, the displacement data of the left and right suspension springs Ⅰ and Ⅱ were monitored (as shown in Figure 2).

The acquisition and storage system is shown in Figure 8. The system can display the curve and numerical value of the concave plate sieve displacement in real time, store historical data and curves, call out the curve and data at any time, and export the data as an Excel format to facilitate subsequent data analysis.

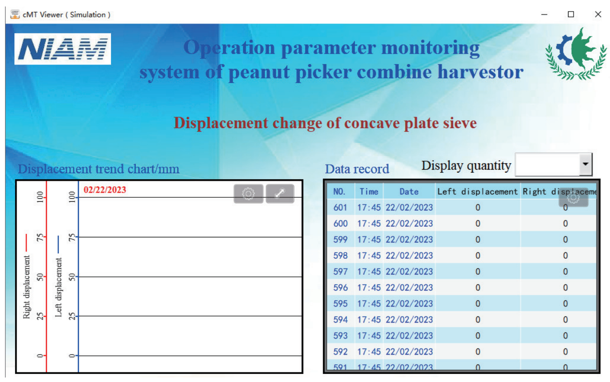


Figure 8 Data acquisition and storage system

4 Test and verification of the model of the feeding rate and concave plate sieve displacement

4.1 Test equipment and materials

To determine the mathematical model of the feeding rate of the picking device and concave plate sieve displacement, a road harvest test was carried out in Zhumadian City, Henan Province, in October 2021 by using a 4HLJI-3000 intelligent peanut pickup combine harvester. The UTM6503 electronic universal testing machine (power of 0.4 kW, maximum test force of 5 kN, accuracy class of 0.5) was produced by Shenzhen Sansi Zongheng Technology Co., Ltd. The measured stiffness of the suspension spring is k=5.20 N/mm. Other test equipment includes benchmarks, stopwatches, tape measures, electronic scales, etc.

The test peanut variety was Wanhua-2. The planting mode was a single ridge and double rows. The soil was sandy loam. The average ridge spacing was 800 mm. The average plant spacing was 260 mm. The average peanut plant height was 400 mm. The average pods number per plant was 16. The yield was 7500 kg/hm^2.

4.2 Test methods

With reference to the GB/T5262-2008 “General Regulations for Determination of Agricultural Machinery Test Conditions” and NY/T 2204-2012 “Technical Specification for Quality Evaluation of Peanut Harvesters”, the concave plate sieve displacement, forwards speed and feeding rate of the full feeding peanut pickup combine harvester under different working conditions were measured. Twenty-two plots were randomly selected in the peanut test field. Each plot was 20 m in length, and the width was the operating width of the peanut pickup combine harvester. To facilitate the test observation and reduce the test cost, the peanut seedlings in each plot were manually collected and then placed on the cement road according to the field status after digging and harvesting (the length, width and laying thickness of the peanut after digging and harvesting in the plot). The harvest test was carried out after the harvester engine speed reached the rated speed and entered a stable state in each test. The above monitoring system was applied to the real-time monitoring of the displacements of the suspension springs on the left and right sides of the concave plate sieve in the test process. The time period after the dynamic displacement curve of the concave plate sieve suspension spring in each test area reached stability was selected as the measurement time. The displacement values of the left and right sides every 1.0 s of this time period were derived, and the average values of the displacement of the left and right sides in this period were taken. The test time was monitored with a stopwatch, and the average forwards speed of each test was calculated. After each test, the fallen peanut seedlings, peanut seedlings in the seedling collection box and peanut pods in the granary were weighed, and the average feeding rate of each test was calculated based on the time spent in each test. To reduce the test error, the test was repeated three times, and the results were averaged. The test situation is shown in Figure 9.

Figure 9 Road test situation

4.3 Test results and analysis

The test results of the displacements of the left and right concave plate sieve suspension springs, forwards speed and feeding rate are listed in Table 4.

Table 4 Test results

Test No.	Forward speed/m·s^{-1}	Feeding rate/kg·s^{-1}	Spring I left displacement y_{11}/mm	Spring II left displacement y_{12}/mm	Spring I right displacement y_{21}/mm	Spring II right displacement y_{22}/mm	Displacement average change y/mm
1	0.54	1.47	1	0	0	–1	0
2	0.50	1.38	0	0	0	0	0
3	0.81	2.29	23	21	21	20	21.25
4	0.53	1.71	5	5	5	4	4.75
5	0.86	2.18	19	18	18	17	18
6	0.88	2.31	26	25	25	24	25
7	0.52	1.57	2	2	2	1	1.75
8	0.67	1.76	7	7	7	7	7
9	0.65	1.68	6	5	4	4	4.75
10	1.12	2.50	34	32	32	31	32.25
11	0.52	1.56	1	1	1	0	0.75
12	0.52	1.57	2	2	2	1	1.75
13	0.55	1.80	9	7	8	8	8
14	0.57	1.75	8	8	8	7	7.75
15	0.45	1.13	0	0	0	0	0
16	0.72	1.83	10	9	9	9	9.25
17	0.71	1.91	11	10	10	9	10
18	1.09	2.45	30	29	28	27	28.5
19	1.10	2.34	27	26	26	25	26
20	0.49	1.53	3	2	3	2	2.5
21	0.53	1.69	5	5	5	4	4.75
22	0.65	1.86	10	10	9	9	9.5

SPSS data processing software was used to perform a curve estimation fitting regression analysis on the displacement change (the part with change greater than 0) and the feeding rate in Table 4, and the significance test of the regression models was also performed. Regarding Reference [39], a linear function, power function, exponential function, quadratic function, cubic function and logarithmic function were used for the fitting analysis of the test data. The fitting curve is shown in Figure 10. The parameters and results of the specific fitting model are as follows:

$$y = 30.704q - 46.882 \quad R^2 = 0.985, \ p < 0.01 \tag{12}$$

$$y = 0.169q^{6.006} \quad R^2 = 0.870, \ p < 0.01 \tag{13}$$

$$y = 0.025e^{2.988q} \quad R^2 = 0.840, \ p < 0.01 \tag{14}$$

$$y = -3.184 - 14.098q + 11.171\,00q^2 \quad R^2 = 0.991, \ p < 0.01 \tag{15}$$

$$y = -16.840 + 7.442q + 1.903q^3 \quad R^2 = 0.992, \ p < 0.01 \tag{16}$$

$$y = 60.220\log(q) - 26.412 \quad R^2 = 0.971, \ p < 0.01 \tag{17}$$

$$y = 0.025 \times 19.854q \quad R^2 = 0.840, \ p < 0.01 \tag{18}$$

It can be seen from the fitting results that the R^2 value of the cubic function is the highest, indicating that the cubic function model obtained from the test has a high fitting accuracy for the prototype. That is, when the combine works stably, the feeding is uniform, the crop state (density and laying thickness) is basically consistent, and the cubic function model of the concave plate sieve displacement of the picking device and the feeding rate have a high degree of coincidence with Equation (11) of the mathematical model obtained from the previous theoretical analysis. In Equation (16), y=0 is set, and q=1.46 is obtained. Thus, the mathematical model of the displacement of the concave plate sieve and feeding rate of the picking device can be written as follows:

$$\begin{cases} y = 0, & q \le 1.46 \\ y = 1.903q^3 + 7.442q - 16.84, & q > 1.46 \end{cases} \tag{19}$$

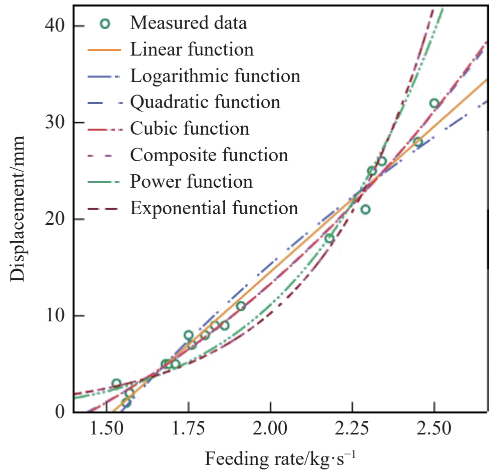


Figure 10 Fitting results of the relational models for the feeding rate and displacement change

4.4 Model verification

To check the correctness of the established mathematical model, according to the above test methods and data extraction methods, five confirmative tests were carried out through Equation (19) of the mathematical model of the feeding rate and the displacement of the concave plate sieve of the picking device. The verification test results are listed in Table 5.

Table 5 Verification test results

Test No.	Forward speed/m·s⁻¹	Feeding rate/kg·s⁻¹	Left measured displacement y_{11}/mm	Left displacement change y_{12}/mm	Right measured displacement y_{21}/mm	Right displacement change y_{22}/mm	Measured displacement average change y/mm	Calculated displacement/mm	Deviation rate/%
1	0.52	1.39	0	0	0	0	0.00	0.00	0.00
2	0.64	1.68	5	5	5	4	4.75	4.69	1.35
3	0.76	1.87	10	10	10	9	9.75	9.52	2.35
4	0.82	2.27	22	22	22	21	21.75	22.31	2.59
5	1.35	2.68	43	41	42	41	41.75	39.74	4.83
Mean									2.22

Table 5 lists the deviation rate between the measured displacement of the concave plate sieve of the picking device and the calculated value of the mathematical model. The verification test results show that the cubic function model of concave plate sieve displacement and feeding rate of the picking device established according to road monitoring test samples has a good accuracy, the absolute deviation rate ranges from 0 to 4.83%, and the average deviation rate is 2.22%. At the same time, Table 5 lists that the larger the feeding rate is, the larger the deviation rate is. This shows that with the increase in the feeding rate, the uncertainty of the displacement change of the picking device concave plate sieve increases, and the accuracy of the fitted cubic function model decreases.

4.5 Field verification test

To test the adaptability and correctness of the mathematical model of the cubic function established in the actual field harvest, according to the above test methods and data extraction methods, field experiments were conducted in Suiping County, Zhumadian city, Henan Province, China, in October 2021. The peanut varieties, planting patterns, field conditions and digging and harvesting methods of peanut were the same as those of road tests. After digging and drying for 4.5 d, the water content of the peanut plants was 15%-23%. The field test is shown in Figure 11, and the results are listed in Table 6.

As seen from Table 6, the deviation rate of the displacement variation of the concave plate sieve in the field test ranges from 0 to 6.19%, and the average deviation rate is 2.73%, which are both larger than the results of the road test. This may be because the working environment in the field is more complex; for example, the road surface in the field is uneven, and the uncertainty of the displacement variation of the concave plate sieve is increased. The measured displacement is smaller than the calculated displacement. This may be because the drying time before the harvest of the peanut seedlings in the field experiment is longer than that in the road experiment, which is 5 d. The water content of the peanut seedlings decreases, the amount of wilting of the peanut seedlings decreases, and the brittleness increases. During harvesting, the peanut seedlings break easily, there are more broken small seedlings falling on the cleaning device through the concave plate sieve, and the thickness of the peanut seedlings decreases.

Display storage device

Displacement monitoring mechanism

Figure 11 Field test

Table 6 Field test results

Test No.	Forward speed/ $(m \cdot s^{-1})$	Feeding rate/ $(kg \cdot s^{-1})$	Left measured displacement y_{11}/mm	Left displacement change y_{12}/mm	Right measured displacement y_{21}/mm	Right displacement change y_{22}/mm	Measured displacement average change y/mm	Calculated displacement/mm	Deviation rate/%
1	0.51	1.33	0	0	0	0	0.00	0.00	/
2	0.68	1.78	8	7	7	6	7.00	7.14	1.99
3	1.27	2.58	34	33	33	32	33.00	35.04	6.19
				Mean					2.73

5 Discussion

1) At present, the combined harvesters such as rice, wheat and maize mainly change the working clearance by changing the diameter of the threshing roller or the position of the concave plate through hydraulic cylinder. Firstly, the feeding rate is detected by a sensor, and then the feeding rate information is sent to the controller for comparison, send out the hydraulic valve control signal to drive the hydraulic cylinder action, and then the working clearance is adjusted. The adjustment has hysteresis. The working clearance of the peanut picking device proposed in this paper is adjusted by the concave screen suspension spring, which has self-adaptability and timeliness. However, this adjustment mechanism has high requirements for the stiffness and preload of the suspension spring, and needs to be optimized and determined through a large number of tests.

2) The mathematical model of the feeding rate of the peanut pickup harvester and the displacement of the concave plate sieve of the picking device studied in this paper was obtained through the cement road test. The state of the peanut vine is different from that naturally laid by the field excavator and harvester to a certain extent, and there is a certain difference between the road walking and the field walking of the combine harvester, which will have a certain impact on the monitoring test results. However, the field test shows that although the displacement deviation rate of the field test is higher than that of the road test, the average deviation rate is still less than 3.0%. The fitted cubic function model still has a high accuracy, which has a good guiding role for the intelligent measurement and control and optimal design of the subsequent peanut pickup harvester.

3) Due to the limitation of the peanut harvest season, only the Wanhua-2 peanut variety in Zhumadian, Henan Province, was tested in this study. The moisture content of the peanut seedlings has a certain influence on the deviation rate of the displacement variation of the concave plate sieve; thus, the test results have certain limitations. Follow-up research can strengthen the monitoring test of different peanut varieties and different drying days in the main peanut production area to optimize the functional relationship between the feeding rate and the displacement change amount of the concave plate sieve and to obtain a more accurate mathematical model.

6 Conclusions

1) Taking the 4HLJI-3000 intelligent peanut picking combine harvester developed by the author as the research object, the overall structure and working principle of the picking device with self-adaptive adjustment of working clearance were analysed. The key components, such as the picking roller, concave plate sieve and concave plate sieve clearance adjustment mechanism, were designed and analysed. The force analysis of the concave plate sieve of the picking device was carried out, and the mathematical model of the displacement variation and feeding rate of the concave plate sieve of the picking device was obtained. A software system for monitoring, storing and analysing the displacement of the concave plate sieve of the picking device based on EasyBuilder Pro software was designed.

2) Through the road monitoring test and data fitting regression analysis of the displacement variation of the concave plate sieve and the feeding rate of the picking device, the cubic function model of the displacement variation of the concave plate sieve and the feeding rate is $y= -16.840+7.442q+1.903q^3$. The model verification test results show that the established cubic function model has a good accuracy, the deviation rate ranged from 0 to 4.83%, and the average deviation rate was 2.22%. The field test results showed that the deviation rate ranged from 0 to 6.19%, and the average deviation rate was 2.73%. The larger the feeding rate is, the greater the deviation rate. This study can provide a theoretical basis and technical reference for the intelligent measurement and control and optimization design of a full-feed peanut pickup combine harvester and other crop picking (threshing) devices.

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