Analysis and performance test on dynamic seed corn threshing and conveying process with variable diameter and spacing

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Abstract: In order to further reduce the damage rate in threshing seed corn, a seed corn threshing testbed with variable diameter and spacing that can realize dynamic adjustment of parameters, such as feed quantity, rotating speed of the threshing device, threshing spacing of the threshing units, was designed in this research. The software of finite element analysis ANSYS Workbench was applied to do modal analysis on the threshing axis designed for variable diameter and spacing of seed corn. The first 8 orders of natural frequencies were distributed in 201.12-1640.20 Hz, with corresponding vibration amplitude in 5.86-27.04 mm, showing reasonable structural design of the threshing axis, which could realize effective seed corn threshing and conveying. Discrete element method was applied to do simulation analysis on the seed corn threshing and conveying process with variable diameter and spacing. Under the condition of different feed quantity, different rotating speed of the thresher, the moving speed of corn clusters and contact force among clusters were measured through simulation, and the working characteristics of the threshing testbed for low-damage and dynamic threshing and conveying of seed corn with variable diameter and spacing were revealed. Working performance test results of the testbed of seed corn with variable diameter and spacing showed that, when the rotating speed of the threshing axis was 190-290 r/min, feed quantity was 1.80-3.80 kg/s, the damage rate of seed corn was 0.32%-0.63%, threshing rate was 99.20%-99.82%, and content impurity rate was 4.23%-5.86%, the mass of threshed corn grains first increased and then decreased along the axial direction. The test verification process was in line with the simulation results; thus, the test results could satisfy the requirements in design and actual operation.
Keywords: seed corn, threshing device with variable diameter and spacing, threshing and conveying process, performance test
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1 Introduction

Seed corn is a living organism with complex physical and mechanical properties, and requires high performance of the threshing device[1]. Seed corn clusters and grains are smaller than commodity corn, and their shape and arrangement are irregular. The bonding force between the grains and the corn cob is large, and the connection strength between the grains and the corn cob in each part of the ear is significantly different, making it difficult to be threshed[2,3]. At present, threshing operation of most seed corn is finished by traditional corn threshers, which mainly work through combination of stirring and striking.

In order to further reduce damage in seed corn threshing, the research on the threshing methods of seed corn and supporting devices have been constantly developed in recent years[4]. He et al.[5] proposed a low-loss extruding threshing method of seed corn by simulating manual rubbing of corn grains; Yu[6] applied finite element analysis software to study the different helical angles and maximum stress on the cutting plate in the corn threshing process on the extruding type corn thresher; Li et al.[7] improved the key components and designed a low-loss floating threshing device. Ma et al. further improved the extruding-rubbing type corn threshing device and fixed a spring tooth and pressure plate mechanism at the rear end of the threshing device. In the preliminary study, Ma et al.[8] designed a spiral plate tooth type seed corn thresher, and found that, it could ensure consistent directions of corn cluster axis and threshing principal axis in threshing, and effectively reduced the number of corn clusters broken off by the plate teeth. Yu et al.[9,10] studied the modeling and threshing process of corn ear using discrete element theory. The axial distribution and radial dimensions of the spiral plate teeth and coronary plate teeth on the threshing axis were determined by the biomechanical characteristic of the seed corn, thus it basically met the requirements of high threshing rate, low damage rate with small number of broken corn cobs in seed corn threshing[11,12].

Therefore, based on the preliminary research results of the research group[13], by analyzing the dynamic threshing and conveying process of the seed corn threshing testbed with variable diameter and spacing with discrete element method, in this study, the dynamic motion rule of seed corn clusters in the threshing device and the variation tendency of moving speed of clusters and contact force among clusters were analyzed, a modal analysis was carried out on the combined spiral plate teeth threshing device with

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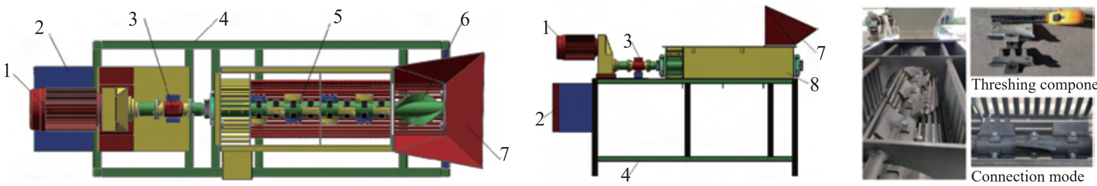
variable diameter and spacing, hoping to further reduce mechanical damages on seed corn clusters in threshing and effectively improve the adaptability of the device on seed corn threshers.

2 Testbed structure and working principles

2.1 Structure

The seed corn threshing test bed with variable diameter and spacing is mainly composed of the threshing device with variable diameter and spacing, a spiral feeding device, an electric motor, an electrical control cabinet, a torque sensor, a frequency converter, a feeding hopper and a body frame. The structure of the testbed is shown in Figure 1[13].

The threshing axis with variable diameter and spacing is the key component of the seed corn threshing device, and its working performance directly influences the overall working performance and test results of the testbed. As shown in Figure 1c, the threshing units on the threshing axis are composed of plate teeth and coronary teeth, which are arranged alternately on the axis to achieve variable diameter and spacing, to adapt to the change of axis diameter of corn clusters in dynamic threshing process, and the spacing between the centers of each spiral plate tooth was set according to literature [6]. Meanwhile, bionic design was made on the coronary teeth threshing units, which first extrude some corn grains on the clusters by using sticks, to ensure better extruding and rubbing of corn clusters by the plate teeth in subsequent threshing process.



1. Electric motor 2. Electrical control cabinet 3. Torque sensor 4. Body frame 5. Threshing device with variable diameter and spacing 6. Spiral feeding device 7. Feeding hopper 8. Threshing bin

Figure 1 Structure of the seed corn threshing testbed with variable diameter and spacing

2.2 Working principle

During operation of the seed corn threshing testbed with variable diameter and spacing, the electrical control cabinet starts the electric motor, and the corn clusters fall into the threshing bin along the feeding hopper. Pushed by the spiral feeding device, the clusters enter into the threshing device with variable diameter and spacing. Under the effect of grid concaves, plate teeth, coronary teeth, the corn clusters to be threshed are driven to revolve in the threshing bin, then the grains on the clusters are extruded and rubbed, and finally threshed, then fall into the feed receiver through the gap between grid concaves. At the same time, the threshed corn cubs are conveyed along axial direction to the cob discharge outlet. After the cobs accumulated to a certain amount, the plate above the cob discharge outlet is gradually propped up, and the cobs are discharged out of the testbed, and the seed corn threshing process is finished.

2.3 Main technical parameters

Main technical parameters of seed corn threshing testbed with variable diameter and spacing are listed in Table 1.

3 Modal analysis of the threshing axis

In the working process of the seed corn threshing testbed with variable diameter and spacing, threshing axis as the most important working component, is subject to the dynamic load from the electric motor and corn clusters. When the frequency produced by the vibration from external dynamic load is close to one order natural frequency of the threshing axis, they will resonate, and the threshing axis will be deformed and cannot rotate along the axis, changing the force between the threshing units and clusters, contact frequency and contact area, seriously affecting the threshing rate, grain damage rate and content impurity rate and thus harming the threshing performance, service life and safe reliability of the threshing testbed. A modal analysis was made on the threshing axis variable diameter and spacing through the ANSYS Workbench software, and the first 8 orders natural frequencies and modes of vibration were extracted, to verify the possibility of resonance and degree of structural deformation when rotating speed of the threshing axis was 150-300 r/min.

Table 1 Main technological parameters of the seed corn threshing testbed

Parameters	Values
Size (Length×width×height)/(mm× mm×mm)	2645×800×1540
Power/kW	5.50
Working performance/kg·h^{-1}	5000
Threshing forms	Extruding and rubbing
Arrangement patterns of threshing units	Spiral line arrangement with variable diameter and spacing
Feed quantity/(kg·s^{-1})	1.80-3.80
Concave forms	Grid concaves
Types of threshing units	Plate teeth, coronary teeth
Rotating speed adjustment method	Adjustment by frequency converter
Rotating speed of the threshing axis /r·min^{-1}	0-300

3.1 Model establishment and mesh division

The 3D model of the threshing axis and its threshing units were established in SolidWorks. The connection of the parts on the axis was rigid coupling (bolt connecting and welding), and the material was C45. The established 3D model was imported from the SolidWorks into the ANSYS Workbench through software interface. In order to improve the calculation speed in the modal analysis of the threshing axis as much as possible, the 3D model underwent some simplification treatments: It was believed that the material of the threshing axis and the threshing units was the same and isotropous, with uniform density in the overall structure, and effect of bolts connecting threshing units on the overall performance of the threshing axis was ignored, and all components were regarded as a whole[14]. The Static Structural and Model program overview was established in ANSYS Workbench, and the 3D model of the threshing axis was saved in .x_t format and imported into Static Structural for mesh division and static stress analysis, then modal analysis was performed in the Model module. The material was then given to the model, and the material parameters of C45 were set as follows: elastic modulus E=210 GPa, density ρ=

7850 kg/m^3, and Poisson's ratio μ=0.31. In ANSYS Workbench Meshing, the Explicit reference type that provides dynamic analysis was selected, and the Patch Conforming module generation function was used for mesh generation.

3.2 Analysis of modal vibration characteristics

The dynamic vibration characteristics of the threshing axis with variable diameter and spacing determine its working performance in bearing the dynamic load. During operation of the threshing testbed, vibration mainly comes from the electric motor in outputting power. After comparing the moving frequency and natural frequency of the threshing axis, the effect of vibration on structure of the threshing axis can be predicted. The Block Lanczos algorithm in the ANSYS Workbench software was used to get the first 8 orders of natural frequencies of the testbed body frame and the maximum vibration amplitude[14], as shown in Figure 2.

It can be obtained through the modal analysis that, the first 8 orders of natural frequencies of the threshing axis with variable diameter and spacing was within the range of 201.12-1640.20 Hz, and the corresponding vibration amplitude was in 5.86-27.04 mm.

The modes of vibration were mainly twisting, swinging and bending. With the increase of the natural frequency of the threshing axis with the ascending modal orders, the vibration distribution of each order was mainly concentrated in the center of the threshing axis, and the vibration direction was along the Y coordinate axis. The working environment and conditions of the threshing testbed was very complicated, and the distribution of the received excitation sources was extensive, however, the dynamic load on the threshing axis mainly came from the power output shaft.

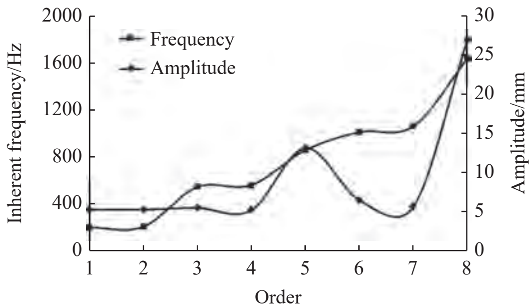
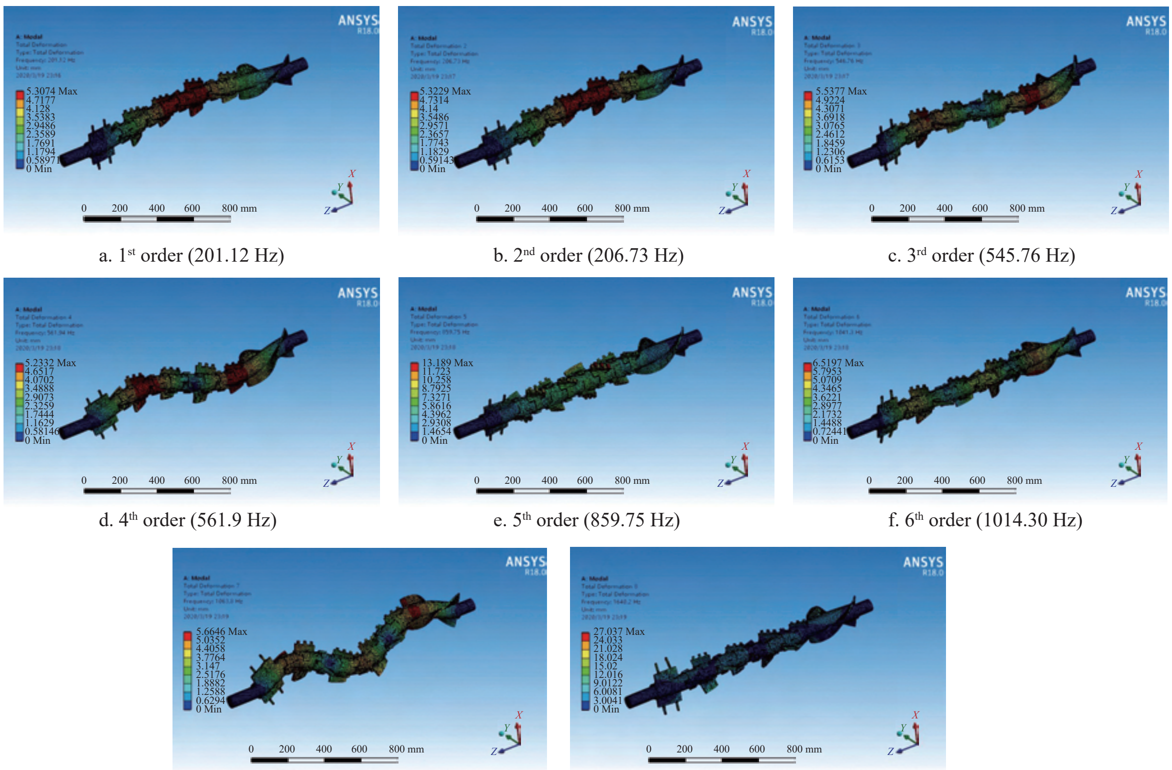


Figure 2 Natural frequencies and amplitude of the first eight orders of the threshing axis

As shown in Figure 3, the maximum vibration amplitude at the 8th natural frequency 1640.20 Hz of the threshing axis was 27.04 mm, which was mainly at the outer edge of the threshing units of the threshing axis, the main vibration direction was swinging from side to side along the Y coordinate axis. The second largest vibration amplitude of 13.189 mm occurred at the 5th natural frequency of 859.75 Hz, the vibration was swinging side to side of the outer edge of threshing units on the threshing axis along the Y coordinate axis, and the diameter of the threshing axis increased at the same time. If the threshing units on the threshing axis underwent vibration deformation, it would seriously affect the force angle and contact area on corn clusters in threshing, thus affecting the efficiency of the threshing testbed.



a. 1st order (201.12 Hz) b. 2nd order (206.73 Hz) c. 3rd order (545.76 Hz)

d. 4th order (561.9 Hz) e. 5th order (859.75 Hz) f. 6th order (1014.30 Hz)

g. 7th order (1063.8 Hz) h. 8th order (1640.20 Hz)

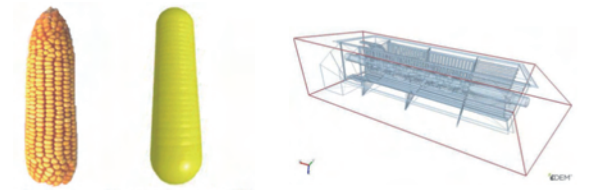
Figure 3 Modes of vibration of the first 8 orders of the threshing axis with variable diameter and spacing

When the ratio between the driving frequency produced in the rotation of the threshing axis and the natural frequency at one certain order is 0.8-1.2, resonance would occur for the whole threshing axis. When the rotating speed range of the threshing axis was 150-300 r/min, the driving frequencies on the threshing axis from the electric motor and the power output shaft was 24 Hz and 2.5-5 Hz, the natural frequency of the threshing axis was greatly higher than the driving frequency, thus resonance would not occur. In this case, the structure of the threshing axis is reasonable and can realize effective threshing.

4 Discrete element simulation of the seed corn threshing and conveying process

4.1 Establishment of the discrete element simulation model

In order to speed up the operation speed of the discrete element simulation of the seed corn threshing and conveying process with variable diameter and spacing, it is necessary to simplify the irrelevant parts of the testbed, and save the simplified 3D model in .x_t format for later calculation in the EDEM software. The 3D modeling software SolidWorks was used to establish the model of seed corn clusters, then the established 3D model was saved in .IGS format. The established discrete element model of seed corn cluster and the simulation model of the threshing device with variable diameter and spacing are shown in Figure 4.



a. Seed corn cluster

b. Simulation model of the threshing device with variable diameter and spacing

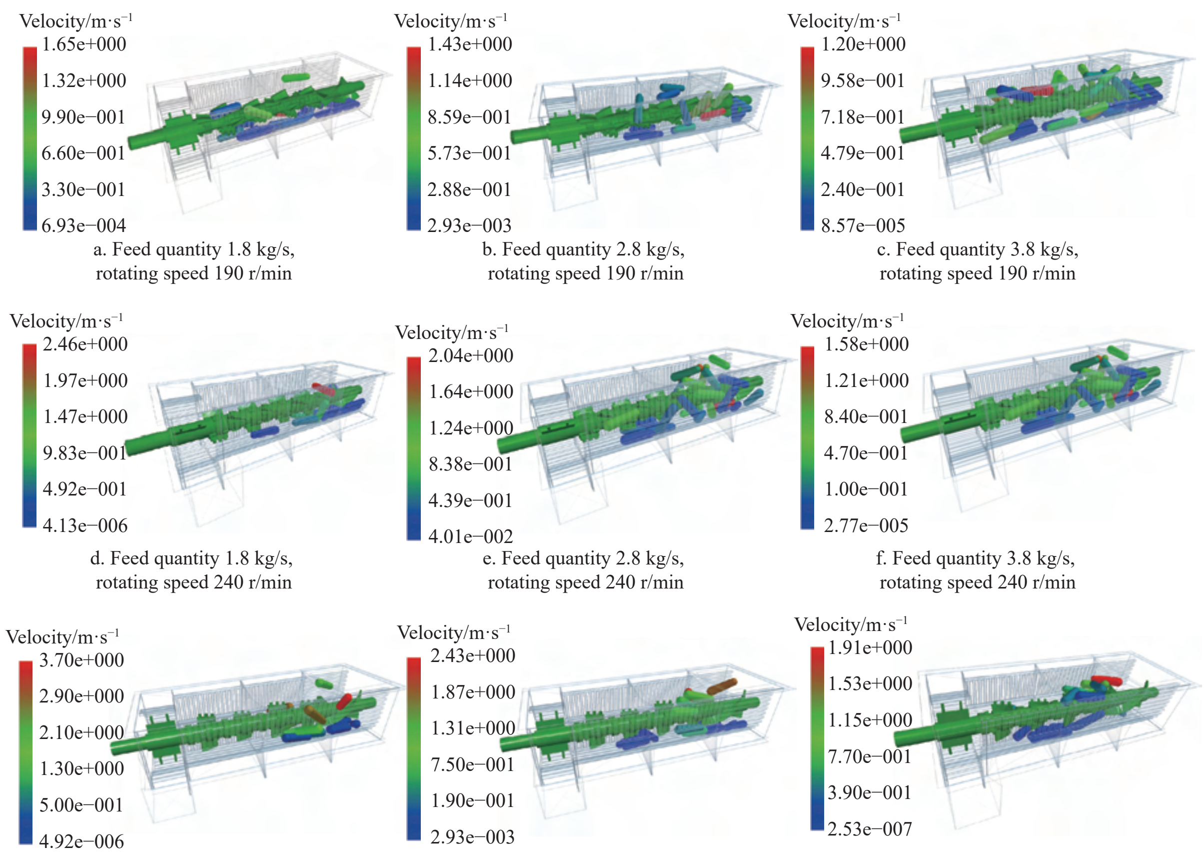
Figure 4 Discrete element simulation of the seed corn threshing and conveying process

According to previous studies[15-19], the Poisson's ratio of the seed corn clusters and the threshing device (steel) was 0.40 and 0.28, shear modulus was 1.37×10^2 MPa and 3.50×10^4 MPa, and density was 1197 kg/m^3 and 7850 kg/m^3, respectively. The recovery coefficients of corn-corn, corn-steel were 0.2 and 0.6, the static friction coefficients were 0.25 and 0.30, and the coefficients of rolling friction were 0.06 and 0.05. In order to ensure the consistency in the simulation process, the time step of the simulation was set as 10%, total simulation time was set as 5 s.

4.2 Simulation analysis of the movement speed of the corn clusters

Simulation analysis was performed on the movement speed of the seed corn clusters in the threshing bin of the threshing testbed with variable diameter and spacing[20,21]. According to the results of previous studies, feed quantity, rotating speed of the threshing axis had significant effect on the threshing performance of the testbed. Therefore, the combination of the factors above was adopted to analyze the movement law of seed corn clusters.

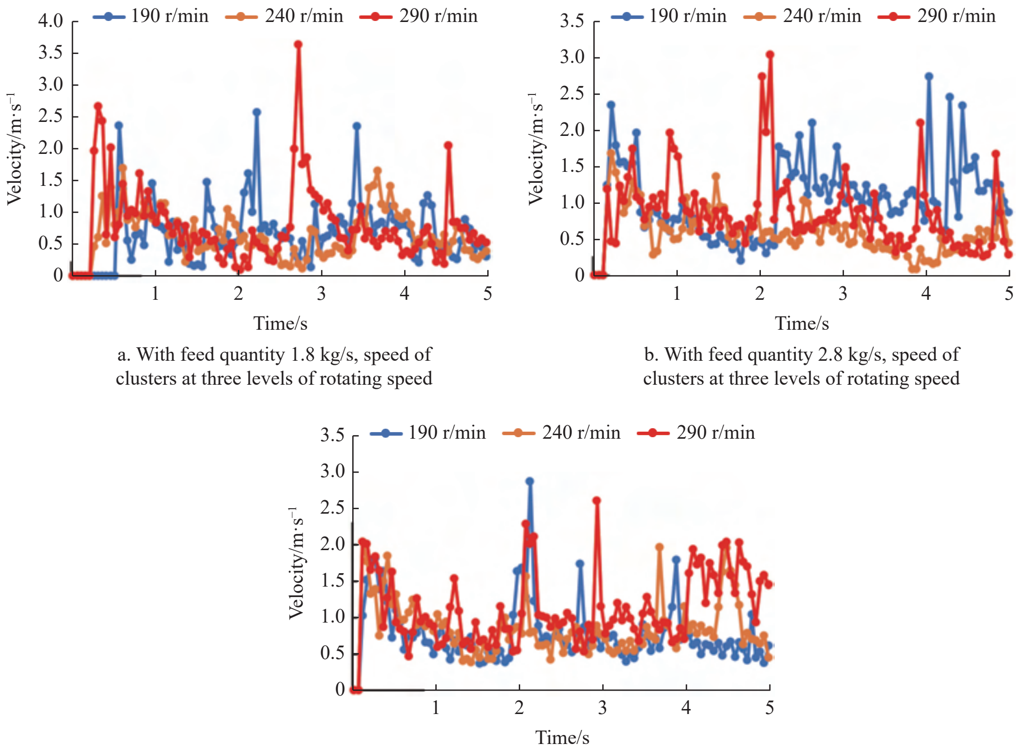
It can be obtained from Figure 5 that, when the rotating speed of the threshing axis with variable diameter and spacing changed from 190 to 290 r/min, the feed quantity increased from 1.8 to 3.8 kg/s, the seed corn clusters gradually accumulated in the threshing bin. When the feed quantity was low and rotating speed of the threshing axis was low, the extruding force among corn clusters was medium, the axial movement speed of corn clusters along the direction of cob discharge outlet was not high, and thus some clusters would accumulate at the feeding part of the threshing axis. With the increase of the feed quantity and rotating speed of the threshing axis, under the effect of the spiral feeding device, the seed corn clusters were pushed forward quickly, and the extruding and rubbing among clusters, between clusters and the threshing axis were significantly increased, ensuring the smooth conveying of the clusters.



a. Feed quantity 1.8 kg/s, rotating speed 190 r/min
b. Feed quantity 2.8 kg/s, rotating speed 190 r/min
c. Feed quantity 3.8 kg/s, rotating speed 190 r/min
d. Feed quantity 1.8 kg/s, rotating speed 240 r/min
e. Feed quantity 2.8 kg/s, rotating speed 240 r/min
f. Feed quantity 3.8 kg/s, rotating speed 240 r/min
g. Feed quantity 1.8 kg/s, rotating speed 290 r/min
h. Feed quantity 2.8 kg/s, rotating speed 290 r/min
i. Feed quantity 3.8 kg/s, rotating speed 290 r/min

Figure 5 Simulation of movement speed of seed corn clusters with different feed quantities

It can be obtained from the variation of speed of seed corn clusters with different feed quantities in Figure 6 that, with the increase of the seed corn feed quantities in the threshing bin, the speed of the corn clusters gradually decreased and became stable at a moving speed of 0-2 m/s. When feed quantity was 3.8 kg/s, the variation fluctuation of speed of clusters under three levels of rotating speed was the lowest and conducive to the sufficient rubbing between clusters and threshing units and among clusters. It shows the advantages of extruding-rubbing type threshing device. Meanwhile, the threshing device with variable diameter and spacing had different axial movement speed with the same feed quantity but different rotating speed. When the rotating speed of the threshing axis reached 290 r/min, the speed of clusters had obvious fluctuation, especially when the feed quantity was 2.8 kg/s, the speed of clusters underwent the most obvious changes (the maximum value was close to 3 m/s). In addition, influenced by the spiral feeding device at the front of the threshing axis with variable diameter and spacing, within 1 s after entering the threshing bin, the speed of corn clusters underwent significant change in moving speed, which was the key reason that caused damage and breakage on corn cobs. By comparing the variation curves of speed of seed corn clusters with different feed quantities and rotating speed of threshing axis, it was found that, when the feed quantity was 2.8 kg/s, rotating speed of the threshing axis was 240 r/min, the axial moving speed of seed corn clusters kept a stable speed variation.



a. With feed quantity 1.8 kg/s, speed of clusters at three levels of rotating speed

b. With feed quantity 2.8 kg/s, speed of clusters at three levels of rotating speed

c. With feed quantity 3.8 kg/s, speed of clusters at three levels of rotating speed

Figure 6 Speed of seed corn clusters with different feed quantities and rotating speed

4.3 Simulation and analysis of contact force on clusters

The variation law of contact forces on clusters under the effect of rotation of the threshing axis with variable diameter and spacing was analyzed based on the combination of feed quantity and rotating speed of the threshing axis[22,23].

When the rotating speed of the threshing axis with variable diameter and spacing changed from 190 to 290 r/min, the feed quantity of seed corn clusters increased from 1.8 to 3.8 kg/s, the variation of contact force among seed corn clusters is shown in Figure 7. It can be obtained from the contact force among corn clusters in the threshing bin that, affected by the spiral feeding device in the front of the threshing axis, the contact force among corn clusters was large. With the gradual increase of the spacing among threshing units, the contact force among clusters gradually went down. The structural design could meet the requirements of dynamic threshing and conveying of the threshing axis with variable diameter and spacing.

Due to the uneven force on seed corn clusters in the threshing bin, after the simulation was finished, in each group, the contact force of 10 corn clusters were extracted in each group and averaged. Under different feed quantities and rotating speed of the threshing axis, the variation of average contact force among seed corn clusters is shown in Figure 8. When the rotating speed of the threshing axis increased from 190 to 290 r/min, the contact force from the threshing units to corn clusters gradually increased, the reason is that, with the increase of rotating speed of the threshing axis, the linear velocity of the outer edge of the threshing units increased, thus enhancing the contact force between threshing units and corn clusters. With a fixed rotating speed of the threshing axis, with the continuous increase of feed quantity in the threshing bin, the interactive contact force between threshing units and corn clusters also gradually enhanced. With an unchanged rotating speed of the threshing axis, the increase of feed quantity will cause accumulation of more corn clusters in unit volume in the threshing bin, increasing the chances of contact between threshing units and corn cluster, thus increasing the contact force between them. Based on previous studies, the instantaneous destructive power that breaks the corn grains is in the range of 124.33-347 N[24]. At the moment of

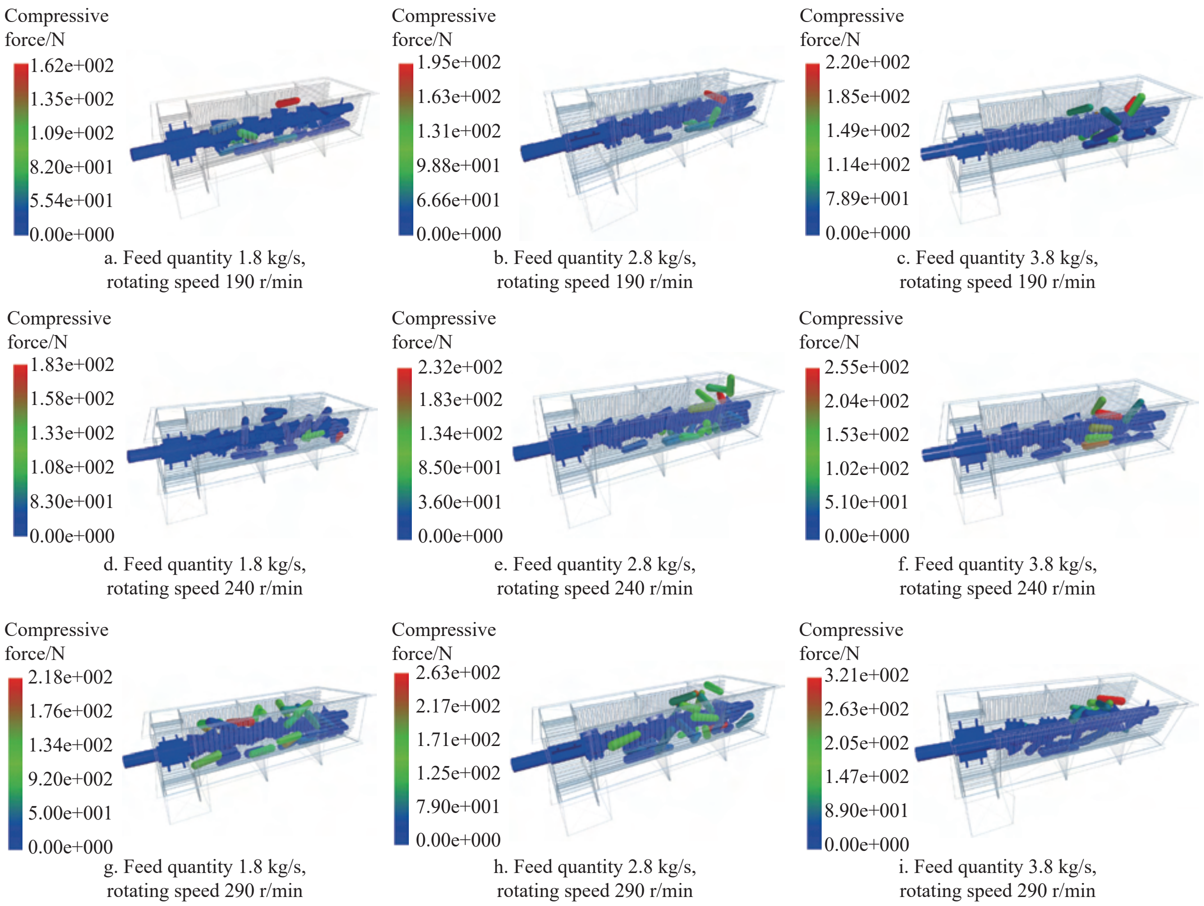


Figure 7 Variation of contact force among seed corn clusters with different feed quantities

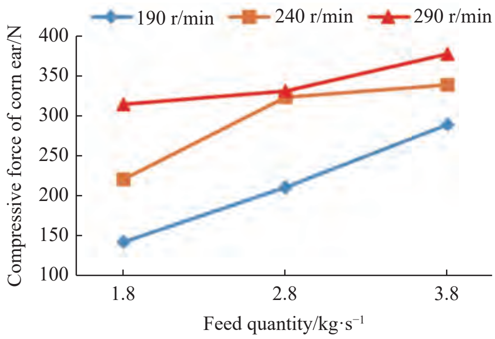


Figure 8 Variation of contact force among seed corn clusters with different feed quantities and rotating speed

separating corn grains from the cob, the rupture force is in the range of 1.97-11.93 N[25]. It can be obtained from Figure 8 that, the contact force between threshing units and corn clusters was above 100 N, which is higher than the rupture force between the grains and the cob, thus it can ensure the threshing rate of corn clusters. At the same time, when the rotating speed of the threshing axis was no more than 290 r/min, the contact force of the corn clusters was lower than range of the destructive power that could break the corn grains, thus the grain damage rate of the threshing device with variable diameter and spacing can be kept in a constant range.

5 Bench test verification

In order to further analyze the dynamic threshing and conveying process of seed corn with variable diameter and spacing and verify the working performance of the testbed, in 2020, a verification test was carried out in Jiuquan OK Seed Machinery Co., Ltd., in Jiuquan, Gansu province, China, as shown in Figure 9. In the process of the test, according to Technical specifications for seed maize rubbing thresher (NY/T 1136-2006) and Measuring methods for agricultural machinery testing conditions - general rules (GB/T 5262-2008), the seed corn threshing testbed with variable diameter and spacing was tested on its working performance. By taking the damage rate, threshing rate, content impurity rate and the axial distribution of mass of threshed grains as test indexes for evaluation[26], and the test was carried out by adjusting the parameters of rotating speed of the threshing axis (controlled by the frequency converter), and feed quantity of seed corn clusters (controlled by the linear speed of the scraper conveyor).

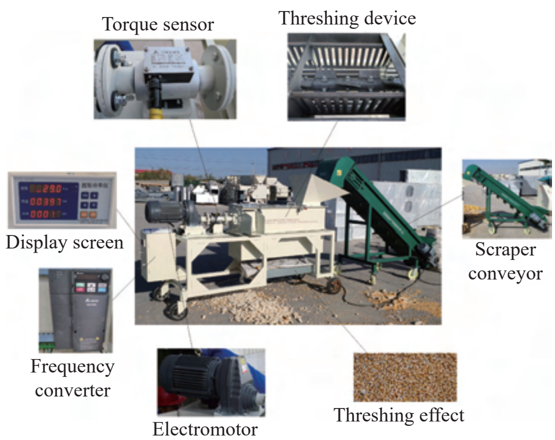
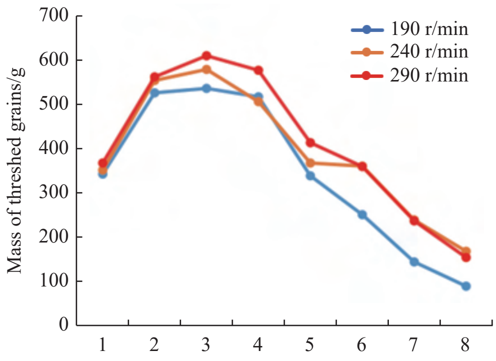


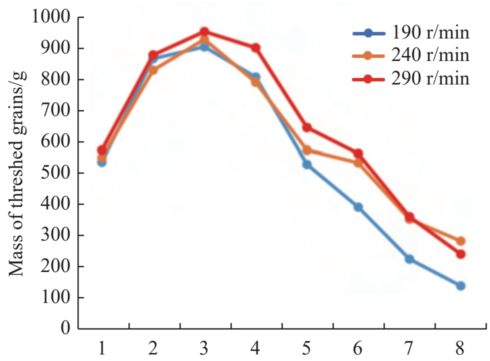
Figure 9 Test on working performance of the seed corn threshing testbed with variable diameter and spacing

Working performance test results of the testbed of seed corn with variable diameter and spacing showed that, when the rotating speed of the threshing axis was 190-290 r/min, feed quantity was 1.80-3.80 kg/s, the damage rate of seed corn was 0.32%-0.63%, threshing rate was 99.20%-99.82%, and content impurity rate was 4.23%-5.86%. All the related test indexes could meet the requirements in design and actual operation.

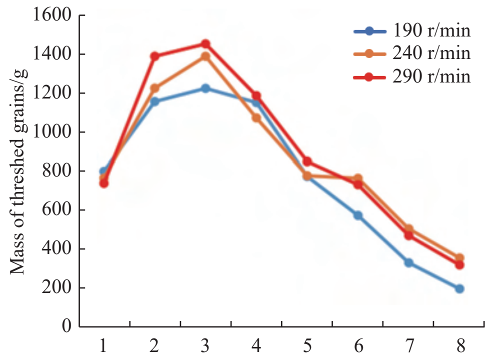
During the test, the material box at the bottom of the threshing device receives the threshed materials in axial distribution in the threshing device and weighs the materials, then the distribution law of corn grains along the axial direction of the threshing device under different feed quantities, and different rotating speed of the threshing axis was obtained, as shown in Figure 10.



a. With feed quantity 1.8 kg/s, mass distribution of threshed grains in the axial direction



b. With feed quantity 2.8 kg/s, mass distribution of threshed grains in the axial direction



c. With feed quantity 3.8 kg/s, mass distribution of threshed grains in the axial direction

Figure 10 Mass distribution of threshing seed corn grains with different feed quantities

It can be known from Figure 10 that, the mass of threshed grains at different levels of rotating speed of the threshing device along the axial direction experienced an increase then a decrease, while the variation tendency with different feed quantities was basically consistent. The mass of threshed corn grains increased quickly in the 1st section, and reached peak value within the 2nd and 3rd sections, then gradually reduced within the 4th and 6th sections, in the 7th and 8th sections, the mass of grains was very low. This distribution law of threshed grains is conducive to reducing the entrainment loss of the seed corn testbed with variable diameter and spacing.

For the same feed quantity, with the constant increase of the rotating speed of the threshing device with variable diameter and spacing, total mass of the threshed seed corn grains also gradually increased, thus reducing the un-threshing rate. It can be obtained from Figure 10 that, the peak value of mass of threshed grains presented a tendency of shifting backwards along the axial direction. The reason is that, with the increase of the rotating speed of the threshing device with variable diameter and spacing, the linear velocity in threshing also increased, elevating the backward threshing and conveying speed of the material flow, including seed corn clusters and grains, and the peak value of mass of corn grains will also shift backwards along the axial direction of the cylinder.

6 Conclusions

1) In order to further reduce the damage rate in threshing of seed corn, a seed corn threshing testbed with variable diameter and spacing was established to realize adjustment of feed quantity, rotating speed of the threshing axis and threshing spacing between centers of threshing units. Through analysis on the modal vibration characteristics of the threshing axis with variable diameter and spacing, the first 8 orders of natural frequencies were among 201.12-1640.20 Hz, with corresponding vibration amplitude in 5.86-27.04 mm. The modes of vibration were mainly twisting, swinging and bending. Test results showed that, the structural design of the threshing axis was reasonable and could achieve effective threshing and conveying effect.

2) The EDEM software was applied to perform discrete element simulation analysis on the seed corn threshing and

conveying process with variable diameter and spacing. Under the condition of different feed quantities, different rotating speed of the thresher, the moving speed of corn clusters and contact force among clusters were measured through simulation in the threshing bin, and the working characteristics of the threshing testbed for low-damage and dynamic threshing and conveying of seed corn with variable diameter and spacing were further revealed.

3) Working performance test results of the testbed of seed corn with variable diameter and spacing showed that, when the rotating speed of the threshing axis was 190-290 r/min, feed quantity was 1.80-3.80 kg/s, the damage rate of seed corn was 0.32%-0.63%, threshing rate was 99.20%-99.82%, and content impurity rate was 4.23%-5.86%. At the same time, the mass of threshed seed corn grains first increased and then decreased along the axial direction under different levels of rotating speed, showing consistent tendency with different feed quantities. The test indexes met the standard requirements of the state and the industry and test results satisfied the actual operation of the seed corn threshers.

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