OPTIMISED DESIGN AND SIMULATION ANALYSIS OF LONGITUDINAL FLOW CORN CONE THRESHING DEVICE
/
纵轴流玉米锥形脱粒装置优化设计与仿真分析

Jinliang GONG[1,2*], Zengjia LUO[3], Yanfei ZHANG[3*]

[1] Collaborative Innovation Center for Shandong's Main crop Production Equipment and Mechanization, Qingdao, Shandong, 266109, China

[2] School of Mechanical Engineering, Shandong University of Technology, Zibo, Shandong, 255000, China

[3] School of Agricultural Engineering and Food Science, Shandong University of Technology, Zibo, Shandong, 255000, China

Tel: +86 18265338441; E-mail: gjlwing@sdut.edu.cn; 1392076@sina.com

DOI: https://doi.org/10.35633/inmateh-73-05

Keywords: *corn harvester; conical threshing drum; threshing concave plate; simulation test*

ABSTRACT

Aiming at the high crushing rate and impurity rate of corn kernel machine harvesting in the Huanghuaihai region, a longitudinal flow conical variable pitch threshing device is designed, which adopts the combined threshing element of "plate teeth + ribs" and the combined threshing concave plate of "leftward round tube type + vertical round tube type". The cob model was established, and the force analysis of the cob threshing process was carried out, and the type of threshing drum and the installation angle of the threshing concave plate round tube were determined as the main influencing factors, and the collision force on the corn cob was taken as the test index. Using EDEM discrete element simulation software, simulation tests were carried out on different types of threshing drums and threshing concave plates with different installation angles of round tubes with corn cobs, and the better threshing method was finally determined: a conical threshing drum at a drum speed of 450 r/min, and a combination of left-facing round-tube-type + vertical round-tube-type threshing concave plates with an installation angle of 10° (front-sparse and back-dense type) were used. Compared with the vertical circular tube type threshing concave plate, the corn cob contact force decreased from 313.5 N to 247.3 N, which was optimal for threshing in the range allowed by the corn kernel destructive force.

摘要

针对黄淮海地区玉米籽粒机收时破碎率和含杂率高等问题，设计了一种纵轴流锥形变螺距脱粒装置，采用"板齿+纹杆"的组合式脱粒元件以及"左向圆管型+垂直圆管型"的组合式脱粒凹板。建立了果穗模型并对果穗脱粒过程进行受力分析，确定了以脱粒滚筒类型和脱粒凹板圆管安装角度为主要影响因素，以玉米果穗受到的碰撞力为试验指标，利用EDEM 离散元仿真软件，分别对不同类型的脱粒滚筒和不同圆管安装角度的脱粒凹板与玉米果穗进行仿真试验，最终确定了较优的脱粒方式：在滚筒转速为450r/min 下，采用锥形脱粒滚筒，安装角度为10°的左向圆管型+垂直圆管型组合式脱粒凹板（前疏后密型）。与垂直圆管型脱粒凹板相比，玉米果穗接触力由 313.5N 下降到 247.3N，在玉米籽粒破坏力允许的范围脱粒效果最优。

INTRODUCTION

With the continuous improvement of the level of mechanized corn harvesting, corn harvester types and functions are becoming more and more abundant. The Huanghuaihai region is one of China's five major corn planting areas *(Wang et al., 2018)*, with the corn sowing area accounting for more than 30% of the national corn area, but cob machine harvesting accounts for 95.2% while seed machine harvesting accounts for only 4.8%. Cob harvesting mainly involves picking and peeling, while kernel harvesting can be completed in one go, including picking, peeling, threshing, cleaning, and collection of work *(Cattaneo et al., 2021)*. With time-saving, increased harvesting efficiency, and lower harvesting costs, corn kernel harvesting is more in line with the direction of the overall process of mechanization development *(Cui et al., 2019)*. The issue of high kernel breakage and impurity content occurs during higher moisture content corn harvesting, which has become a key issue to be addressed in corn kernel harvesting in the Huanghuaihai region.

One of the key components of a corn kernel harvester is the threshing device, and differences in threshing device performance have a significant impact on kernel breakage (*Steponavičius* et al., *2018*). Most experts and scholars at home and abroad research from the crushing mechanism of corn kernels and mechanical structure optimization. For example, *Vlădut et al., (2022),* rounding of the angular portion of the gridded concave plate ensures threshing quality.

Khawaja et al., (2022), explored the mechanism of corn kernel breakage by studying the forces on corn inside the threshing device through DEM software. *Aneliak et al. (2023),* determined the threshing efficiency by studying the material movement of alfalfa in a threshing unit. *Hou et al. (2023)*, improved the threshing form and threshing elements, and the threshing efficiency was greatly improved. *Deng et al., (2023),* designed a high moisture content corn threshing device, determined the optimal operating parameters, the effect was more satisfactory. *Cujbescu et al., (2021),* achieved low-loss threshing by investigating the effect of threshing device length on threshing quality. *Geng et al., (2020),* analyzed the collision contact between the flexible spike tooth and the cob, and designed the flexible spike tooth with a reduction in the rigidity of the impact. EDEM is commonly used in discrete element simulation tests, and the standardization of corn cob model affects the accuracy of simulation results. Due to the different morphology of the cob and the lack of adhesion on the surface, the corn cob model was established by SolidWorks 3D modeling software and imported into EDEM software, and the model was filled by the sphere combination method, and the number of filled balls was 24 *(Yan et al., 2020; Wang et al., 2023).* The leftward round tube type threshing concave plate can reduce the collision force on the corn cob. In the past, the installation angle of the round tube of the threshing concave plate was less studied, and the agricultural machinery design manual mentioned that the installation angle of the round steel tube should not be too large, and excessive installation angle of the round steel tube may lead to blockage of corn cobs in the threshing drum. *(Editor-in-chief of China Academy of Agricultural Machinery, 2007).*

Therefore, in order to solve the problems of kernel breakage rate and high impurity rate in the process of corn kernel harvesting in the Huanghuaihai region, this paper designs a conical threshing device, which adopts the combined threshing element of "plate teeth + ribs" and the combined threshing concave plate of "leftward round tube type + straight round tube type". It verifies the mechanical properties of the threshing device through simulation tests, so as to provide reference for the research of longitudinal flow corn conical threshing devices.

MATERIALS AND METHODS

Structure

The overall structure of corn conical variable pitch threshing device is shown in Fig. 1, which mainly consists of a feeding hopper, screw blade, threshing drum, plate teeth, D-type ribs, cover plate, threshing concave plate, separating concave plate, and debris deflector plate. The support frame fixes the upper cover plate and the segmented combined threshing concave plate together to form the threshing chamber. Inside the device, there are plate-tooth threshing elements fixed on the circumferential surface of the first half of the threshing drum; in order to offset the movement of the core axial side during threshing as well as the drum's imbalance, the latter half of the drum adopts D-type grain rods arranged alternately in the left and right grain directions. The threshed corn kernels shaft are discharged at the tail end through the debris deflector.

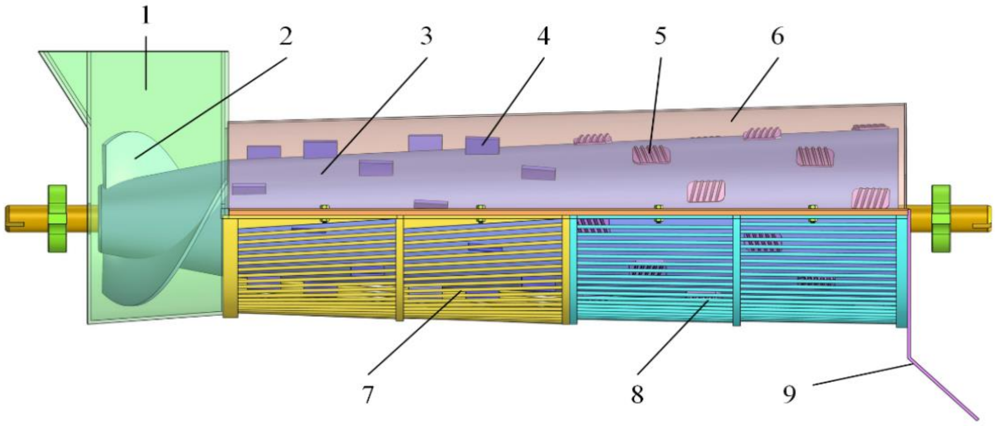


Fig. 1 - Structural diagram of variable pitch corn threshing device

1.feed hopper; 2.spiral blade; 3.threshing drum; 4.plate teeth; 5.D-type ribs; 6.cover plate; 7.threshing concave plate; 8.separation concave plate; 9. discharge deflector plate

Working Principle

The conical variable pitch threshing unit mainly consists of four stages such as feeding, threshing, separating and discharging as shown in Fig. 2.

During operation, the power system drives the input shaft of the conical drum, which in turn makes the threshing drum rotate at high speed; when the corn cob reaches the spiral blade through the feeding hopper, the cob enters the threshing chamber through the thrust effect of the spiral blade to complete the cob feeding process. The spiral arrangement of plate teeth with axial thrust effect, the cob along the axial movement, by the impact of the plate teeth, collision and threshing concave plate extrusion, in the plate teeth and threshing concave plate under the joint action of the part of the cob on the grain is gradually removed. In the second half of the drum, as the diameter of the cob becomes smaller, the circular tube gap of the concave plate decreases, the cob is rubbed under the action of the ripple bar, the cob that has not been threshed continues to be threshed, the corn kernels are separated from the cob through the circular tube gap of the concave plate. After the completion of the threshing, the corn kernel shaft is discharged through the end of the discharging port, and the whole process of threshing is completed.

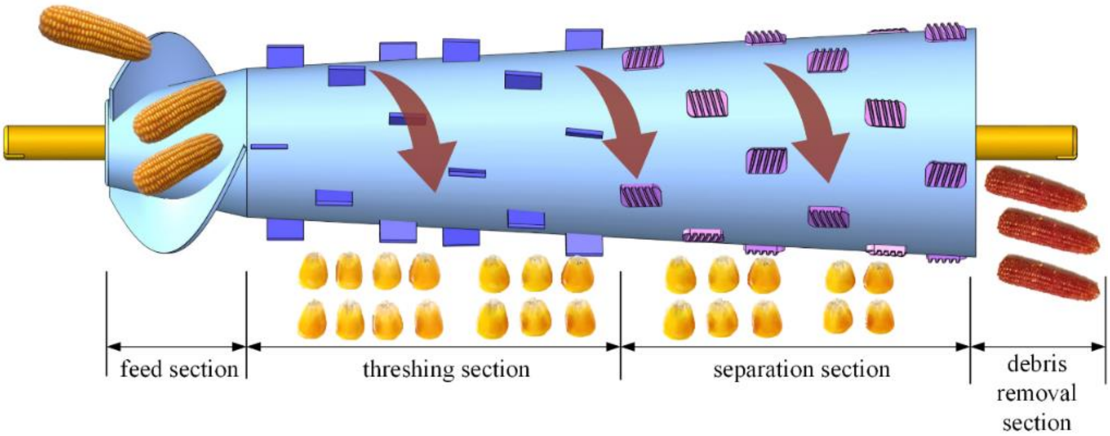


Fig. 2 - Hematic working diagram of the conical variable pitch threshing device

Determination of key parameters

Determination of the parameters of the conical threshing drum

The length of the drum has a significant impact on the threshing quality. The longer the drum, the greater the quality of the whole machine and the working load, and the corn kernels and corn cobs are seriously broken. The threshing drum length is calculated as:

$$L \geqslant q / q_0 \tag{1}$$

In the formula, L - roller length, m; q - threshing device feeding volume, kg/s; q_0 - unit length of the drum can withstand the feeding volume, in the corn harvester to take the value of 3～4 kg/(s·m).

To feed 6 kg/s into the (1) formula can be obtained, the longitudinal axial flow conical threshing drum length *L* value range of 1.5 to 2 m. In order to ensure the quality of threshing under the premise of consideration of the machine power consumption and the weight of the relationship between the length of the drum in this paper will take the value of 1.6 m.

When corn cobs enter the drum, the impact force on the plate teeth is relatively large. Therefore, the threshing drum adopts a conical design with a "small diameter at the front and large diameter at the rear". As the diameter decreases towards the front end, the linear velocity of the plate teeth also decreases. This means that the impact force on the cobs during the feeding process is reduced, which helps to minimize grain breakage. *(Wang et al., 2021)*.

The formula for calculating the linear velocity is as follows:

$$D = d_a + 2h_t \tag{2}$$

$$v = \frac{\pi D n}{60} \tag{3}$$

where D -- the diameter of the root circle of the drum teeth, mm; d_a -the diameter of the drum at point a, mm; h_t - the height of the threshing element, the plate teeth are taken as 50 mm, and the ribs are taken as 30 mm.

According to the new edition of agricultural mechanics, the recommended conical roller diameter for the big end is generally 450～550 mm, and the diameter for the small end is 350～450 mm *(Geng, 2011)*, the small end of the diameter of this paper takes 360 mm, roller cone angle of 6°, the big end of the diameter is 528 mm.

Determination of threshing element spacing

The speed of movement of corn cobs in the drum affects the rate of threshing. When the cobs are just fed into the threshing room, cobs between the individual density is larger, the seeds are arranged more densely, and threshing is more difficult *(Li et al., 2017)*. At this point, it is necessary to reduce the speed of axial movement of the cob within the drum as a means of increasing the number of contacts of the threshing element with the corn cob. The combined threshing element adopts the arrangement of equiangular conical spirals with gradually increasing pitch, effectively extending the threshing time and the number of threshing actions. With the shedding of corn kernels, the density of the material gradually decreases, and the pitch increases to aid material flow. That is, the use of small load, multi-circulation threshing method, effectively reducing the kernel breakage.

The parametric equations of the equiangular conic helix are as follows:

$$\begin{cases} x = ce^{m_a t} \sin\zeta \cos t \\ y = ce^{m_a t} \sin\zeta \sin t \\ z = ce^{m_a t} \cos\zeta \end{cases} \tag{4}$$

In the formula, c - the distance of the start of the helix from the top of the cone; ζ - the half cone angle of the threshing drum, 3°; t - the angle parameter (taking the value $2k\pi$, $k \geq 0$); m_a are constant values.

The radius of the helix is given by Eq.(4):

$$\rho = \sqrt{x^2 + y^2} = ce^{m_a t} \sin\zeta \tag{5}$$

The helix pitch is:

$$\rho = ce^{4\pi m_a} \tag{6}$$

Then the kth pitch is:

$$L_k = Z_k - Z_{k-1} = c\left[e^{2m_a k\pi} - e^{2m_a(k-1)\pi}\right]\cos\zeta \tag{7}$$

From equation (4), $R_{\min} = c\sin\zeta = 180$ mm, the calculation gives c = 3439.32.

The average length of corn cob in Huanghuaihai region is about 210 mm *(Chen et al., 2020)*, and the initial threshing spacing of the selected threshing plate teeth is 2/3 of the cob length, so L_1=140 mm, so it can be obtained from equation (7):

$$L_1 = Z_1 - Z_0 = c\left(e^{2\pi m_1} - 1\right)\cos\zeta = 140\,\text{mm}$$

The calculation gives: m_1 = 0.006359.

The maximum radius of the drum is known to be R_5=264 mm, which can be obtained by substituting into equation (4): $x = 180e^{m_4 8\pi}\cos 8\pi = 264$, calculated as m_4 = 0.019196.

The whole section of this design is divided into 4 pitches, and m_1 and m_4 are linearly interpolated and calculated to obtain m_2 = 0.010638 and m_3 = 0.014917. Substituting $m_1 \sim m_4$ into equation (7) gives the pitch: L_1=140 mm, L_2=253 mm, L_3=406 mm, L_4=632 mm.

Parameterization of segmented combined concave plates

In threshing, the separation of seeds is accomplished by the joint action of the drum and the concave plate, and most of the conventional concave plate adopt the grid-type concave plate, which is easy for the seeds to collide with the top of the cross partition plate, resulting in serious seed crushing. For this reason, the concave plate designed in this paper adopts a round tube-type structure, when compared with the angular grid-type concave plate, the round tube-type concave plate with a rounded surface is favorable to reduce the impact on the cob and reduce the seed damage.

As shown in Fig. 3(a) and (b), segmented combination threshing concave plates are arranged in a leftward circular tube type and a vertical circular tube type. The diameter of round pipe is 16 mm Q235 structural steel with superior material performance. The welding direction of the round steel pipe in the leftward round pipe type concave plate deviates from the axis of the concave plate by a certain angle; the welding direction of the round steel pipe in the vertical round pipe type concave plate is perpendicular to the bracket of the concave plate.

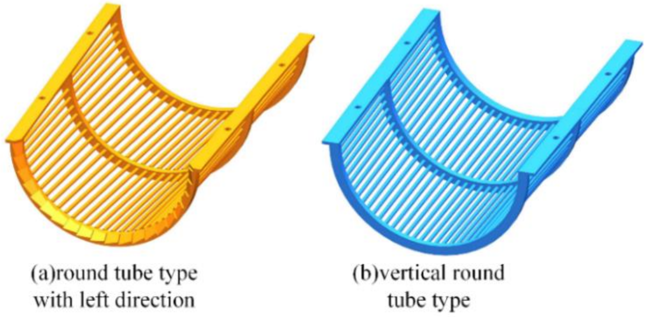


Fig. 3 - Structure of the concave plate for two mounting orientations

In this paper, in order to verify the effect of the concave plate of two installation directions on the collision strength of the cob, the force analysis is carried out between the round tube and the cob of two installation directions, as shown in Figs. 4 and 5.

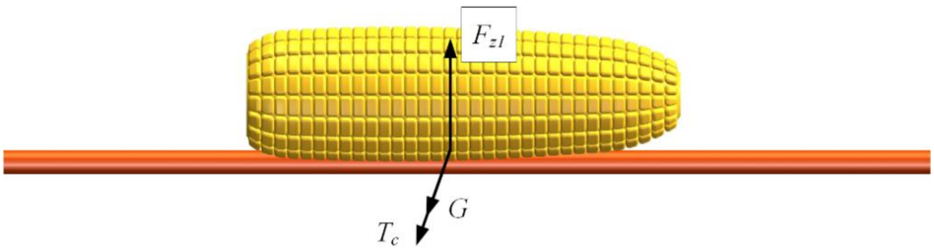


Fig. 4 - Front view of the force on the fruit cob and the vertical circular tube type concave plate

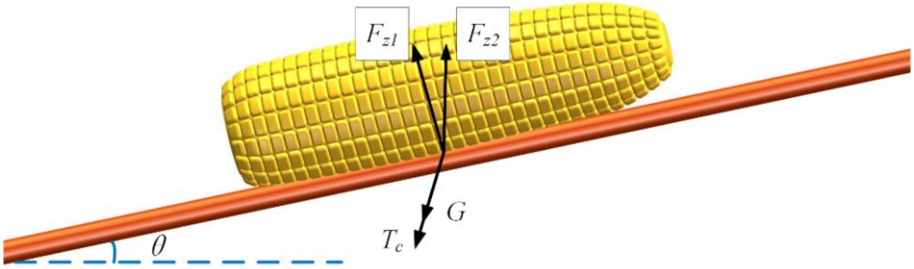


Fig. 5 - Front view of the cob and the leftward circular tube type concave plate under force

As can be seen from Figs. 4 and 5, during the contact between the cob and the circular steel tube, the cob force calculation formula can be expressed as respectively:

$$F_{z1} = \left(G + T_c\right)\cos\frac{\beta}{2} \tag{8}$$

$$F_{z2} = \left(G + T_c\right)\cos\frac{\beta}{2}\cos\theta \tag{9}$$

In the formula, F_{z1} is the collision reaction force of the cob by the vertical type round steel tube, N; F_{z2} - the collision reaction force of the cob by the leftward type round steel tube, N; T_c – the collision force of the cob on the round steel tube, N; β – the cone angle of the threshing drum, 6°; θ – the angle of the round steel tube deviating from the axis to the left.

From equations (8) and (9):

$$F_{z1} - F_{z2} = \left(G + T_c\right)\cos\frac{\beta}{2}\left(1 - \cos\theta\right) > 0 \tag{10}$$

From equation (10), $F_{z1} > F_{z2}$. Under the condition of a certain threshing drum speed, the collision force experienced by the cob is constant. At this point, the collision reaction force experienced by the cob in the vertical round steel tube is greater than that in the left round steel tube.

This confirms that the left circular tube type threshing concave plate effectively reduces the collision force experienced by the cob. Therefore, the use of a left-oriented threshing concave plate in the first half of the threshing drum is conducive to reducing seed breakage.

In the second half of the threshing drum, where the density and diameter of the cob are smaller, a vertical circular tube-type concave plate with a smaller gap is used in conjunction with the ripple-type threshing element. It relies on the rubbing force for flexible threshing, thereby facilitating the separation of seeds and grains.

RESULTS

EDEM-based simulation test and analysis

Modeling of corn cob collisions

The material parameters and material contact parameters of the corn cob and threshing unit are shown in Tables 1 and 2.

Table 1

Model material parameters

Parameter name	**Corn cob**	**Threshing device**
Poisson's ratio	0.4	0.3
Shear modulus [Pa]	1.30×10^{8}	3.5×10^{10}
Densities[kg·m^{-3}]	1197	7850

Table 2

Model contact parameters

Parameter name	**Between the ears of fruit**	**Ears of fruit with steel**
Crash recovery factor	0.182	0.659
Static friction factor	0.44	0.326
Kinetic friction factor	0.008	0.02

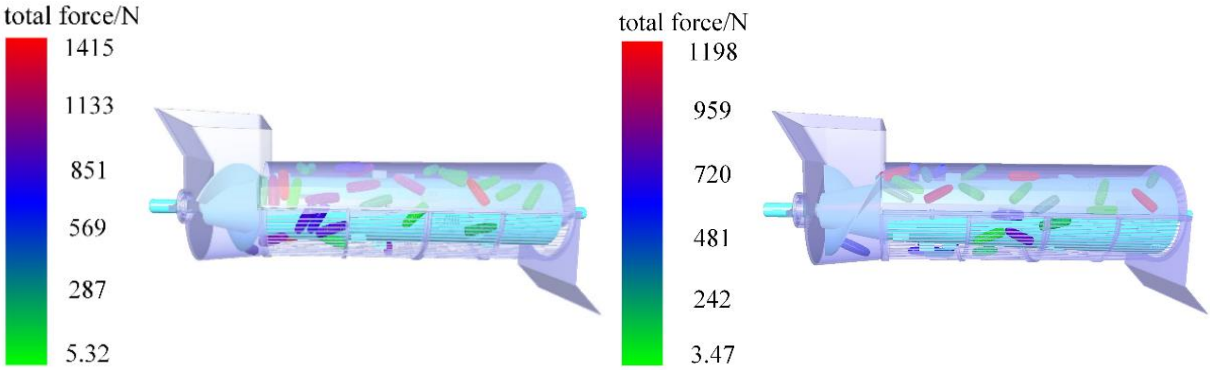
Threshing drum simulation test and analysis

Threshing drum simulation test method

Simulation tests allow for simulating the threshing process of the cob in the threshing chamber. Using the type of threshing drum as an influencing factor, the study was carried out on cylindrical and conical drums with plate teeth and ripple bar matching threshing elements, and the concave plate types were all of the vertical round tube type. In the EDEM software, the pellet plant was set up at the feeding port with a pellet mass of about 0.25 kg each and a generation rate of 24 per second, so the feed rate was about 6 kg/s. The mechanical simulation test of corn cob was carried out under the conditions of roller speed of 400 r/min and simulation time of 10s.

Analysis of threshing drum simulation test results

The force cloud maps of corn cob under different types of threshing drums were output by EDEM post-processing module, as shown in Fig. 6(a) and (b).



(a) cylindrical threshing drums (b) conical threshing drum, cone angle 6°

Fig. 6 - Cloud diagram of cob force process under different threshing drums

As seen in the cloud view of the force process on the corn cob in Fig. 6, close to half of the corn cobs were blue or red inside the cylindrical threshing device. However, the number of dark-colored cobs was lower in the conical threshing unit compared to the former, indicating that the conical threshing unit reduces the impacts from the threshing elements under the same constraints and employs a "small load, many cycles" threshing method.

Through the EDEM software post-processing module of the total force exerted on the corn cob, the data were summarized, and the average contact force between the threshing element and the cob was obtained through calculation and imported into the data visualization software Origin for data plotting, as shown in Fig.7.

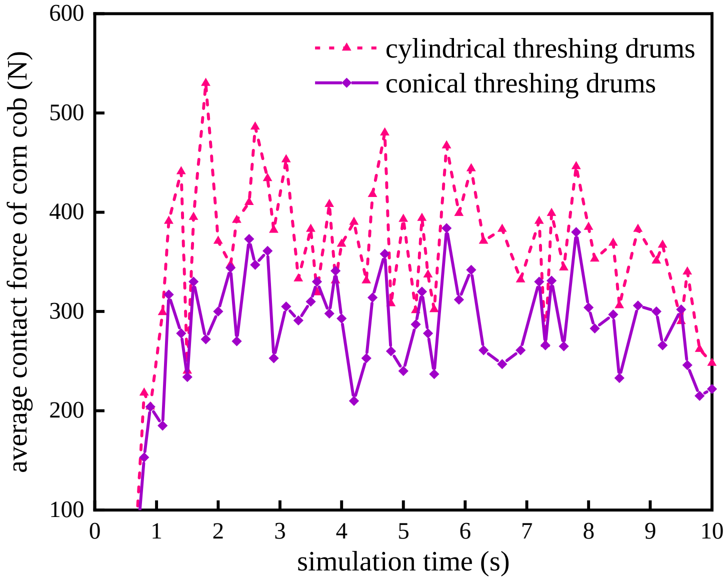


Fig. 7 - Line graph of force on corn cob at different threshing drums

As can be seen in Fig. 7, from 0 to 0.7 s, the cob produced by the pellet plant enters the threshing chamber through the spiral blades. From 0.7 to 6.5 s, the cob contacts the plate tooth threshing element. During this stage, each sudden change in cob force means a collision between the cob and the cob, and the cob and the threshing element, but the cob is subjected to the contact force of the cylindrical threshing drum as a whole more than that subjected to the cone-shaped threshing drum's Contact force. From Fig. 7 conical threshing drum line graph can be seen, the cob in the conical threshing drum in the first half of the intensive degree of force mutation compared to the second half of the more intensive, indicating that the use of variable pitch structure arrangement of the threshing element helps to increase the number of times and prolong the time of threshing; in the second half of Fig. 7, along with the shedding of grains, the radius of the cob decreases, cob force mutation number of times to reduce the number of cob collision, so cob collision number is reduced. Thus, the rationality of using a ripple type threshing element in the latter half of the threshing drum and a larger pitch structure was confirmed, and all subsequent studies used conical variable pitch threshing drums.

Simulation test and analysis of threshing concave plate

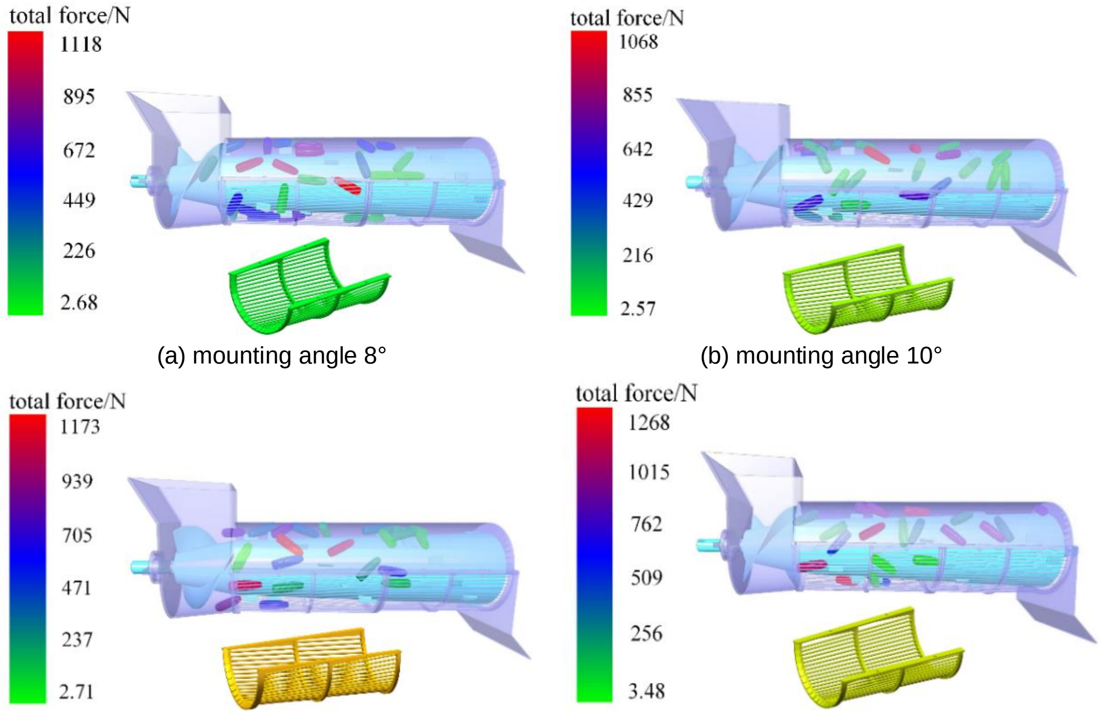
Threshing concave plate simulation test method

In this subsection, by using EDEM simulation software, the circular steel pipe installation angle is selected as the influencing factor, and the circular steel pipe installation angles of the leftward circular pipe-type concave plate are 8°, 10°, and 12°, respectively, and these are compared with the vertical circular pipe-type concave plate. Conical threshing drums were used for all threshing units, and drum speeds of 250, 350, 450, and 550 r/min were selected.

Analysis of threshing concave plate simulation test results

The force cloud diagrams of corn cobs under different threshing concave plates were output by EDEM post-processing module, as shown in Fig. 8(a) to (d).

Within the threshing device under the leftward circular tube-type threshing concave plate, as can be seen from the cloud diagram of the force process of the corn cob in Fig. 8(b), the corn cob has a darker portion of the corn cob than in Fig. 8(a) and Fig. 8(c); and for the threshing device with a vertically circular tube-type threshing concave plate in Fig. 8(d), the corn cob has a darker portion of the corn cob than in the first three.



(a) mounting angle 8° (b) mounting angle 10°

(c) mounting angle 12° (d)vertical round tube type

Fig. 8 - Cloud diagram of the force process of the cob under the threshing concave plate with different installation angles of the round tube

The average contact force applied to the corn cob was calculated by the post-processing module and the results are shown in Table 3.

Table 3

Simulation results of threshing concave plate with different round tube installation angles [unit: N]

Drum speed [r/min]	Threshing concave plate round tube installation angle			
	mounting angle 8°	mounting angle 10°	mounting angle 12°	vertical round tube type
250	131.6	128.3	153.1	186.5
350	163.7	169.2	207.8	235.4
450	256.8	247.3	276.2	313.5
550	365.4	358.6	382.4	423.7

The data were plotted in Table 3 by Origin plotting software to obtain the change curve of corn cob contact force under different drum speeds and round tube installation angles, as shown in Fig. 9.

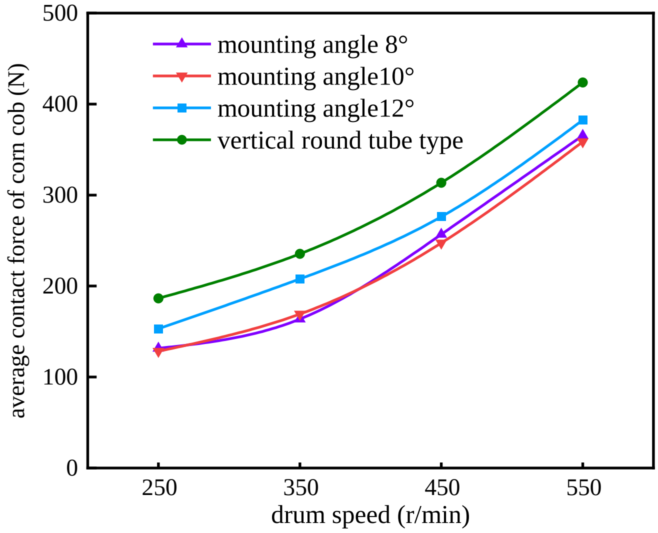


Fig. 9 - Variation of contact force of corn cob at different round tube mounting angles

As can be seen from Fig. 9, with the gradual increase in drum speed, the average contact force on the corn cob is also increasing to varying degrees; at the same speed, the contact force on the cob is smaller in the former compared to the three installation angles of the leftward circular tube-type threshing concave plate and the vertical circular tube-type threshing concave plate, confirming that the leftward circular tube-type threshing concave plate can reduce the contact force on the corn cob.

When the threshing drum is at a lower rotational speed, the contact force of the vertical round tube-type threshing concave plate on the corn cob is greater than that of the leftward round tube-type threshing concave plate; the contact force on the corn cob under the round steel tube mounted at an angle of 8° and 10° threshing concave plate is approximately the same. When the threshing drum is at a higher speed, the contact force on the corn cob under the threshing concave plate at an angle of 8° for the installation of the round steel tube is greater than that on the corn cob under the threshing concave plate at an angle of 10° for the installation of the round steel tube; the corn cob under the threshing concave plate at an angle of 12° for the installation of the round steel tube and the vertical round tube is subjected to a larger contact force, and the kernels are easy to be broken. From the perspective of reducing the collision force, seed crushing rate, comprehensive analysis of the data in Table 3 and Figure 9 curve, select the round steel pipe installation angle of 10 ° threshing concave plate, and the simulation test results are more satisfactory.

CONCLUSIONS

A conical threshing unit was designed using SolidWorks software with combined threshing elements and the threshing elements were arranged according to variable pitch. A combined threshing concave plate was used and the main structure and parameters were determined.

Using EDEM software, simulation tests were carried out on the type of drum and the installation angle of the concave plate circular steel pipe, and the conical drum was better than the cylindrical drum; the installation angle of the concave plate circular steel pipe was optimal at 10°, which was conducive to reducing the collision force of the seeds.

ACKNOWLEDGEMENT

This work was funded by the Key Research and Development Program of Shandong Province (Major Innovative Project in Science and Technology) (2020CXGC010804), Shandong Provincial Natural Science Foundation (ZR2021MC026), the Collaborative Innovation Center for Shandong's Main crop Production Equipment and Mechanization.

REFERENCES

[1] Cattaneo A., Sanchez M V., Torero M., et al. (2021). Reducing food loss and waste: Five challenges for policy and research [J]. *Food Policy,* Vol. 98, pp.101974.

[2] Chen R.J., Zhang J., Liu X.Z., et al. (2020). Research on breeding technology of new maize varieties in Huanghuaihai [J] (黄淮海玉米新品种育种技术研究). *China Seed Industry*, Vol. (02), pp. 22-24.

[3] Cui T., Fan C.L., Zhang D.X., et al. (2019). Analysis of research progress of mechanized corn harvesting technology [J] (玉米机械化收获技术研究进展分析). *Journal of Agricultural Machinery*, Vol. 50(12), pp.1-13.

[4] Cujbescu D., Gageanu I., Iosif A. (2021). Mathematical modeling of ear grain separation process depending on the length of the axial flow threshing apparatus. *INMATEH - Agricultural Engineering*, Vol. 65(3), pp. 101-110.

[5] Deng Y.J., Zhang G.H., Zhang A.Q., et al. (2023). Experimental analysis of threshing maize seeds with high moisture content. *INMATEH - Agricultural Engineering*, Vol. 69(1), pp. 131-144.

[6] Geng D.Y., Tan D.L., Yu X.R., et al. (2020). Design and test of threshing element of corn flexible threshing drum [J] (玉米柔性脱粒滚筒脱粒元件设计与试验). *Journal of Jilin University (Engineering Edition)*, Vol. 50(05), pp.1923-1933.

[7] Geng D.Y. (2011). *New Agricultural Mechanics* [M] (新编农业机械学). Beijing: National Defense Industry Press.

[8] Hou Y.X., Shang S.Q., Li X., et al. (2023). Discrete element method (EDEM) simulation and parameter optimization: Design and testing of a low-loss and high-efficiency corn threshing device. *INMATEH - Agricultural Engineering*, Vol. 71(3), pp. 194-204.

[9] Khawaja A.N., Khan Z.M. (2022). DEM study on threshing performance of "compression-oscillation" thresher [J]. *Computational Particle Mechanic*s, Vol. 9(6), pp. 1233-1248.

[10] Li X.P., Ma L., Geng L.X., et al. (2017). Performance test and parameter optimization of corn seed bionic thresher [J] (玉米种子仿生脱粒机性能试验与参数优化). *Journal of Agricultural Engineering*, Vol. 33(05), pp. 62-69.
[11] Aneliak M., Kuzmych A., Stepanenko S., Lysaniuk V. (2023). Study of the process of threshing leguminous grass seeds with a drum-type threshing device. *INMATEH - Agricultural Engineering, Vol.* 71(3), pp. 83-92. https://doi.org/10.35633/inmateh-71-06
[12] Steponavičius D., Pužauskas E., Špokas L., Jotautienė E., Kemzūraitė A., Petkevičius S. (2018). Concave design for high-moisture corn ear threshing [J]. *Mechanics, Vol.* 24(1), pp.80-91.
[13] Vladut N.V., Biris S.Ş., Cardei P. et al. (2022). Contributions to the Mathematical Modeling of the Threshing and Separation Process in An Axial Flow Combine [J]. *Agriculture,* Vol. 12(10), pp. 1520.
[14] Wang Y.G., Zhang G.H., Zhang H., et al. (2018). Analysis of the current situation of summer corn harvesting in the Huanghuaihai region [J] (黄淮海地区夏玉米收获现状分析). *Chinese Journal of Agricultural Mechanical Chemistry*, Vol. 39(11), pp. 112-115.
[15] Wang Z.D., Cui T., Zhang D.X., et al. (2021). Design and test of low-loss variable-diameter threshing drum for corn harvester [J] (玉米收获机低损变径脱粒滚筒设计与试验). *Journal of Agricultural Machinery*, Vol. 52(08), pp. 98-105.
[16] Wang H.B., Fan Z.P., Urantuya, et al. (2023). Parameter calibration of a discrete element model for the simulation of spiral conveying of kneaded corn stover [J] (揉碎玉米秸秆螺旋输送仿真离散元模型参数标定). *China Agricultural Science and Technology Bulletin*, Vol. 25(03), pp.96-106.
[17] Yan B.X., Wu G.W., Fu W.Q., et al. (2020). Research on the influence factors of high seed placement position of corn precision sowing based on EDEM [J] (基于 EDEM 的玉米精播高位投种着床位置影响因素研究). *Journal of Agricultural Machinery*, Vol. 51(S2), pp. 47-54.
[18] ***China Agricultural Machinery Research Institute, ed. (2007). *Agricultural machinery designs manual* [M] (农业机械设计手册 下). Beijing: China Agricultural Science and Technology Press.