DESIGN AND TESTING OF A GAP ADJUSTABLE ELASTIC LOW DAMAGE CORN PICKING HEADER BASED ON ADAMS
/
基于 Adams 的间隙可调弹性低损玉米摘穗割台的设计与试验

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ABSTRACT
To address the high damage rate and impurity content in corn ear picking, this study proposes the design of a gap-adjustable elastic low damage corn picking header. Theoretical analysis of the adaptive gap adjustment mechanism for the picking plate and the flexible picking mechanism will be conducted. Simulation experiments will be performed considering three factors: the stiffness coefficient of the compression spring, the rotational speed of the stalk-pulling roller, and the thickness of the flexible body. The test results indicate that the minimum collision force on the fruit cluster occurs when the stiffness coefficient of the compression spring is 36 N/mm, the rotational speed of the stalk-pulling roller is 700 r/min, and the thickness of the flexible body is 6 mm. When the header tilt angle was 25 degrees and the working speed was 3 km/h, using the stalk roller speed as the experimental variable, the collision force of the gap-adjustable elastic low-damage corn picking header was compared to that of the ordinary plate-type corn picking header. The results indicated that the collision force of the gap-adjustable elastic low-damage corn picking header was reduced by more than 25 % compared to the ordinary plate-type corn picking header.

摘要
为解决玉米割台摘穗损伤率高以及含杂率高的问题，本研究提出设计一台间隙可调弹性低损玉米摘穗割台。对摘穗板间隙自适应调节结构和柔性摘穗机构进行理论分析，在压缩弹簧的刚度系数、拉茎辊转速、柔性体厚度三因素下，进行仿真试验。试验表明，在压缩弹簧刚度系数为 36 N/mm、拉茎辊转速 700 r/min、柔性体厚度为 6 mm 时，果穗碰撞力最小。在割台倾角为 25°，作业速度为 3 km/h 时，以拉茎辊转速为试验变量，将间隙可调弹性低损玉米摘穗割台和普通板式玉米摘穗割台进行果穗碰撞力对比，试验结果表明，弹性低损玉米摘穗割台比普通板式玉米摘穗割台碰撞力减少 25%以上。

INTRODUCTION

Corn is an important grain and economic crop in China. High ear damage rates and high stalk loss rates have always been significant issues during the operation of corn harvesters' headers (*Bu et al., 2016; Cui et al., 2019; Zhang et al., 2021*). In recent years, with the widespread use of corn harvesters, the issue of ear picking loss caused by the header has become increasingly severe (*Chen, 2014; Guo et al., 2018*). Therefore, there is an urgent need to address the ear picking losses caused during the corn header picking process.

The main reason for corn ear damage is that the external force on the kernels exceeds the connecting strength between the kernels and the cob. When corn experiences a forward pulling picking force, it is prone to damage at the bottom of the ear and kernel breakage (*Chen et al., 2021; Yi et al., 2016; Shin et al., 2020*). The primary causes of stalk loss and blockage are the inability of the picking plate to adaptively adjust to the corn plant. Researchers at home and abroad have conducted extensive studies on the mechanisms of kernel damage during corn picking. Chen analyzed the physiological characteristics of corn kernels and found that kernel moisture content is a key factor affecting kernel breakage (*Chen et al., 2009*).

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Tai performed simulation tests on the kinematic and dynamic performance of the corn stalk separation device, corn plant, and ear-picking rollers using ADAMS virtual simulation technology, and developed a method for evaluating both the corn stalk separation and ear-picking performance（*Tai et al., 2020*）. Li measured the number of kernels shed under the impact of three different shapes of punch heads and concluded that the wedge-shaped punch head was most conducive to kernel shedding (*Li et al., 2014*). Zhang Hongmei analyzed the collision process of corn ears and found that picking losses were mainly related to the picking mechanism and materials (*Zhang et al., 2024*). Chen Meizhou through high-speed photography, discovered that ear retention on the picking roller and bouncing were the main causes of secondary damage during picking (*Chen et al., 2017*). He Junlin studied the mechanism and characteristics of ear damage caused by roller-type picking devices and found that roller type and roller gap were important factors affecting ear damage (*He et al., 2006*). Srivastava studied the shear properties of corn under impact loads and found that the shear strength of corn is inversely proportional to moisture content and directly proportional to impact velocity (*Srivastava et al., 1976*).

In terms of measures to reduce corn picking damage, scholars have also conducted extensive research. Fu Qiankun designed a wheel-type rigid-flexible coupling low-damage corn picking header and found that its kernel loss rate was significantly lower than that of the plate-type picking mechanism through comparative experiments (*Fu et al., 2019*). Li Tianyu addressing the issue of high ear damage rates in corn harvesting devices, conducted an in-depth analysis of the shearing mechanism for ear picking and designed a shearing-type ear picking mechanism (*Li et al., 2023*). Luo Huizhong designed a narrow-width low-damage picking header using the principle of elastic buffering to achieve flexible low-damage picking (*Luo et al., 2021*). Geng Duanyang studied the picking mechanism of upright roller-type headers and found that the main causes of picking damage were the picking gap not meeting plant passage requirements, large impact forces during the picking process, and suboptimal ear positions during picking. They optimized the structure and motion parameters of the upright roller (*Geng et al., 2017; Xin, 2020; Zhang et al., 2005; Geng et al., 2017*). Zhang Zhilong designed a comb-type picking unit that reduced ear damage by upward combing picking (*Zhang et al., 2014*). Cheng Xiupei designed an upward pulling ear-picking corn harvesting device based on the principle of top-down ear picking (*Cheng et al., 2016*). Zhu Guangqiang designed a bionic picking device for fresh corn by mimicking the manual ear-picking posture (*Zhu et al., 2023*). The JOHN DEERE company in the United States reduced corn kernel loss by adjusting the hydraulic picking plate parameters in the 708C header. Zhang Zhen identified the factors influencing corn harvesting losses through experimental research and theoretical analysis, and determined the optimal parameter combination for efficient corn ear picking (*Zhang et al., 2021*).

MATERIALS AND METHODS

Structural Design

Through the analysis of the corn ear-picking process, it is found that the impact force on the corn ear is mainly related to the stiffness coefficient and damping coefficient of the ear-picking system. To reduce the stiffness coefficient and increase the damping coefficient of the ear-picking plate, a flexible surface and buffer spring ear-picking mechanism were designed. To reduce the impurity rate of corn stalks, a self-adaptive adjustment device for the gap between the ear-picking plates was designed. As shown in Figure 1, the structural diagram of the gap-adjustable low-damage elastic corn ear-picking header consists of the main frame, gearbox, stalk-pulling roller, gathering chain, transmission device, flexible cantilever ear-picking plate, and ear-picking plate gap-adjusting device.

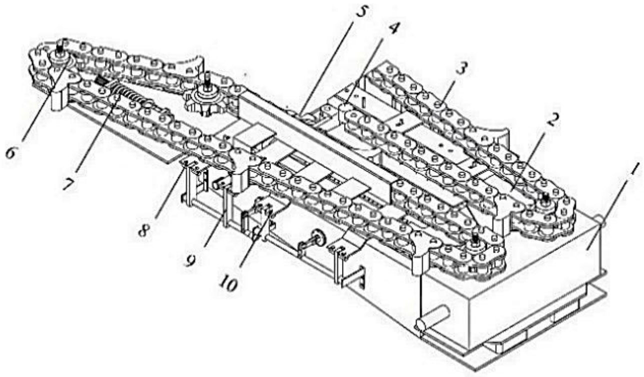


Fig.1 - Structural diagram of the low-damage elastic corn ear-picking header

1. Gearbox; 2. Frame; 3; Gathering chain; 4. Elastic ear-picking device; 5. Stalk-pulling roller; 6. Driven gear; 7. Gathering chain tensioning device; 8. Front ear-picking plate; 9. Ear-picking plate gap-adjusting mechanism; 10. Rear ear-picking plate

Working Principle

Under the combined action of the conical guide section at the front end of the stalk-pulling roller and the gathering chain, the corn stalk enters the gap between the ear-picking plates. Since the initial gap between the designed ear-picking plates is smaller than the diameter of the corn stalk, when the corn stalk enters the gap, the ear-picking plates move to both sides under the squeezing force of the corn stalk, thereby increasing the gap. Under the action of the spring adjustment device, the gap between the ear-picking plates can be adaptively adjusted according to the diameter of the corn stalk. After the corn stalk enters the ear-picking position, the stalk-pulling roller clamps and pulls downwards. The corn ear collides with the ear-picking plate, and under the action of the flexible surface and buffer spring, the kinetic energy of the collision is converted into potential energy of the spring and flexible body and dissipated, reducing the grain loss caused by the collision. When the flexible cantilever ear-picking plate is subjected to the pressure of the corn ear, the ear-picking plate moves downward under the compression of the buffer spring, reducing the gap between the ear-picking plates, increasing the clamping force on the ear stem, making it easier to pick the ear and reducing the collision force on the ear.

Design of the Self-Adaptive Gap Adjustment Device for the Picking board

The designed self-adaptive gap adjustment device for the ear-picking plate can adjust the gap according to the diameter of the corn plant. The self-adaptive gap adjustment system for the ear-picking plate, as shown in Figure 2, mainly consists of the ear-picking plate, spring adjustment device, rotating shaft, rotating plate, and connecting plate.

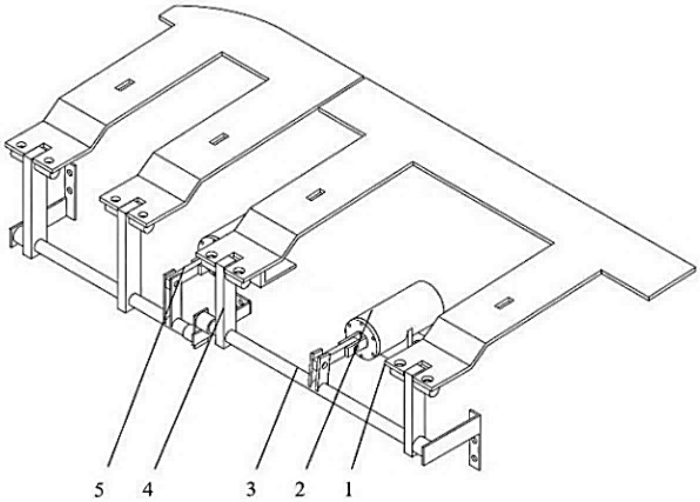


Fig. 2 - Adaptive adjustment system for the gap between heading plates

1. Ear picking plate; 2. Spring adjustment device; 3. Rotating shaft; 4. Rotating plate; 5. Connecting plate

When adjusting the gap of the ear-picking plate, the gap reaches its minimum value under the pre-tightening force of the spring adjustment device and the action of the limit slot. To ensure the consistency of the movement of the ear-picking plate during gap adjustment and to avoid the mechanism from getting stuck during the adjustment process, the self-adaptive adjustment device is designed as a rotating shaft type. To ensure quick and accurate adjustment, the spring is placed vertically with respect to the frame. Therefore, the circular motion of the rotating plate needs to be converted into the linear motion of the spring. A connecting plate is designed between the rotating shaft and the adjustment spring to ensure the uniformity and continuity of spring adjustment. To ensure the adjustment range of the ear-picking plate, a limit slot is set on the ear-picking plate to limit the maximum and minimum adjustment range of the ear-picking plate. Figure 3 shows the movement analysis of the heading plate during the gap adjustment process.

As shown in Figure 3, the adjustment range of the ear-picking plate gap is related to the length *L* of the rotating plate and the rotation angle *α* of the rotating shaft.

$$d = L \sin \alpha \tag{1}$$

where: d - Horizontal adjustment range of the ear-picking plate, mm; L - Length between the two mounting holes of the rotating shaft, L = 70mm; *α* - Rotation angle of the rotating shaft, °.

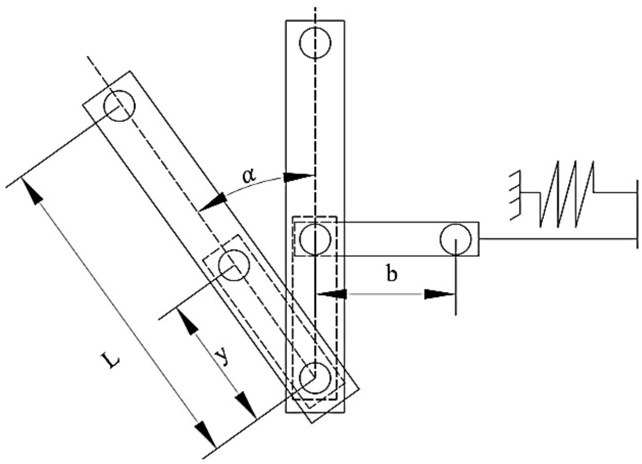


Fig. 3 - Movement analysis diagram of the gap adjustment device for ear picking plates

The adjustment range of the ear-picking plate gap depends on the physical characteristics of the corn ear and the corn plant. By measuring the physical characteristics of the corn ear and the corn plant, the minimum diameter of the larger end of the corn ear is 42.4 mm, and the minimum diameter of the corn plant at the ear-picking position is 19.3 mm. To ensure better working performance, the self-adaptive adjustment range of the ear-picking plate gap is designed to be 18-40 mm. That is, d_{max} = 11 mm, substituting into formula (1), the value of α is 9°.

The stiffness coefficient and length of the spring are key parameters of the design. By analyzing the movement of the ear-picking plate, the compression length of the spring is:

$$x = (y\sin\alpha + b) - \sqrt{b^2 - (y - y\cos\alpha)^2} \tag{2}$$

where: x - Compression amount of the spring, mm; y - Distance from the center of the rotating shaft to the connecting plate hole, mm; b - Length of the connecting plate, mm

Due to the limitation of the installation position, the length of the connection between the rotating shaft and the connecting plate is designed to be 35 mm, and the length of the connecting plate b = 40 mm, resulting in the maximum compression length of the spring being 6.8 mm.

Design of Spring Adjustment Device

The stiffness coefficient of the spring is a crucial parameter affecting the self-adaptive gap adjustment of the picking plates. If the spring stiffness coefficient is too high, it can cause the stalks to break, whereas if it is too low, the picking plates may oscillate and fail to quickly adjust the gap according to the diameter of the corn stalks, resulting in poor gap adjustment performance. Figure 4 shows the structure of the spring adjustment device, which mainly consists of an outer cylinder, a compression spring, and a pull rod. An adjustment slot is provided on the outer cylinder to adjust the pre-tightening force of the spring.

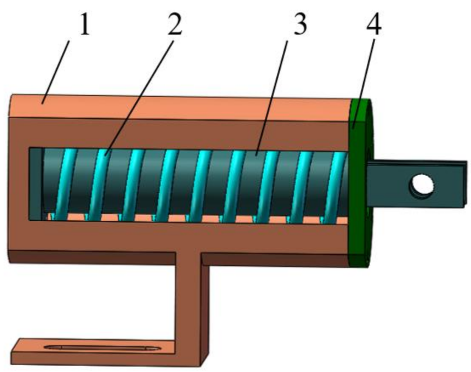


Fig. 4 - Spring adjustment device

1.Outer cylinder; 2. Spring; 3. Tie rod; 4. Outer cylinder cover

During the gap adjustment process, the clamping force of the picking plates on the stalks is shown in Figure 5.

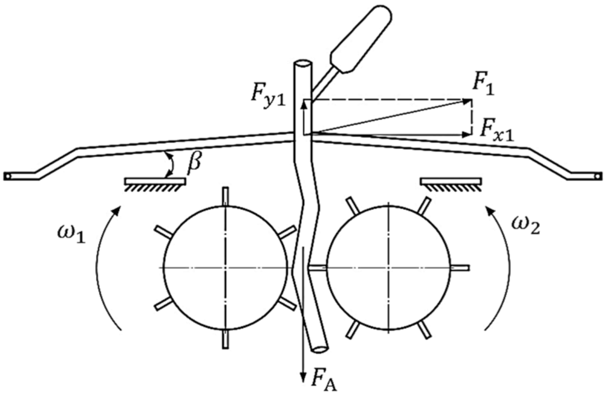


Fig. 5 - Force Diagram of Corn Stalks During Gap Adjustment

β-represents the angle between the picking plate and the bracket;
F_1 - The clamping force of a single picking plate on the stalks, N;
F_A - The stem roller has the maximum force on the corn stalk, N

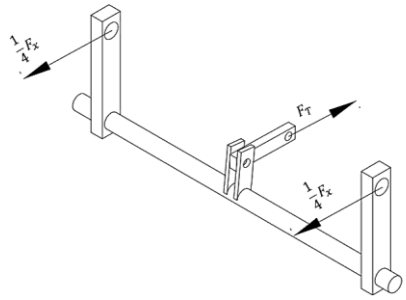


Fig. 6 - Force analysis of lever structure

The forces acting on the corn stalks in the horizontal and vertical directions are:

$$\begin{cases} F_x = 2F_1 \cos\beta \\ F_y = 2F_1 \sin\beta \end{cases} \quad (3)$$

F_x - Sum of forces on corn stalks in the horizontal direction; F_y - Sum of forces on corn stalks in the vertical direction.

To prevent the clamping force of the picking plates from being too high and causing the stalks to break, the following condition must be met:

$$F_x f + F_y < F_L \quad (4)$$

where:

f - the friction coefficient between the picking plate and the corn stalks; F_L-the pulling force required to break the corn stalks, N.

Figure 6 illustrates that the picking plate and the spring adjustment device can be regarded as a lever mechanism, where the two rotating plates on the pivot axis can be seen as lever arms:

$$\frac{1}{2} F_x L = F_T y \quad (5)$$

$$\frac{L}{y} = 2 \quad (6)$$

Sorted out:

$$F_T = F_x < \frac{F_L}{0.22 + \tan\beta} \quad (7)$$

where: F_T - The elastic force of the spring

The corn ear attachment is the weakest part of the corn stalk. Tensile tests on corn plants using an electronic universal testing machine show that when the moisture content of the corn kernels is 30%, the force required to break the stalk at the ear attachment is no less than 300 N. The pulling force for the corn ear stalk ranges from 264 N to 673 N, with an average value of 468.5 N. To ensure that the stalk does not break during ear picking, F_L is taken as 200 N. Substituting this into equation (8):

$$F_T < \frac{200}{0.22 + \tan\beta} \quad (8)$$

Due to installation position constraints, β<10, solving for F_T <500 N. During operation, excessive horizontal clamping force of the picking plates will also affect the pulling speed of the corn plants. Therefore, the spring stiffness coefficient should be as small as possible while ensuring operational effectiveness. The best ear-picking effect is achieved when the corn ear is picked at 1/3 to 1/2 of the pulling section. Hence, the spring stiffness coefficient should be chosen to be moderate.

Design of Flexible Picker Device

When picking ears of corn, the corn ears fall off under the obstruction of the picking plates, which results in significant impact between the ears and the picking plates. Therefore, the picking plates are treated with a flexible material to reduce the direct impact. The picking plates are made of 3 mm thin steel plates covered with a layer of flexible rubber material. During the self-adaptive gap adjustment process of the picking plates, to avoid interference between two corn plants, the picking plates are designed in two segments. Each segment interacts with only one corn plant during ear picking. The relationship between the length of the first segment of the picking plate and the corn plant spacing *B* is:

$$S \leq \frac{B}{\cos\theta} \tag{9}$$

where: θ - header inclination angle.

When the header inclination angle is between 20-30°, the ear-picking loss is minimized. This study selects a header inclination angle of 25°. The corn plant spacing *B* generally ranges from 250 to 330 mm. To minimize interference between two corn plants, the plant spacing *B* is set to 200 mm, and the picking plate length *S* ≤220 mm. The length of the pulling section of the pulling roller used in this study is 610 mm, and the total length of the pulling roller is 730 mm. Therefore, the total length of the picking plates is designed to be 730 mm, with the length of the second segment being 510 mm.

During ear picking, the picking plates are compressed downward by the impact force of the ears, thereby increasing the collision time between the ears and the picking plates and reducing ear damage. The movement of the picking plates during ear picking is shown in Figure 7.

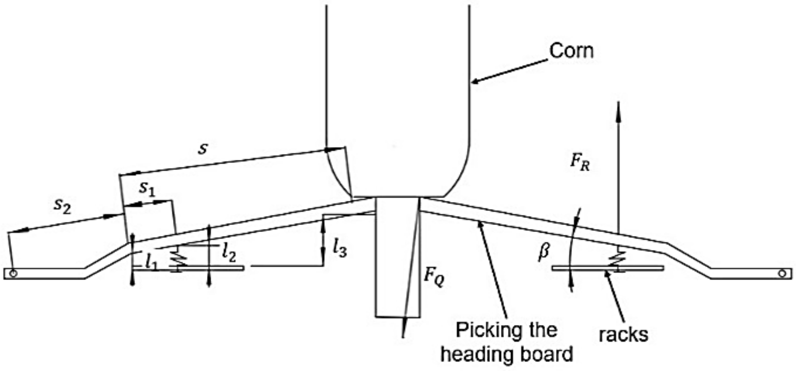


Fig. 7 - Movement of picking plates during ear picking

F_Q-represents the collision force of the ears on the picking plates, N; F_R-represents the supporting force of the compression spring on the picking plates, N; l_1-represents the minimum gap between the picking plates and the bracket, mm; l_2-represents the compression length of the compression spring, mm; l_3-represents the maximum gap between the picking plates and the bracket, mm; s_1-represents the length from the bending point of the picking plates to the spring, mm); s_2-represents the length from the installation hole of the picking plates to the bending point, mm; s-represents the length of the bending point of the picking plates, mm

Due to installation size constraints, the maximum height between the picking plates and the bracket should not exceed 30 mm, and the maximum height is:

$$l_3 = l_1 + s\sin\beta \tag{10}$$

The maximum compression height of the buffer spring

$$l_2 = s_1\sin\beta + l_1 \tag{11}$$

This design requires that during ear picking, the picking plates can compress the spring to the maximum value, the impact force between the ears and the picking plates is greater than the supporting force of the buffer spring on the picking plates. The maximum working load of the buffer spring occurs when the picking plates are compressed to the lowest point, so it must be ensured that the torque exerted by the corn ears driving the picking plates to rotate is greater than the torque resisting the rotation of the picking plates by the buffer spring, i.e.:

$$F_Q \;\; s + s_2 \;\; > F_R(s_1 + s_2)\cos\beta \tag{12}$$

The row spacing for corn planting is 600-700 mm. This study designs the row spacing of the corn header to be 630 mm, and the length of the picking plates is designed to be 270 mm, with s = 200 mm, s_1 = 50 mm, and s_2 =70 mm.

Therefore:

$$\frac{s+s_2}{s_1+s_2}=\frac{27}{12} \tag{13}$$

As previously mentioned, the pulling force of the corn ear stalk ranges from 264 N to 673 N. To pick the ears without causing blockage:

$$F_Q\cos\beta<\frac{1}{2}F_{A\min} \tag{14}$$

where: F_{Amin}- the minimum pulling force of the ear stalk, F_{Amin}=264 N.

From equations 24, 25, and 26, the maximum elastic force of the compression spring is:

$$F_R\le\frac{F_{A\min}\ \ s+s_2}{2(s_1+s_2)} \tag{15}$$

This study designs the minimum height between the picking plates and the bracket l_1=10 mm. Calculations show that β does not exceed 5°; taking β=5°, the maximum compression height of the compression spring l_2=15.23 mm. Calculations show that: F_R≤ 297 N. To minimize the impurity rate of the stalks, the maximum elastic force of the spring is taken as 250 N, resulting in a spring stiffness coefficient not exceeding 20.2 N/mm. To reduce the vibration of the picking plates when unloaded, a certain pre-tightening force must be applied to the spring. Based on the weight of the picking plates, the pre-tightening force of the buffer spring is designed to be no less than 50 N. The buffer spring should withstand more than 10^6 cycles of cyclic impact during ear picking, classified as Class I load. Table 1 shows the main parameters of the spring.

Table 1

Main parameters of compression springs

Project	Spring parameters	Project	Spring parameters
Diameter of the material	3.5 mm	Spring center diameter	22 mm
Ultimate load	484.52 N	The amount of deflection in a single turn	3.481 mm
Number of valid laps	7	Total number of laps	9
Stiffness factor	19.86 N/mm	Single-turn stiffness	139 N/mm
Helix angle	5.78°	Free height	54.25 mm
Outside diameter	25.5 mm	Inner diameter	18.5 mm
Pitch	7 mm	Unfolded length	622.04 mm
The amount of deformation under the ultimate load	24.367 mm		

RESULTS

Harvesting header Model building

During the optimal corn harvest season, the physical properties of corn are measured to establish models of corn ears and stalks. Based on the reference materials, the physical properties of the corn and picking plate were determined, and the corresponding parameters were configured in ADAMS as shown in Table 2 (*Gao et al., 2003; Zhang, 2003*).

Table 2

Physical properties of steel and rubber

Type of material	Elastic modulus（N/m²）	Density (N/m³)	Poisson's ratio
steel	2.06×10^{11}	7800	0.3
rubber	7.84×10^{6}	1500	0.47
Ears of corn	1.37×10^{8}	1197	0.4
Corn stalks	1.1×10^{10}	450	0.3

To make the simulation results of the self-adaptive gap adjustment of the picking plates more realistic, simulations are conducted on different nodes of the same stalk during the simulation process. Additionally, a modal analysis of the corn stalks is performed in ANSYS software. This allows for a clear visualization of the operation of the self-adaptive gap adjustment structure of the picking plates as the diameter of the stalks changes. Based on actual measurements of corn stalks, the simulation targets the five nodes below the ear, with diameters of 41 mm, 37 mm, 34 mm, 30 mm, and 24 mm, and a length of 150 mm. The simulation model after setting is shown in Figure 8.

During the simulation of the corn ear-picking process, flexible Bushing connections are established between the stalk and the ground, and between the stalk and the ear. Collision force sensors are added between the corn ear and the picking plates. When the sensor value exceeds 500 N, the bushing force fails, causing the ear to separate from the ear stalk.

The simulation model after setting is shown in Figure 9.

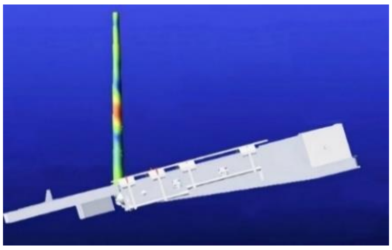


Fig. 8 - Single-factor simulation process

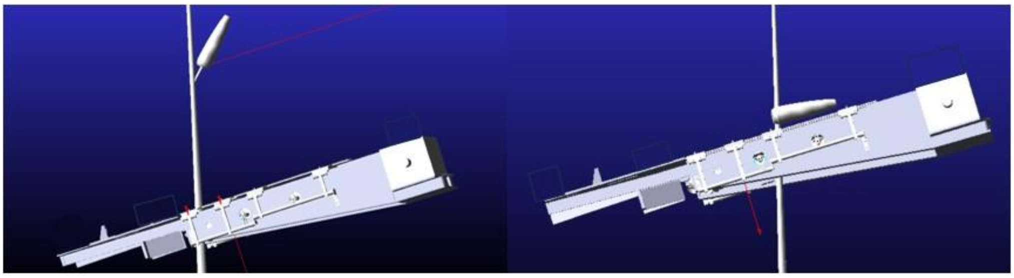


Fig. 9 - Simulation process of heading

Simulation results of the adaptive adjustment mechanism for ear-picking plate clearance

To analyze the impact of the spring stiffness coefficient on the self-adaptive gap adjustment of the picking plates, a single-factor experiment on the stiffness coefficient of the compression spring was conducted. Figure 10 shows the displacement curve of the picking plates in the y-axis direction under different spring stiffness coefficients.

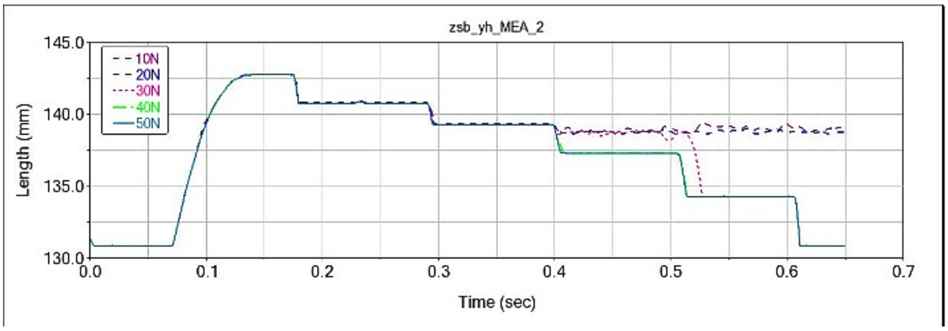


Fig.10 - Dynamic analysis of heading plates under different spring stiffnesses

From Figure 10, it can be seen that the corn plant contacts the picking plates at 0.07 seconds, causing the picking plates to move outward until reaching the maximum value. When the spring stiffness coefficient is 10 N/mm, the picking plates cannot move when the corn stalk diameter reaches 30 mm. This is mainly due to the internal friction within the picking plate adjustment device, preventing the picking plates from moving and causing oscillation. When the spring stiffness coefficient is 20 N/mm, the picking plates cannot quickly adjust to the changes in the corn stalk diameter when it decreases to 30 mm, though the vibration amplitude of the picking plates is reduced. When the spring stiffness coefficient is 30 N/mm, the picking plates can adjust according to the corn stalk diameter, but the adjustment process is delayed when the stalk diameter is 30 mm, preventing quick adjustments. When the spring stiffness coefficient is 40 N/mm, the picking plates stabilize when the corn plant diameter is 24 mm, with minimal displacement fluctuation. The fluctuation at a stiffness coefficient of 50 N/mm is similar to that at 40 N/mm, indicating that the optimal spring stiffness is between 30 N/mm and 40 N/mm.

Experimental Factors and Indicators

A three-factor, three-level quadratic regression rotational orthogonal experiment was conducted to analyze the collision force on the corn ears during the ear-picking process. The factors included the stiffness coefficient of the compression spring for the self-adaptive gap adjustment of the picking plates, the rotational speed of the pulling roller, and the thickness of the flexible material. Table 3 shows the factors and levels of the virtual orthogonal experiment.

Table 3

Virtual orthogonal test factors and levels

Experimental level	The stiffness coefficient of the compression spring /(N/mm)	Stem pulling roller speed /°	The thickness of the flexible material / mm
1	30	700	2
2	35	850	4
3	40	1000	6

Using Design-Expert 13 software, the experimental design and analysis were conducted. Each combination was tested three times, and the virtual orthogonal experiment scheme and results are shown in Table 4. The stiffness coefficient of the compression spring, the rotational speed of the pulling roller, the thickness of the flexible material, and the ear contact force are represented by x_1, x_2, x_3, and Y, respectively.

Table 4

Test protocol design and test results

Serial number	x_1 / (N/mm)	x_2 / °	x_3 / mm	Y / N
1	30	700	4	563
2	40	700	4	536
3	30	1000	4	954
4	40	1000	4	902
5	30	850	2	728
6	40	850	2	716
7	30	850	6	672
8	40	850	6	628
9	35	700	2	561
10	35	1000	2	969
11	35	700	6	510
12	35	1000	6	870
13	35	850	4	638
14	35	850	4	640
15	35	850	4	632
16	35	850	4	645
17	35	850	4	642

Variance analysis of the experimental results was conducted using Design-Expert 13 software, yielding the response function for the ear contact force Y.

$$Y = 639.4 - 16.87x_1 + 190.63x_2 - 36.75x_3 - 6.25x_1x_2 - 8x_1x_3 - 12x_2x_3 + 28.92x_1^2 + 70.42x_2^2 + 17.68x_3^2 \quad (16)$$

Variance analysis of the experimental results, as shown in Table 5, indicates that the regression model for the ear contact force is highly significant with a P ≤0.0001, and the lack of fit test value P>0.05 (0.4163), indicating a high degree of fit for the regression equation. The determination coefficient R_2 is 0.9995, indicating that the model can explain more than 99 % of the evaluation indices. Therefore, the working parameters of the elastic low-damage corn picker header can be optimized using this model.

Table 5

ANOVA of quadratic response surface regression model

Variance source	Sun of squares	Degree of freedom	Mean square	F	P
Model	332400	9	36936.81	1428.89	<0.0001
x_1	2278.12	1	2278.12	88.13	<0.0001
x_2	290700	1	290700	11245.77	<0.0001

Variance source	Sun of squares	Degree of freedom	Mean square	F	P
x_3	10804.50	1	10804.50	417.97	<0.0001
x_1x_2	156.25	1	156.25	6.04	0.0436
x_1x_3	256.00	1	256.00	9.90	0.0162
x_2x_3	576.00	1	576.00	22.28	0.0022
x_1^2	3522.76	1	3522.76	136.28	<0.0001
x_2^2	20882.87	1	20882.87	807.85	<0.0001
x_3^2	1315.39	1	1315.39	50.89	0.0002
Residual	180.95	7	25.85		
Lack of Fit	85.75	3	28.58	1.20	0.4163
Pure Error	95.20	4	23.80		
Cor Total	332600	16			

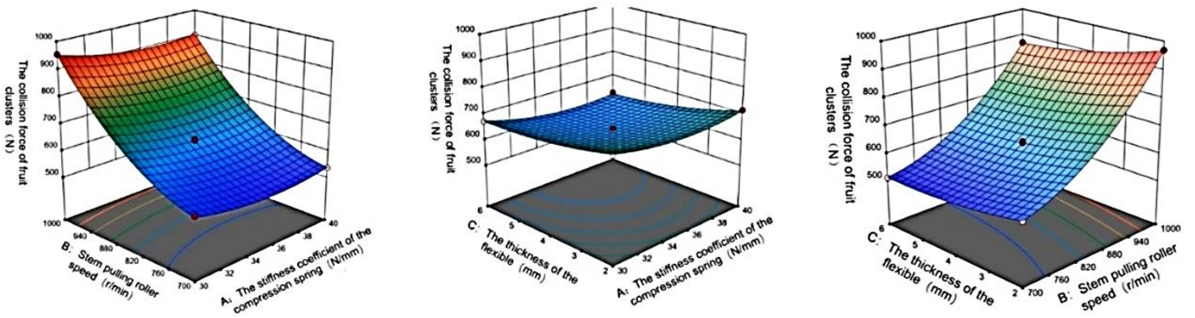
Note: P<0.01 (highly significant**); P<0.05(significant*).

The impact of each parameter on the regression equation can be reflected by the P<0.01 indicates a highly significant impact, and P<0.05 indicates a significant impact.

In the ear contact force *Y* model, x_1, x_2, x_3, x_2x_3, x_1^2, x_2^2 and x_3^2 are all highly significant, while x_1, x_2 and x_1, x_3, are significant.

Response Surface Analysis of Each Factor

The experimental results show significant differences in ear collision forces under different structural parameters. Response surface analysis of the experimental results was conducted to determine the optimal parameters for the elastic low-damage corn picker header. Figure 11 shows the response surfaces of each factor in the regression model.



a) Compression spring stiffness coefficient and pulling roller speed

b) Compression spring stiffness coefficient and flexible body thickness

c) Pulling roller speed and flexible body thickness

Fig. 11 - The influence of different factors on the collision force of fruit ears

From Figure 11a, it can be seen that when the rotational speed of the pulling roller is constant, the ear collision force initially decreases and then stabilizes and slightly increases with the increase in the spring stiffness coefficient. This is because the increase in the spring stiffness coefficient allows the picking plates to clamp the ear stalk during ear-picking, reducing the force exerted by the pulling roller on the stalk. When the spring stiffness coefficient exceeds 36 N/mm, the clamping force on the ear stalk by the picking plates becomes too large, preventing the corn ears from being quickly picked upon contact with the picking plates, leading to an increase in the ear collision force. When the spring stiffness coefficient is constant, the ear collision force is positively correlated with the rotational speed of the pulling roller, as an increase in the pulling roller speed increases the downward speed of the corn plant, leading to a higher ear collision force according to the kinetic energy theorem. The influence of the rotational speed of the pulling roller on the ear collision force is greater than that of the spring stiffness coefficient.

From Figure 11b, it can be seen that when the spring stiffness coefficient is constant, the ear collision force decreases with the increase in the thickness of the flexible material. When the thickness of the flexible material exceeds 4 mm, the ear collision force stabilizes as the flexible material's elastic performance dissipates most of the collision kinetic energy of the ear. Thus, when the thickness of the flexible material exceeds 4 mm, the ear collision force remains stable.

From Figures 11a, 11b, and 11c, it can be seen that the factors affecting the ear collision force, in order of significance, are the rotational speed of the pulling roller, the thickness of the flexible material, and the stiffness coefficient of the compression spring. Using Design-Expert 13 software to solve the regression equation with the constraint of minimizing the ear collision force, the optimal solution is obtained: a spring stiffness coefficient of 36 N/mm, a pulling roller speed of 700 r/min, and a flexible material thickness of 6 mm.

Comparative Validation Experiment

Comparative experiments were conducted between the designed elastic low-damage corn picker header and a conventional plate-type corn header under different working conditions. The experiments were conducted with the designed spring stiffness coefficient of 36 N/mm and a flexible picking plate thickness of 6 mm. The gap between the picking plates of the conventional plate-type header was set to 35 mm. Figure 15 shows the comparison of ear force and collision acceleration at a pulling roller speed of 700 r/min, a header inclination angle of 25°, and a travel speed of 3 km/h.

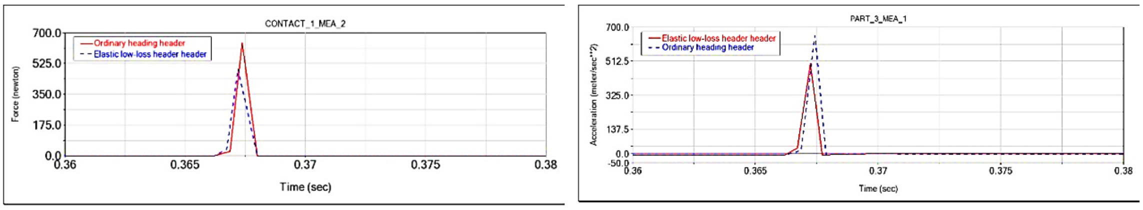


Fig.12a-Comparison of ear collision forces during ear **Fig.12b-Comparison of acceleration at ear collision**

Fig.12 - Comparative analysis of ear collision force and acceleration

From Figure 12, it can be seen that the collision force of the elastic low-damage corn picker header is 505 N, compared to 648 N for the conventional plate-type header. The collision acceleration of the elastic low-damage corn picker header is 500 m/s², compared to 655 m/s² for the conventional plate-type header. This indicates that the designed elastic low-damage corn picker header can effectively reduce collisions.

Table 6 shows the factors and results of the comparative experiments. At a pulling roller speed of 700 r/min, the collision force on the ears is reduced by 25.66 % compared to the conventional plate-type header. At a pulling roller speed of 850 r/min, the collision force is reduced by 30.81 %, and at a pulling roller speed of 1000 r/min, the collision force is reduced by 31.71 %. This demonstrates that the designed elastic low-damage corn picker header can effectively reduce the collision force on the ears.

Table 6

Comparative analysis of elastic and low-damage corn ear picking header and ordinary plate header

Serial number	Stem pulling roller speed （r/min）	Header inclination / °	Travel speed (km/h)	Elastic and low-damage header ear contact force / N	Ear contact force of ordinary plate header / N
1	700	25	3	505	648
2	850	25	3	613	886
3	1000	25	3	840	1230

CONCLUSIONS

An elastic low-damage corn picker header was designed to address the high rate of ear damage and the issue of ear loss and clogging present in current corn picking devices. The design achieves high efficiency and low damage in corn harvesting. Structural design and parameter calculations were conducted for the picking plate gap adjustment device, picking plates, and compression spring adjustment structure.

Virtual simulation experiments of the corn ear-picking process were conducted using ADAMS software. The range of the stiffness coefficient of the compression spring for the picking plate gap adjustment mechanism was determined to be 30-40 N/mm through simulation. The contact force during the corn ear-picking process was analyzed using sensors and script control methods. Virtual orthogonal experiments analyzed the collision force on the corn ears under different spring stiffness coefficients, pulling roller speeds, and flexible material thicknesses. Response surface analysis determined the optimal parameter combination for harvesting: a spring stiffness coefficient of 36 N/mm, a pulling roller speed of 700 r/min, and a flexible material thickness of 6 mm.

Comparative experiments under different pulling roller speeds, with a header inclination angle of 25° and a forward speed of 3 km/h, showed that the designed elastic low-damage corn picker header reduced the collision force on the ears by more than 25 % compared to the conventional plate-type header, meeting operational requirements.

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