DESIGN AND EXPERIMENT OF HIGH LEVEL UNLOADING LARGE GRAIN COLLECTION BOX FOR FRESH CORN COMBINED HARVESTER

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鲜食玉米联合收获机高位卸粮大型集粮箱设计与试验

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ABSTRACT

In response to the problems of low unloading height, small collection box capacity, and high ear damage rate during grain collection in the fresh corn combine harvester, a large collection box with buffering and shock absorption mechanism and high unloading height was designed based on the 4YX-6 fresh corn combine harvester, which is a fully hydraulic driven fresh corn combine harvester. The device mainly consists of a box body, a buffering and shock-absorbing mechanism, a grain unloading extension mechanism, an electro-hydraulic system, etc. According to the agronomic requirements for fresh corn cultivation, the volume of the grain collection box is designed to be 10 m^3. According to the height range of the grain receiving truck during the harvest of fresh corn, the unloading stroke height of the grain collection box is designed to be 2.9 m~4.4 m. To achieve synchronization of lifting and flipping actions during high-level unloading, a synchronous series hydraulic system is designed. Conduct force analysis on the drop of fruit ears to the bottom of the grain collection box and design a buffering and shock-absorbing mechanism. The designed grain collection box was installed on the 4YX-6 fresh corn combine harvester for field experiments, with ear damage rate and unloading time as performance indicators. The results showed that the ear damage rate ranged from 0.5% to 0.8%, the unloading time was from74 s to 126 s, and there were no safety issues such as deformation or tilting of the device during operation. The ear damage rate met the standards, and the working performance was stable, meeting the operational requirements.

摘要

针对鲜食玉米联合收获机卸粮高度低、集粮箱容积小、集粮时果穗损伤率高的问题，基于4YX-6型鲜食玉米联合收获机设计了具备缓冲减震机构、可高位卸粮的全液压驱动鲜食玉米联合收获机大型集粮箱。该装置主要由箱体、缓冲减震机构、卸粮延长机构、电液系统等组成。根据鲜食玉米种植的农艺技术要求，将集粮箱容积设计为10 m^3。根据鲜食玉米收获期间接粮车的厢体高度范围，将集粮箱卸粮行程高度设计为2.9 m ~ 4.4 m，为实现高位卸粮时升举、翻转动作的同步性，设计了同步串联式液压系统。对果穗掉落到集粮箱底部时进行受力分析，设计缓冲减震机构。将设计的集粮箱安装在4YX-6型鲜食玉米联合收获机上进行田间试验，以果穗破损率和卸粮时间为性能指标，结果表明：果穗损伤率范围在0.5% ~ 0.8%，卸粮时间在74 s~126 s，作业过程中装置未出现形变、倾斜等安全性问题，果穗损伤率符合标准，工作性能稳定，满足作业要求。

INTRODUCTION

Fresh corn, including sweet corn and glutinous corn, refers to a type of corn that can be processed and consumed after harvesting or directly harvested for consumption (*Zhou et al., 2020; Zhao et al., 2011; Li et al., 2019*). Due to its delicious taste, sweet and glutinous texture, and high nutritional value that are beneficial to the human body, it has attracted increasing attention, and therefore its planting area has been increasing year by year (*Chen et al., 2023; Zhu et al., 2012; Zhang et al., 2023*). At present, the annual planting area of fresh corn in China has reached 1.67 million hectares, and the annual market consumption has reached 75 billion ears. China has become the world's largest producer and consumer of fresh corn. Against the backdrop of the current promotion of green and high-quality development strategies, the Ministry of Agriculture and Rural Affairs has also issued a notice stating that the area of fresh corn should remain stable at over 20 million acres (*Islam et al., 2021; Geng et al., 2023*).

For fresh corn, its harvest period is relatively short. After reaching the picking conditions, it should be picked and sent to the production line for processing as soon as possible. If the optimal picking time is exceeded, it will cause the aging of fresh corn, which not only affects the quality and taste of fresh corn, but also leads to nutrient loss, affects the processing flow, and ultimately affects sales, causing property losses and a series of other problems.

At present, technical personnel have conducted extensive research on the issue of grain collection boxes in combine harvesters. Scholar analyzed and summarized various structures of ear boxes, such as side flip and back flip, and analyzed the structural characteristics and operational advantages and disadvantages of different styles of ear boxes (*Zhou, 2013*). Scholars from Heilongjiang academy of agricultural machinery engineering sciences analyzed a loss reduction and diversion device was designed for the problem of ear damage caused by impact of fresh corn entering the grain collection box, effectively reducing the ear damage rate (*Zhang et al., 2025*). Scholars from Modern Agricultural Equipment Co. Ltd. analyzed optimization of the support structure for the ear box of the corn harvester for seed production has been carried out, improving the stress strength of the ear box (*Liu et al., 2017*). Foreign scholars often use DEM methods to design grain tanks and study the motion and mechanical characteristics of grains in the silo, providing assistance for the design of harvesting machinery grain tanks (*González-Montellano et al., 2012; Ma et al., 2022; Balevičius et al., 2011*). In response to issues such as large capacity grain tanks and high position unloading, major foreign companies have designed corresponding products to reduce the number of unloading times and improve operational efficiency (*Fu, 2020; Yan, 2016*). Existing research has mainly focused on the design of grain collection boxes for ordinary grain corn. Although the volume and unloading height have been improved, the effect of the improvement is not significant for fresh corn combine harvesters, and the damage caused by the collision between fresh corn ears and the box body has not been considered.

In response to the above challenges, this article presents the design of a large grain collection box for a fully hydraulic-driven fresh corn combine harvester, based on the 4YX-6 model. The collection box features a buffering and shock-absorbing mechanism and is capable of high-position unloading. The design includes the external structure, functional components, and dimensional specifications of the grain collection box, tailored to meet the unloading method and operational requirements. Field performance tests were conducted to evaluate the effectiveness and reliability of the proposed design.

MATERIALS AND METHODS

Whole machine structure and working principle

This article focuses on the design of a large grain collection box for the 4YX-6 fresh corn combine harvester, with a side flip unloading method. The main external structure of the host of the 4YX-6 fresh corn combine harvester is shown in Fig. 1.

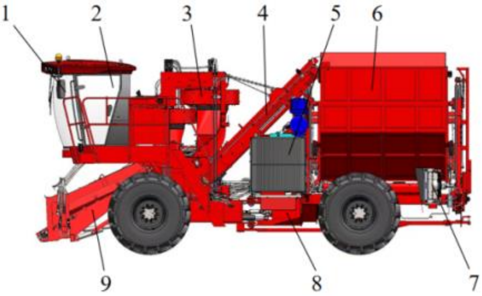

Fig. 1 – 4YX-6 Fresh corn harvester

1. Electrical system; 2. Driving cab; 3. Fan; 4. Elevator; 5. Powertrain; 6. Grain collection box; 7. Hydraulic system; 8. Chassis; 9. Bridge elevator

The main technical parameters are shown in Table 1.

Table 1

Main Technical Parameters

Technical parameter	Numerical value
Overall dimensions (length x width x height) / (mm×mm×mm)	11280×3390×3840
Number of working rows	6
Row spacing/mm	700/400
Working width/mm	3300
Fuel tank capacity/L	460

Technical parameter	Numerical value
Hydraulic oil tank capacity/L	205
Wheelbase/mm	4180
Track width/mm	2920
Rated power/kW	194
Grain collection box capacity/m^3	10

Structure and working principle of grain collection box

The grain collection box is mainly composed of a box body, a box body bracket, a buffering and shock-absorbing mechanism, a grain unloading extension mechanism, a hydraulic system, etc. Fresh corn ears are transported via an elevator and enter the bottom of the grain collection box. When the grain collection reaches a certain level, it can be unloaded at a high position either at the center or head of the cornfield. The box body is connected to the bracket through a hydraulic cylinder. The bracket itself is securely fixed to the chassis of the harvester. The overall structure of the grain collection box is illustrated in Fig. 2.

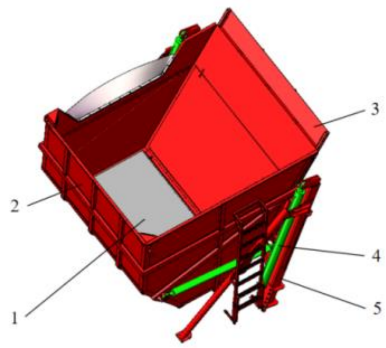

Fig. 2 – Structure of grain container

1. Buffer and shock absorber mechanism; 2. Box; 3. Unloading extension mechanism;
4. Hydraulic cylinder; 5. Anti-nose-dive leg

Fresh corn has a higher moisture content at harvest and is more prone to damage compared to grain corn. Therefore, a buffer and shock absorber mechanism is installed on the bottom plate of the grain collection box to reduce the probability of damage caused by rigid collision between fresh corn and the bottom plate. To increase the unloading distance between the harvester and the grain receiving truck, an unloading extension mechanism is designed. To achieve stable and fast lifting and flipping of the grain collection box when unloading to the high-level grain receiving truck, a hydraulic compensation directional valve is developed, and a synchronous series hydraulic system with adjustable lifting and flipping speeds is designed.

Box design

Due to the short optimal harvesting period of 2-3 days for fresh corn after maturity, the harvesting efficiency should be improved. If the volume of the grain collection box is small, it will increase the number of grain unloading times and reduce the harvesting efficiency. To reduce the frequency of unloading grain and lower transportation costs, large trailers are often parked on the ground and directly loaded onto the trailers from the harvester. According to the agricultural technology requirements for fresh corn cultivation, the planting method in Northeast China is mostly large ridges and double rows, with a ridge width of 1100 mm and a plant spacing of 250 mm to 280 mm (*Cui et al., 2024*). The length of a single ridge is usually around 500 meters. Taking a 6-row fresh corn harvester as an example, one round trip of the grain collection box can store about 24000 ears of fresh corn.

Using the variety Wannuo 2000 fresh corn as the research object, the drainage method was used to measure the volume of a single ear (*Tang, 2024*). Taking the average of multiple experiments, the volume of a single ear was found to be 0.0003 m^3. After calculation, it was found that the volume of an ear harvested in one round trip was 7.2 m^3. Due to the irregular arrangement of fruit clusters in the grain box and the large gaps between them, the total volume needs to exceed 7.2 m^3. In actual harvesting operations, the grain collection box cannot be filled to the brim, otherwise it will fall and lose. Therefore, in order to leave sufficient space, the volume of the grain collection box is set to 10 m^3. The box structure is shown in Fig.3 (a).

(a) Axonometric drawing
1-Reinforcement board; 2-Rubber baffle; 3-Unloading and flipping axis; 4-ladder

(b) Front view of the box

Fig. 3 – Box structure

Figure 3(b) shows the structural dimensions from the front view of the grain collection box. The left slope in the figure represents the unloading side. To prevent tipping or sliding of fresh corn after the box is lifted to its highest position, the slope angle should exceed the natural rolling angle of fresh corn. Therefore, θ1 is designed at 25°. Additionally, due to the installation of a cooling fan at the lower right section of the box, the opposite slope angle (θ2) is set at 35°, and the distance d is designed at 0.93 mm to accommodate and avoid interference with the fan's position. The chassis of the 4YX-6 fresh corn combine harvester is designed with a 1.0 m distance and a 2.5 m length between the two support beams that hold the grain collection box. Accordingly, the width (e) of the grain collection box is set to 1.1 m, and the length in the front–rear direction (l) is set to 2.5 m to match the chassis structure. In field operations, grain is often unloaded into small trucks with guardrails typically around 2.5 meters high. To improve unloading efficiency, the design adopts a method that allows unloading without lifting. Considering the chassis height, the box height (f) is designed to be 2.2 meters. Based on geometric and structural calculations, the value of c is determined to be 1.27 meters. The remaining dimensions, a and b, can be calculated using Equations (1) and (2):

$$a = f \tan\theta_1 + dan\theta_2 + e \tag{1}$$

$$b = d \tan\theta_1 + dan\theta_2 + e \tag{2}$$

The calculation shows that a is 2.77 m and b is 1.8 m. The volume of the box is:

$$V = \left[\frac{(b+e)d}{2} + \frac{(a+b)c}{2}\right]l \tag{3}$$

By inputting the relevant data into the above equation, the volume can be obtained as 10.625 m^3. To increase the ability of the box to resist deformation, all steel plate materials are selected as Q345B, and reinforcing ribs are used around the ear box for reinforcement.

Design of Unloading Extension Mechanism

During the unloading process, the distance between the harvester and the grain receiving truck needs to be maintained within the range of 0.3 m to 0.4 m, which requires accurate control of their relative positions to achieve the goal of unloading all grain into the grain receiving truck. However, when the two are very close, it is easy to cause scratches and safety hazards during unloading. When the two are far apart, it is easy to cause the grain to not be accurately dumped onto the receiving truck during unloading, resulting in waste. Therefore, it takes a long time to adjust the relative position of the two, greatly reducing the efficiency of the operation. Therefore, a retractable unloading extension mechanism is installed on the unloading outlet side of the grain collection box through a connecting plate. During harvesting, the opening of the box is facing upwards, and the moving extension plate slides in a fixed slide through a pulley under the action of gravity, naturally contracting to an unexpanded state without blocking the opening of the box or exceeding its own height. When it is necessary to dump grain, the box flips over, and the moving extension plate slides out naturally under the action of gravity. The moving extension plate can be limited in travel by a locking slider. A limit plate can be optionally installed in the fixed slide, which is divided into two gears and can be selectively installed according to different operating conditions to adjust the travel of the slide. The unloading extension mechanism is shown in Fig.4.

The dimensions of the mobile extension plate designed here are 2500 mm in length and 600 mm in width. Due to the locking slider, the actual extendable stroke is 400 mm, which can achieve unloading of grain within a distance of 0.7 m between the harvester and the grain receiving vehicle. The unloading distance is greatly increased, avoiding repeated adjustment of vehicle distance, accelerating unloading efficiency, and reducing safety hazards.

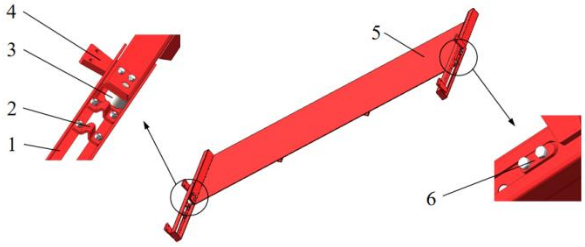

Fig. 4 – Unloading extension mechanism

1. Fixed slide; 2. Limit plate; 3. Pulley; 4. Connecting plate; 5. Mobile extension board; 6. Lock slider

Dynamic analysis of fruit ear

The harvest period of fresh corn is during the milk or wax ripening stage, when the grain moisture content is very high at around 65%, which can easily cause serious damage during rigid impact (*Zhang et al., 2019；Gao et al., 2024*). The corn ears are thrown out by the elevator and then dropped into the box in an inclined manner, resulting in a height difference between the ears and the bottom plate of the box. Due to the steel plate material of the box, the fruit clusters that enter the box at the beginning of harvesting will directly fall onto the bottom plate of the box, causing severe collision between the clusters and the steel plate, resulting in significant damage and loss. When the bottom plate is covered with a layer of fruit clusters, elastic collisions between clusters will occur inside the box, reducing or eliminating damage. To solve this problem, a buffering and shock-absorbing mechanism is installed on the bottom plate of the box, so that the initially entering fruit clusters come into elastic contact with the box to reduce damage.

Study on the mechanical properties of fresh corn

Fresh corn has a high moisture content and crisp grain texture. To provide reference for the design of buffering and shock-absorbing mechanisms, the mechanical properties of fresh corn ears during harvesting were studied. The variety Wannuo 2000 was used for the experiment of fresh corn ears, and 10 ears of fresh corn were randomly picked from the experimental field for measurement. The compressive strength and elastic modulus of the ear during harvest are important parameter indicators. This article used the RGT series desktop universal testing machine (speed accuracy ± 0.5%, load accuracy ± 0.5%) to measure 10 fruit ears (*Zhao et al., 2022*). Compression tests were conducted on the front, middle, and tail sections of the fruit ears, and the results were averaged. When the grain underwent significant deformation to the point of bleeding, it was considered damaged. The experimental process is shown in Fig.5.

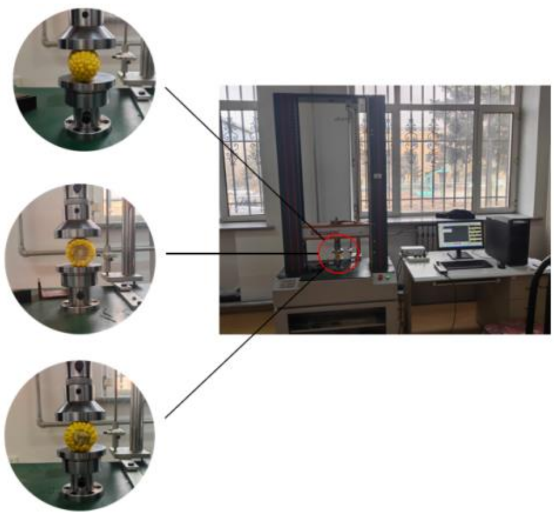

Fig. 5 – Mechanical measurement test

Statistical analysis was conducted on 10 fruit ears, with an average compressive strength of 8.16×10^4Pa, an average elastic modulus of 0.82 MPa, and a Poisson's ratio of 0.35.

Dynamics analysis of corn ear

Fresh corn was thrown out of the conveyor belt and entered the grain collection box in a diagonal motion. The dynamic analysis of the movement process of the ear is shown in Fig.6.

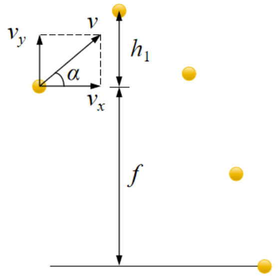

Fig. 6 – Movement process of the fruit ear

The movement of fruit ears in the air is divided into two stages: ascending and descending. Analyzing the movement stages of fruit ears includes:

$$\begin{cases} v_x = v\cos\alpha \\ v_y = v\sin\alpha \\ h_1 = v_y^2/(2g) \\ h = h_1 + f \end{cases} \tag{4}$$

where:

v—represents the initial velocity at which the ear leaves the conveyor belt, m/s;

V_x—horizontal velocity of the fruit ear, m/s;

V_y—vertical velocity of the fruit ear, m/s;

α—the angle between the initial velocity of the fruit ear and the horizontal direction, (°);

H_1—the distance at which the ear rises to the highest point, m;

G—gravitational acceleration, taken as 9.8 m/s^2;

H—the distance between the fruit ear being thrown to the highest point and falling onto the bottom plate of the grain collection box, m;

The speed range of the conveyor belt was 300-350 r/min, and the installation angle between the conveyor belt and the horizontal ground α was 45°. This article takes the middle value of the speed as calculate based on 325 r/min, with an initial velocity v of 3.4 m/s. By substituting the data into the above equation, h can be obtained as 2.5 m.

When the corn ear came into collision contact with the bottom plate, its contact stress was calculated to evaluate the impact force (*Wei, 2023*).

$$\begin{cases} \sigma_c = \dfrac{F_j}{A_c} \\ A_c = 0.8973h + 112.2 \end{cases} \tag{5}$$

where:

σ_c —represents the contact stress between the ear and the bottom plate during collision, Pa;

F_j—the contact force between the ear and the bottom plate during collision, N;

A_c—contact area at the time of collision, mm^2;

The previous analysis showed that *h* was 2.5 m, and the calculated contact area at the time of collision was 2355.45 mm^2.

According to the contact mechanics calculation formula, the load and compressive deformation at the point of contact between the corn ear and the steel plate were analyzed to evaluate the mechanical response during impact.

$$\begin{cases} F_j = \frac{4}{3} E^* \sqrt{R^*} \delta^{\frac{3}{2}} \\ \frac{1}{E^*} = \frac{1-\mu_1^2}{E_1} + \frac{1-\mu_2^2}{E_2} \\ R^* = \frac{1}{R_1} + \frac{1}{R_2} \\ \delta = \left(C\sigma \frac{\pi\sqrt{R^*}}{2E^*} \right)^2 \\ C = \min\left(1.295e^{0.763\mu_1}, 1.295e^{0.763\mu 2}\right) \end{cases} \tag{6}$$

According to the above formula:

$$F_j = \frac{(\pi C\sigma)^3}{6} \left(\frac{E^*}{R^*} \right)^2 \tag{7}$$

where: E^*—Comprehensive modulus of elasticity, MPa;

R^*—Compressing equivalent radius, m;

δ—The compression deformation amount when the ear undergoes deformation, mm;

μ_1—Poisson's ratio of fruit ear;

μ_2—Poisson's ratio of steel plate;

E_1—Elastic modulus of fruit ear, MPa;

E_2—Elastic modulus of steel plate, MPa;

R_1—Vertical radius of collision between fruit clusters and steel plates, mm;

R_2—The radius of the steel plate when in contact, mm;

C—Stress coefficient, take the smaller value;

σ—Yield stress of fruit ear, taken as 0.27 MPa.

The previous experiment has measured the elastic modulus of the fruit ear to be 0.82 MPa and the Poisson's ratio to be 0.35. According to the Mechanical Design Manual, the elastic modulus of the steel plate is 2.1×10^5 MPa and the Poisson's ratio is 0.3. By measuring the external dimensions of the ear, the diameters of the top, middle, and tail of the ear were measured separately, and the average diameter was 40 mm, which was used as the vertical radius when the ear collided with the steel plate. Since the steel plate is located at the bottom of the grain collection box as a plane, its radius can be considered infinite.

By substituting the relevant data into equations (6) and (7), the contact force between the ear and the bottom plate during collision was 294.95 N. As mentioned earlier, the contact area between the ear and the bottom plate during collision was 2355.45 mm^2. Combining equation (5), the contact stress between the ear and the bottom plate was 12.8×10^4 Pa. In the section on mechanical properties of the ear, the average compressive strength of the ear was measured to be 8.16×10^4 Pa, which means that the contact stress between the ear and the bottom plate was greater than the compressive strength of the ear. Therefore, when the ear was thrown out of the conveyor belt and came into contact with the steel plate, it was damaged.

Design of buffer and shock absorption mechanism

The buffering and shock-absorbing mechanism is installed on the bottom plate of the grain collection box and is required to bear the majority of the load from the accumulated corn ears. When the box is full, the mechanism must remain structurally intact and capable of restoring to its original state after unloading. To ensure its reliability, it is essential to calculate the maximum pressure the buffering and shock-absorbing mechanism can withstand. For this purpose, the front view of the grain collection box was simplified, as shown in Figure 7, and a force analysis was conducted based on this model.

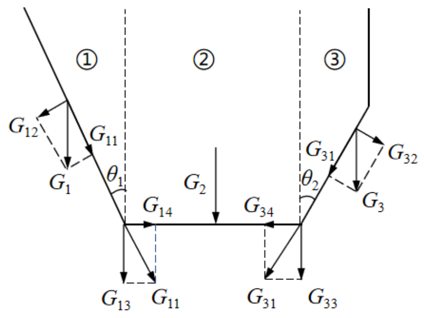

Fig. 7 – Force analysis of the box body

According to the structure of the box, the box is divided into three areas ①, ②, and ③ for separate force analysis. The first regional analysis is:

$$\begin{cases} G_{11} = G_1 \cos\theta_1 \\ G_{12} = G_1 \sin\theta_1 \\ G_{13} = G_{11} \cos\theta_1 \\ G_{14} = G_{11} \sin\theta_1 \end{cases} \tag{8}$$

where: G_1—total gravity of fruit ears in the first region, N;

G_{11}— component of G_1 along the inclined plane, N;

G_{12}— component of G_1 perpendicular to the inclined plane, N;

G_{13}—G_{11} vertical bottom plate force, N;

G_{14}—G_{11} component force along the bottom plate, N.

For Region ②, the entire gravitational force G_2 of the fruit ears acts directly and vertically on the bottom plate.

The third regional analysis is:

$$\begin{cases} G_{31} = G_3 \cos\theta_2 \\ G_{32} = G_3 \sin\theta_2 \\ G_{33} = G_{31} \cos\theta_2 \\ G_{34} = G_{31} \sin\theta_2 \end{cases} \tag{9}$$

where: G_3—total gravity of fruit clusters in the third region, N;

G_{31}—G_3 component force along the inclined plane, N;

G_{32}—the force component of G_3 vertical inclined plane, N;

G_{33}—G_{31} vertical bottom plate force, N;

G_{34}—G_{31} component force along the bottom plate, N.

From the above analysis, it can be seen that the total gravity of the fruit clusters inside the box does not act entirely on the bottom plate, but is partially shared by the inclined surfaces on both sides, reducing the pressure that the air cushion needs to bear. In section 2.1, it was calculated that a 6-row fresh corn combine harvester can harvest 24000 ears of fresh corn in one round trip. The average weight of a single ear was 290 g measured in the field, and the total weight was 6960 kg with a total gravity of 68208 N. The cross-sectional area ratio of the three regions is the ear gravity ratio, and the area of the three regions is calculated as:

$$\begin{cases} S_1 = \dfrac{f^2 \tan\theta_1}{2} \\ S_2 = ef \\ S_3 = \dfrac{(c+f)d\tan\theta_2}{2} \end{cases} \tag{10}$$

where: S_1 - the cross-sectional area of the region ①, m^2;

S_2 - the cross-sectional area of the region ②, m^2;

S_3 - the cross-sectional area of the region ③, m^2;

Enter data to obtain S_1: S_2: S_3 =G_1: G_2: G_3 =1.13:2.42:1.13. Calculate G_1, G_2, and G_3 as 16469N, 35270N, and 16469N, respectively. The total pressure on the bottom plate of the box, G_z, is:

$$G_Z = G_{13} + G_2 + G_{33} \tag{11}$$

Combining equations (8), (9), and (11), the total pressure exerted on the bottom plate is 59684 N.

The area S_d of the bottom plate of the box is:

$$S_d = el \tag{12}$$

The calculated area of the bottom plate is 2.75 m^2.

Combining equations (11) and (12), it can be concluded that the pressure exerted on the bottom plate is 21.7 kPa. Therefore, the designed shock absorber pad should have a compressive strength greater than 21.7 kPa and a load capacity greater than 6.9 t. There are very few products that can achieve such a large load capacity and restore elasticity after compression in this area, and the price is expensive. The actual production and application costs are high. Therefore, this article designs a buffering and shock-absorbing mechanism with a simple structure and low cost. The schematic diagram of the buffer and shock absorber mechanism is shown in Fig.8.

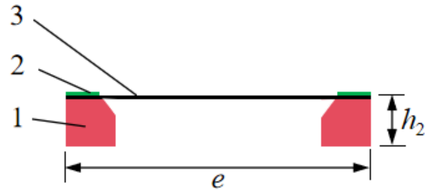

Fig. 8 – Schematic diagram of buffer and shock absorber mechanism

1.Heel; 2.Splint; 3.High elasticity rubber

High elasticity rubber is fixed by pads and clamps, with the pads fixed to the bottom plate of the box. To reduce stress concentration caused by downward bending of the rubber, a 20 mm chamfer is designed on the inside of the pads. Due to the thin thickness of the rubber sheet, which is much smaller than its length and width, and the linear elastic deformation of the rubber, a certain horizontal pre tension T is applied to the rubber sheet during clamping to ensure sufficient buffering deformation space between the rubber and the bottom plate of the box. The pre tension taken in this article is 500 N.

When the ear falls onto the rubber plate, the calculation condition is based on the ear falling into the middle of the rubber plate. The deformation of the rubber sheet can be regarded as the result of the combined action of pre tension and intermediate pressure. To calculate the deformation of the rubber sheet:

$$\begin{cases} \delta_1 = \dfrac{PL^3}{192D} \cdot \dfrac{1}{1 + \dfrac{TL^2}{12D}} \\ D = \dfrac{E_3 H^3}{12\left(1-\gamma^2\right)} \end{cases} \tag{13}$$

Where: δ_1—Rubber deformation amount, mm;

P—Contact force between fruit ear and bottom plate collision, N;

L—Rubber sheet length, taken as 2.5 m;

D—Rubber sheet bending stiffness;

E_3—Rubber elastic modulus, 4×10^6 Pa;

H—Rubber sheet thickness, m;

γ—Rubber Poisson's ratio, taken as 0.47.

This article takes a rubber sheet thickness of 10 mm. The deformation obtained by inputting the data into the above equation is 0.09 m. In order to provide sufficient buffer space when the ear comes into contact with the rubber, the height h_2 of the cushion block is designed to be 100 mm. As the number of fruit clusters in the box gradually increases, the high elasticity rubber deforms and comes into contact with the bottom plate. After unloading the grain, the rubber rebounds and continues to play a buffering role.

Design of hydraulic system

The grain collection box is connected to the plunger pump oil supply system through hydraulic fittings and joints. The hydraulic system circuit is shown in Fig.9, mainly including hydraulic compensating directional valves, hydraulic cylinders, overflow valves, and other auxiliary components. When the system is in operation, the inlet P and outlet T are respectively connected to the oil supply system and oil tank of the pump body. When solenoid valves 3 and 4 are powered on, they can respectively achieve the lifting function of the grain collection box, and when solenoid valves 1 and 2 are powered on, they can respectively achieve the flipping function of the grain collection box. The overflow valve regulates the system pressure and protects the hydraulic circuit from overpressure conditions.

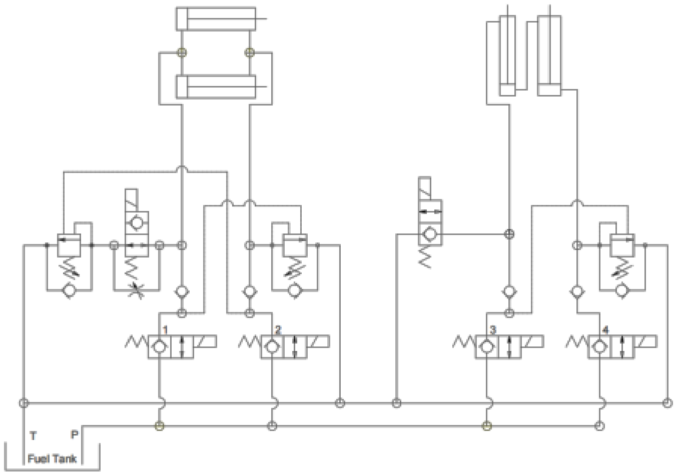

Fig. 9 – Hydraulic circuit of grain collection box

The grain box bracket for installing the lifting oil cylinder moves through a slide. Due to the uneven distribution of the weight of the fruit clusters in the grain box, the load on the grain box is the highest during lifting. If the lifting speed of the two oil cylinders is not the same, it will cause the grain box to tilt. In mild cases, the grain box will be stuck and unable to move, and in severe cases, the grain box frame will deform, causing safety issues. To ensure stable lifting, the two hydraulic cylinders must operate in synchronization. Therefore, the lifting oil cylinder design uses synchronous series oil cylinders, which should ensure that the effective working area of the two series oil cylinders is equal. Due to leakage in the series circuit during actual operation, a hydraulic compensation type reversing valve is designed in the circuit to replenish oil to the system. When the oil cylinder is in a constant power state during the lifting process, it can stop at any position within the stroke range at any time. When the oil cylinder is in a stationary state, the system is in a constant pressure state. The maximum working pressure of the oil source system is 16 MPa, and the maximum load-bearing ear weight calculated earlier is 68208 N. The theoretical thrust of the hydraulic cylinder can be calculated using the following formula:

$$F_u = \eta \frac{\pi}{4} D_0^{\ 2} P_1 \tag{15}$$

where: F_u—Theoretical thrust of the hydraulic cylinder, N;

η— Mechanical efficiency, taken as 0.85;

D_0— Diameter of the main piston in the synchronized hydraulic cylinder, mm;

P_1— Working oil pressure, Pa.

Select the hydraulic cylinder based on the above analysis. Refer to the product manual and select the HSG type hydraulic cylinder for engineering use. The synchronous main oil cylinder uses a hydraulic cylinder with a piston diameter of 140 mm and a piston rod diameter of 70 mm. Based on the above formula, the maximum pressure can reach 209249 N, which is greater than the total weight of the ears and grain collection box when fully loaded, meeting the lifting requirements. Due to the fact that the effective working area of the two series connected oil cylinders should be equal, that is, the cross-sectional area of the main cylinder with a rod chamber is equal to the cross-sectional area of the auxiliary cylinder without a rod chamber, when selecting, the piston rod diameter of the auxiliary cylinder and the main cylinder should be kept consistent. After calculation, the piston diameter of the auxiliary cylinder is 121.2 mm.

The flipping cylinder has relatively low synchronization requirements during flipping operations, so parallel cylinders are selected for flipping cylinders. During the operation, the box rotates around the flipping axis under the extension of the reverse oil cylinder. The force analysis of the reverse oil cylinder operation process is shown in Fig.10. In the figure, O_1 is the support point of the flipping cylinder, simplifying the fruit clusters inside the box into particle O_2, O_3 is the hinge point of the flipping axis when the box is flipped, and O_4 is the hinge point of the flipping cylinder. O_1O_3 is the direction of the connection between the support point of the flipping cylinder and the hinge point of the flipping shaft, O_1O_4 is the length direction of the flipping cylinder, O_2O_3 is the direction of the connection between the grain particle and the hinge point of the flipping shaft, and O_3O_4 is the direction of the connection between the hinge point of the flipping cylinder and the hinge point of the flipping shaft.

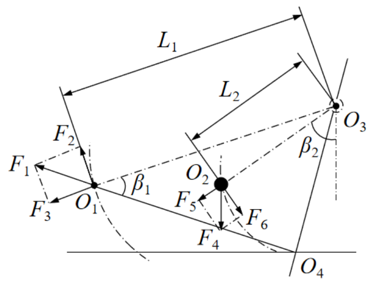

Fig. 10 – Force analysis of flipping cylinder operation

To achieve the flipping of the box, it is necessary to meet the following requirements:

$$\begin{cases} F_2L_1 > F_6L_2 \\ F_2 = F_1 \sin \beta_1 \\ F_6 = F_4 \sin \beta_2 \end{cases} \tag{16}$$

where: F_1—The force exerted by the flipping cylinder, N;

F_3—The force component of F_1 in the O_1O_4 direction, N;

F_2—F_1 component perpendicular to O_1O_4 direction, N;

F_4—Total gravity of box and ear, N;

F_5—Force component of F_4 in the direction of O_2O_3, N;

F_6—F_4 component perpendicular to O_2O_3 direction, N;

β_1—Angle between O_1O_3 and O_1O_4, (°);

B_2—The angle between O_2O_3 and the vertical direction, (°);

During the unloading reversal process, the maximum hydraulic cylinder pressure is required when the box is about to flip, so this state is analyzed. According to the installation structure of the grain collection box, the length of L_1 is 2381 mm and β_1 is 25 °. To obtain the length of L_2, the position of the center of mass needs to be obtained. In the 3D software SolidWorks 2020, 6960 kg of mass is added to the inside of the box according to the shape of the box, and material properties are added to each component of the grain collection box. After calculation, the box mass is 800 kg, β_2 is 81 °, and the length of L_2 is 1412 mm. Combining equation (16), it can be concluded that F_1 should meet the minimum requirement of 60686 N. Therefore, the HSG type hydraulic cylinder with a piston diameter of 80 mm and a piston rod diameter of 40 mm is selected for the flipping cylinder.

Design of electronic control system

All functions of the grain collection box are operated inside the cab, and the buttons use a reset switch. The control system mainly includes power supply, handle, controller, solenoid valve, etc. To streamline the system structure, a hydraulic compensating directional valve has been developed, with all solenoid valves concentrated on top. The lifting and flipping functions are controlled by solenoid valves to control the oil cylinder. To achieve rapid unloading of grain, a speed regulating valve is added to the flipping circuit of the grain collection box. Fast flipping can be selected according to the actual harvest situation. When the grain collection box is not fully loaded and the load is close to half, fast flipping unloading can be selected to reduce unloading time and improve operational efficiency. The control logic is shown in Fig.11.

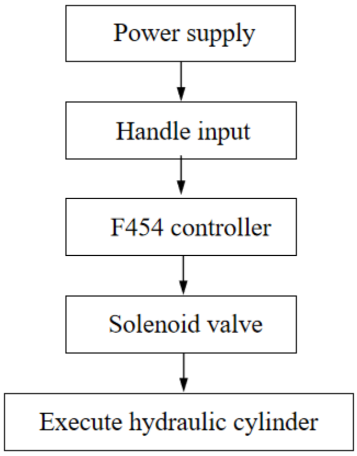

Fig. 11– Logic schematic diagram

Draw the grain collection box in the 3D software SolidWorks 2020 and configure its lifting and flipping operation modes, as shown in Fig.12.

(a) Ascending status *(b) Flip state*

Fig. 12 – Operating status of grain collection box

RESULTS

Field performance test

The experiment was conducted in September 2024 at the 47th parallel farm in Yi'an County, Qiqihar City, using the 4YX-6 fresh corn combine harvester. The fresh corn variety planted on the experimental plot was Wannuo 2000. At the time of the experiment, the fresh corn was in the milk ripening stage, which met the harvesting conditions for fresh corn. The planting mode adopted a large ridge double row, with a ridge length of 500 m, a ridge spacing of 1.1 m, and a plant spacing of 0.25 m.

The basic parameters of the fruit ear were measured using random sampling method, and the results are shown in Table 2.

Table 2

Determination of Basic Parameters of Ears

Parameter	Average value
Ear length/mm	173
Large end diameter of fruit ear/mm	46
Grain quality/g	291
Moisture content/%	69

The measurement was conducted based on the ear damage rate and unloading time as experimental indicators, and the GB/T 21961-2008 Corn Harvesting Machinery Test Method (*Wang, 2023*) was used as the ear damage evaluation standard. The field experiment site is shown in Fig.12.

(a) Small grain truck unloading grain

(b) Large grain trucks unloading grain

Fig. 12 – Field unloading experiment

When conducting ear damage statistics, the main consideration is the ears in direct contact with the bottom of the box. Therefore, during the experiment, the harvester advances ten meters each time and stops immediately after harvesting ten meters to conduct damage statistics on the ears in the grain collection box. The experiment is repeated five times, and the damage rate ranges from 0.5% to 0.8%, which meets the operational requirements.

There are two main types of grain receiving vehicles used in field operations, namely small grain receiving vehicles pulled by high-powered tractors (low-level unloading) and large heavy-duty trucks (high-level unloading). During the experiment, unloading tests were conducted on both types of grain receiving vehicles. The experiment is conducted when the grain collection box is empty (without fruit ears) and full (harvested by the harvester back and forth once), and the entire process time from the start of lifting the grain collection box to the end of unloading and returning to its original position is taken as the unloading time. To obtain an accurate range of unloading time, various situations were used to calculate the unloading time, and the unloading time was found to be between 74 s and 126 s. The correspondence between operating status and unloading time is shown in Table 3.

Table 3

Operating Status and Unloading Time

Work status	Time/s
Empty load low position quick flipping unloading of grain	74
Empty high position quick flipping unloading of grain	113
Fully load low position normal flipping unloading of grain	86
Full load high position normal flipping unloading of grain	126

The whole machine did not experience any safety issues such as tilting, overturning, or cracking of the frame during operation, and both the harvester and the grain receiving truck can unload grain within a range of 0.7 meters, with an unloading height of 2.9 meters to 4.4 meters. The operation is stable and safe.

CONCLUSIONS

(1) A large grain collection box suitable for fresh corn harvesting was developed to address key issues in existing combine harvesters, including low unloading height, limited grain box capacity, and a high damage rate to corn ears during collection. The box volume was designed to be 10 m³, based on agronomic requirements and harvesting operation needs. To extend the unloading reach between the harvester and grain-receiving trucks, a grain unloading extension mechanism was incorporated. Additionally, dynamic analysis of the unloading process was performed, leading to the design of a buffering and shock-absorbing mechanism to reduce ear damage during impact.

(2) To improve the convenience of unloading grain, an electro-hydraulic control system was designed. It can achieve synchronization of hydraulic mechanism operation and has fast flipping function, reducing unloading time.

(3) Field experiments revealed that the damage rate of corn ears resulting from direct contact with the bottom of the grain collection box ranged between 0.5% and 0.8%. Statistical analysis of unloading time under various working conditions showed that the unloading height ranged from 2.9 m to 4.4 m, while the unloading time ranged from 74 s to 126 s. The test results meet relevant standards and satisfy operational requirements, demonstrating the effectiveness and reliability of the proposed design.

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REFERENCES

[1] Balevičius R., Sielamowicz I., Mróz Z., Kačianauskas R., (2011). Investigation of wall stress and outflow rate in a flat-bottomed bin: A comparison of the DEM model results with the experimental measurements. *Powder Technology, Vol.214*, pp.322-336. Lithuania.

[2] Chen, S., Yi, K., Zhang, X., Jiang, C., Wang, Q., Huang, X., (2023). Design and test of longitudinal axial flow high and low roller type fresh corn flexible peeling device (高低辊组合式鲜食玉米柔性剥皮装置设计与试验). *Transactions of the Chinese society for agricultural machinery*, Vol. 54(S2), pp. 30-42. China.

[3] Cui, J., Xiao, Q., Xing, Q., Wu, M., Mu, J., Mei, Z., Bo, T., (2024). High yield cultivation techniques for fresh corn (鲜食玉米高产栽培技术). *Rural science and technology*, Vol. (06), pp. 7-11. China

[4] Gao, P., Zhang, X., Jiang, C., Yi, K., Zhang, X., Ma, Z., (2024). Optimized design and test of axial roller fresh corn threshing device (轴向滚筒式鲜食玉米脱粒装置优化设计与试验). *Transactions of the Chinese society for agricultural machinery*, Vol. 55(S2), pp. 145-156. China.

[5] Geng, N., Li, Y., Zhang, Y., (2023). Effects of modified dietary fiber from fresh corn bracts on obesity and intestinal microbiotain high-fat-diet mice. *Molecules,* Vol. 28(13), pp. 4949. China.

[6] González-Montellano C.., Ramírez A., Fuentes J.M., Ayuga F., (2012). Numerical effects derived from *en masse* filling of agricultural silos in DEM simulations. *Computers and Electronics in Agriculture*, Vol.81, pp.113-123. Spain.

[7] Guan, X., (2023). Design and mechanism of low loss debris removal device for fresh corn ears harvesting (鲜食玉米果穗收获低损除杂装置的设计及机理研究). Harbin: Northeast Agricultural University. China.

[8] Islam M.S., Liu, J., Jiang, L., (2021). Folate content in fresh corn: effects of harvest time, storage and cooking methods. *Journal of Food Composition and Analysis*, Vol. 103, pp. 104-123. Islam.

[9] Li, T., Zhou, F., Guan, X., Wu, H., (2019). Design and experiment on flexible low-loss fresh corn picking device. *International Agricultural Engineering Journal*, Vol.28(2), pp. 233-247. China.

[10] Liu, S., Tang, Z., (2017). Structure optimization of ear box bracket of 4YZS-4 type corn for seed harvester (4YZS-4型制种玉米收获机果穗箱支架结构优化). *Agricultural Engineering*, Vol. 7(01), pp. 64-67+71. China.

[11] Ma, Z., Souleymane, N., Zhu, Y., Li, Y., Xu, L., Lu, E., Li, Y., (2022). DEM simulations and experiments investigating of grain tank discharge of a rice combine harvester. *Computers and Electronics in Agriculture*, Vol.198,107060. China.

[12] Tang H. (2018). *Design and mechanism analysis of ripple surface pickup finger maize precision seed metering device (波纹曲面指夹式玉米精量排种器设计及其机理研究).* Harbin: Northeast Agricultural University. China.

[13] Wang L., Zhang, Z., Liu, T., Wang, Y., Jia, F., Jiang, J., (2020). Design and experiment of device for chopping stalk of header of maize harvester (玉米收获机割台砍劈式茎秆粉碎装置设计与试验). *Transactions of the Chinese society for agricultural machinery*, Vol. 51(07), pp. 109-117. China.

[14] Wei Z., Wang, Y., Li, X., Wang, J., Su, G., Meng, P., Han, M., Jing, C., Li, Z., (2023). Design and experiments of the potato combine harvester with elastic rubbing technology (弹性揉搓式马铃薯联合收获机设计与试验). *Transactions of the CSAE*, Vol.39(14), pp. 60-69. China.

[15] Yan K. (2016). John Deere S660 combine harvester (约翰迪尔S660型联合收获机). *Modernizing Agriculture*, Vol. (05), pp. 44. China.

[16] Zhang X., Yuan, Y., Nie, M., Li, Z., Ye, T., (2023). Design and testing of a double fan high-pressure impurity removal and cleaning device for fresh corn harvesters. *Engenharia Agrícola*, Vol.43(n4), pp. e20230069. China.

[17] Zhang X., Zhao, W., Nie, M., Li, Z., Liu, X., Lan, H., Chang, J., Yang, J., Ye, T., (2025). Design and test of diversion device for reducing the loss of fresh corn harvester ear box (鲜食玉米收获机果穗箱减损导流装置设计与试验). *Journal of Agricultural Mechanization Research*, Vol.47(03), pp. 41-47. China.

[18] Zhang X., Wu, H., Wang, K., Li, A., Shang, S., Zhang, X., (2019). Design and experiment of 4YZT-2 type self-propelled fresh corn double ridges harvester (4YZT-2型自走式鲜食玉米对行收获机设计与试验). *Transactions of the CSAE*, Vol.35(13), pp.1-9. China.
[19] Zhao S., Zhang, X., Yuan, Y., Hou, L., Yang, Y., (2022). Design and Experiment of powder organic fertilizer drilling fertilizer distributor (粉末状有机肥条施排肥器设计与试验). *Transactions of the Chinese society for agricultural machinery*, Vol.53(10), pp.98-107. China.
[20] Zhao Y., He, X., Shi, J., Liu, Q., Shao, G., Xie, Q., (2011). Design and experiment of sweet and waxy corn husker (鲜食玉米剥皮机的设计与试验). *Transactions of the CSAE*, Vol.27(02), pp.114-118. China.
[21] Zhou F., Guan X., Tang Z., et al. (2020). Parameter optimization and experiment of negative pressure impurity removal device for fresh corn ear harvest (鲜食玉米果穗收获负压除杂装置参数优化与试验). *Transactions of the Chinese society for agricultural machinery*, Vol.51(11), pp.138-147. China.
[22] Zhou H. (2013). A brief discussion on the ear box structure of corn harvester (浅议玉米收获机的果穗箱结构). *Hebei Agricultural Machinery*, Vol.No.185(05), pp.46-47. China.
[23] Zhu G., Li T., Zhou F. (2022). Design and experiment of flexible clamping and conveying device for bionic ear picking of fresh corn (鲜食玉米仿生摘穗柔性夹持输送装置设计与试验). Journal of Jilin University (Engineering Edition), Vol. (10), pp. 2486-2500. China.