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STUDY AND EXPERIMENT ON THE OPERATIONAL ADAPTABILITY OF SLOPE CORN HARVESTERS

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KEYWORDS

harvester, hilly slopes, cross rollers, telescopic tracked chassis, cob loss rate.

ABSTRACT

Studies on the operational adaptability of slope corn harvesters on hilly slopes are of great significance to improve the performance and safety of the whole machine, but there are few studies on this aspect at the present. Therefore, this paper takes a self-developed small sloping land crawler corn harvester as the object combined with the special topography of the hilly sloping land and the technology adopted by the machine to make a mathematical analysis of its operational adaptability on the sloping land. Through the field test, the forward speed of the corn harvester, track wheel spacing and slope angle are used as the test factors, and the harvest loss rate of the corn ear is used as the assessment index to carry out the orthogonal test on the slope land. The analysis of the results based on the Design-expert response surface was completed. The results show that the ear loss rate of the experiment under different conditions is less than 5% of the national standard. The corn harvester has good adaptability to sloped land, which can realize the mechanized operation of corn on the hilly and sloped land, and has good agricultural production application value.

INTRODUCTION

Maize is one of the most commonly planted grains in China. In 2020, the corn planting area of China reached 4.2×10^7 hm^2 (National Bureau of Statistics of the People's Republic of China, 2020), ranking first worldwide, which is of great strategic significance for ensuring the country's food security (Li et al., 2021). It has led to the rapid development of China's corn harvesting mechanization technology. By 2020, China's corn harvesting level has reached 89.76% (National Bureau of Statistics of the People's Republic of China, 2020; Ministry of Agriculture and Rural Affairs of the People's Republic of China, 2020). In the hilly mountainous area (with a slope angle of 15-25 °) accounting for 9.2% of the total land area, the mechanization level of corn harvesting in the hilly and mountainous area is only 8.9%. Therefore, Luo et al. pointed out that to accelerate the development of mechanization in hilly and mountainous areas, the strategic focus and priority should be placed on the development of high-efficiency and small-scale mechanized equipment (Luo, 2017; Yao, 2020).

To solve the problem of mechanized corn harvesting in sloping fields, experts at home and abroad have done work in this area. Gibson developed a divided car chassis that solved the problem of overturning agricultural equipment on hills and slopes, which improved the car's adaptability to complex terrain on slopes (Gibson et al., 1971). Bauer Wolfgang used hydraulic technology to adjust the attitude of the car bridge. Based on the chassis attitude information of the car on the slope, and the ratio of the load difference to a load of some of the equipment on the slope as the evaluation index for car rollover. An early warning model for car rollover prevention has been developed (Bauer, 2011). Iman Ahmadi developed a model for the effects of forwarding speed, slope angle, and wheel-to-bottom friction coefficient on the lateral stability of a tractor under positional disturbances (Ahmadi, 2011). Thomas Keller proposed a model for predicting the vertical stress distribution at the rubber track-soil interface to improve the accuracy of predicting soil stress and compaction risk in rubber-tracked agricultural vehicles (Keller & Arvidsson, 2016). Mężyk analysed the suspension system of high-speed tracks when working in rough terrain, developed a model for

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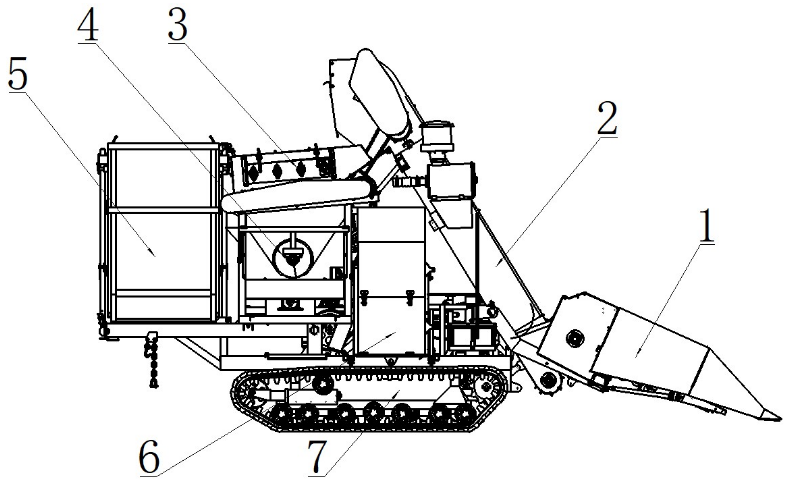
the suspension system of high-speed tracks, and explored the effect of different tensioning forces on the driving performance of tracked vehicles through simulations (Mężyk et al., 2017). Mao developed the 4YZP-2 self-propelled corn harvester from the perspective of reducing the structure of the whole machine (Mao et al., 2011, 2016). Its longitudinal dimension is reduced by 27% compared with the traditional harvester. Also, the weight of the whole machine is lower than the average of the domestic two-line harvester. The weight is reduced by 34%. It can provide mechanized equipment for corn harvesting in hilly and sloping fields. Liu established a mathematical model of track chassis steering considering many factors affecting track chassis steering, such as track grounding length, track gauge, track width, and speed of two tracks (Liu et al., 2010).

In summary, although experts have done much research in this area, further research on how to improve the structure of the harvester and the adaptability and performance of corn harvesters is needed. Therefore, this paper aims to point out that the corn harvester technology adopted by this machine is more adaptable to corn harvesting on sloping land and provides a new equipment for improving mechanized corn harvesting on hills and slopes.

MATERIAL AND METHODS

Structure of the Harvester

A sloping corn harvesting equipment comprised of a header, ear lifter, peeling device, collecting box, and adjustable wheel spacing is shown in Figure 1 and Table 1.



(1) Header (2) Ear lifter (3) Peeling device (4) Grain recovery device (5) Ear collection box (6) Powertrain (7) Wheel spacing adjustable chassis

FIGURE 1. Structure diagram of corn harvester.

TABLE 1. Main technical parameters.

Projects	Unit	Specification
Model specification	/	4YZP - 2L
Form of structure	/	Self-propelled crawler
Calibrated engine power	kw	48
Calibrated engine speed	r/min	2200
Whole machine size	mm	4300 * 1300 * 2600
Number of working rows	row	2
Working width	mm	1130
Track width	mm	230
Theoretical forward speed	（km/h）	1.9 - 2.8
Picking roller type	/	Horizontal spiral
Collection box	kg	300
Operating hour productivity	hm^2/h	0.3 - 0.4

Research and realization of adaptability of sloping corn harvester

China is a vast country with complex terrain. According to relevant information, the area and proportion of sloping land among arable land in China is shown in Table 2(The research group of the Department of Agricultural Mechanization Management, 2019; Ministry of Agriculture and Rural Affairs, 2019; Zhang, 2020; National Bureau of Statistics of the People's Republic of China, 2020; TABLE 2).

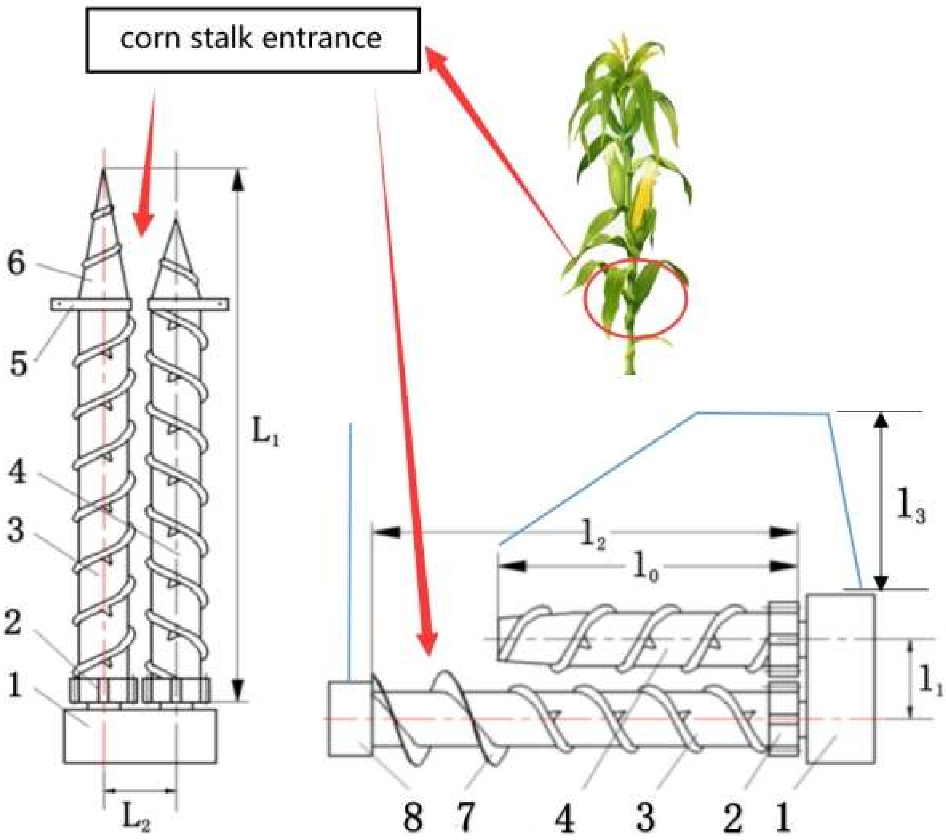
TABLE 2. Survey results of the area and proportion of sloping land in China′s arable land.

Cultivated land slope/°	Area/khm^2	Percentage/%
$\beta \leq 15$	106531.8	87.5
$15 \leq \beta \leq 25$	11143.2	9.2
$\beta > 25$	4040.9	3.3

The area of arable land with a slope of less than 25° reaches 1176745 khm^2, accounting for 96.7% of the total slope area. Therefore, the development of slope mechanization equipment suitable for slopes of less than 25° is the key to improving the level of mechanization in hilly and mountainous areas.

Longitudinal Size of Header

In view of the small working area of sloping farmland and the complex terrain, combined with the working characteristics of the sloping harvester. The harvester adopts a horizontal roller picking mechanism (Figure 2B) on the basis of the longitudinal lying picking structure of the traditional model (Figure 2A), which shortens the longitudinal dimension of the machine. The horizontal roller can improve its adaptability to complex terrain.



(a) (b)

(1) Gearbox (2) Strong pull section (3) Ear picking section (4) Short picking roller (5) Gap adjustment mechanism (6) Guide cone section (7) Leading blade (8) Front bearing seat

FIGURE 2. Longitudinal roller picking structure (a) Horizontal roller picking structure (b).

It can be seen from Figure 2A that the longitudinal dimension is L_1 (ignoring the influence of the size caused by the tilt). According to the agricultural machinery design manual, generally, L_1 = 1100–1300 mm. For the horizontal roller picking structure, the longitudinal dimension is l_1 = 250–350 mm. Combined with the horizontal roller picking, the ears are equipped with an independent grain divider, and its length is l_0 = 350–450 mm. So, the longitudinal reduction size of the whole harvester Δ is:

$$\Delta = L_1 - l_1 + l_3 \tag{1}$$

Where:

L_1 is the length of the longitudinal roller picking structure;

l_1 is the length of the horizontal roller picking structure;

l_3 is the length of the grain divider (mm), and

Δ is the shortening.

Obviously, substituting the above data shows that the length of the whole machine is effectively shortened by 500–700 mm, which is 13–20% shorter than the traditional whole machine. It can improve the adaptability of the harvester to small plots of work.

Load Transfer of Slope Field Operation

The transverse structure is more adaptable to small plots of land than the longitudinal structure. Considering the sloping land operation process, the left and right wheels may be at different levels. It will lead to a transfer of load between the left and right wheels (Jin et al., 2007; Duan & Qiu, 2018). It means a significant increase in the load of the lower wheels and a significant decrease in the load of the higher wheels. This leads to problems of sinking, side sliding, and even tipping of the whole vehicle. Therefore, the harvester uses a crawler driving device (Zhang, 2019; Xie, 2020), which increases the contact area between the corn harvest and the ground surface. It also prevents the risk of sinking and side sliding of the whole vehicle. Furthermore, to determine the rate of load-deflection that occurs in sloping operations, a force analysis was carried out (Figure 3).

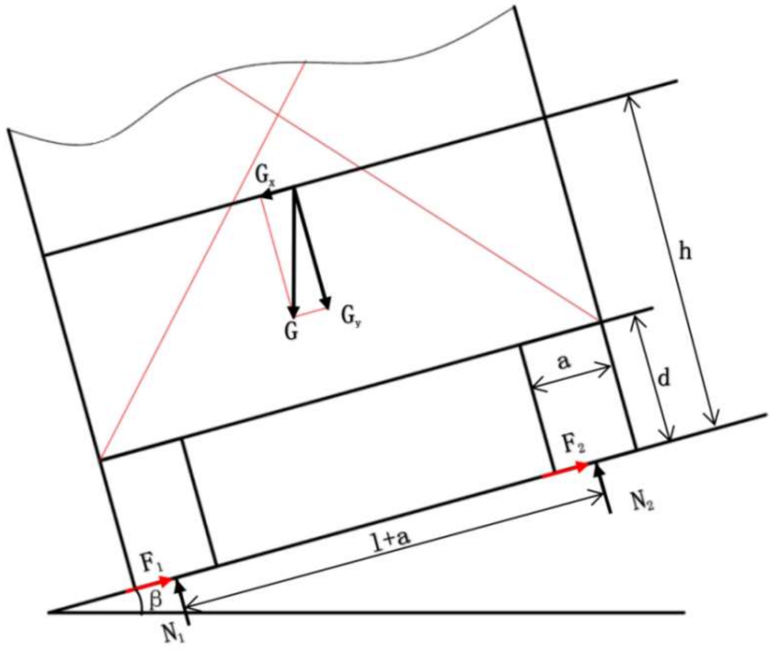


FIGURE 3. Analysis on the force of corn harvested on the slope.

When corn is harvested on a slope, harvester mainly bears the gravity G and the supporting forces N_1 and N_2 of the left and right driving wheels. The frictional forces F_1 and F_2 caused by the uneven ground surface slide down. The wheel width is $2a$, the center of gravity height is h, the driving wheel diameter is d, and the slope angle is β. Then, based on

$\begin{cases}\sum x=0\\ \sum y=0\end{cases}$, we can get:

$$\begin{cases}N_1+N_2=G_y=G\cos\beta\\ F_1+F_2=G_x=G\sin\beta\end{cases} \quad (2)$$

Based on $\sum M(x)=0$, we can get:

$$N_2(l+a)+G_xh=G_y\frac{l+a}{2} \quad (3)$$

Combining the above equations:

$$\begin{cases}N_1=\frac{G}{2}(\cos\beta+\frac{2h}{l+a}\sin\beta)\\ N_2=\frac{G}{2}(\cos\beta-\frac{2h}{l+a}\sin\beta)\end{cases} \quad (4)$$

Where:

G is the gravity of the harvester;

G_x is the component of G along x;

G_y is the component of G along y;

N_1= the supporting force of the ground to the left wheel;

N_2 is the supporting force of the ground to the right wheel;

h is the height of the center of gravity;

l is the wheel spacing, and

a is the Crawler bandwidth.

Clearly, when working on a slope, it will cause the deviation of the load of the left and right wheels. Assuming the load deviation ratio is the ratio of the offset load of the two wheels to the load on the flat ground, the deviation rate K is:

$$K=\frac{N_1-N_2}{N_0}=\frac{4h}{1+a}\sin\beta \quad (5)$$

Where:

K is the deviation rate;

N_1 is the supporting force of the ground to the left wheel;

N_2 is the supporting force of the ground to the right wheel, and

N_0 is the supporting force of the ground to the harvester.

As can be seen from the above equation, the load transfer rate of the left and right wheels is influenced by three factors: the position of the center of gravity, the size of the slope, and the wheel spacing of the left and right wheels (including the width of the driving wheels touching the ground). As the height of the center of gravity and the slope angle increase, the wheel spacing of the left and right wheels decreases. The load transfer rate will increase, while the safety of the maize harvesting operation will decrease. Considering that the center of gravity height is affected by the full load of the ear, chassis height, and other factors as well as the non-selectivity of operating terrain, which adopted the method of increasing the left and right wheel spacing to improve the safety of the corn harvester (Zhang et al., 2010; Pan, 2015; Zhu et al., 2020).

Anti-load Transfer Strategy

As mentioned above, in order to avoid a large load transfer rate of the corn harvester in the slope operation process, the strategy of increasing the left and right wheel track can be adopted. However, there are two ways to increase the spacing of the left and right wheels. One is to increase the spacing of the left and right wheels by means of unilateral wheel extension, and the other is to increase the spacing of the two wheels by means of double wheel extension. In order to determine the impact of the two methods on load transfer, the load distribution is analyzed (Figure 4).

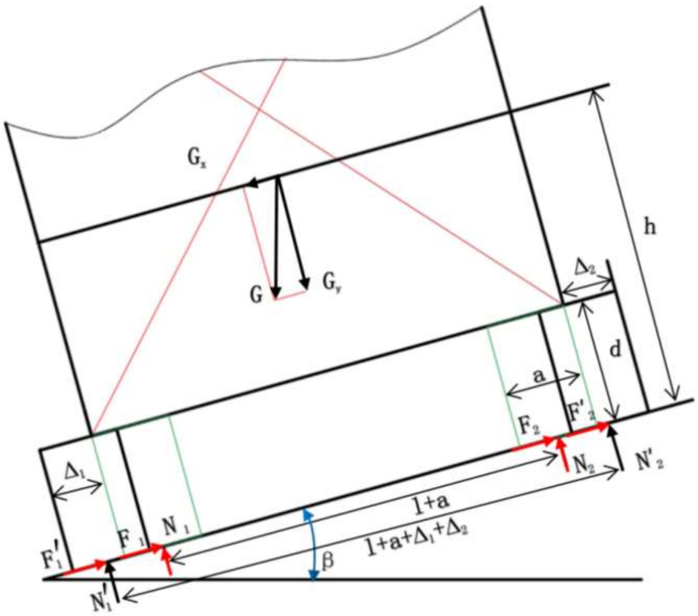


FIGURE 4. Load-bearing analysis after the driving wheel is extended.

Assume that the extension of the low wheel is Δ_1. The extension of the high wheel is Δ_2. The low wheel receives the supporting force N_1' and the friction force F_1'. The high wheel receives the supporting force N_2' and the friction force F_2'. Then, based on $\begin{cases}\sum x = 0 \\ \sum y = 0\end{cases}$, we can get:

$$\begin{cases} N_1' + N_2' = G_y = G\cos\beta \\ F_1' + F_2' = G_x = G\sin\beta \end{cases} \tag{6}$$

Based on $\sum M(x) = 0$, we can get:

$$N_2'(l + a + \Delta_1 + \Delta_2) + G_x h = G_y \frac{l+a}{2+\Delta_1} \tag{7}$$

Combining eqs. (6) and (7):

$$\begin{cases} N_1' = \frac{G}{2}\frac{(l+a+2\Delta_2)\cos\beta + h\sin\beta}{l+a+\Delta_1+\Delta_2} \\ N_2' = \frac{G}{2}\frac{(l+a+2\Delta_1)\cos\beta - h\sin\beta}{l+a+\Delta_1+\Delta_2} \end{cases} \tag{8}$$

Obviously, the load transfer rate after adjusting the left and right distance is:

$$K' = \frac{N_1'-N_2'}{N_0} = \frac{2(\Delta_2-\Delta_1)\cos\beta + 4h\sin\beta}{1+a+\Delta_1+\Delta_2} \tag{9}$$

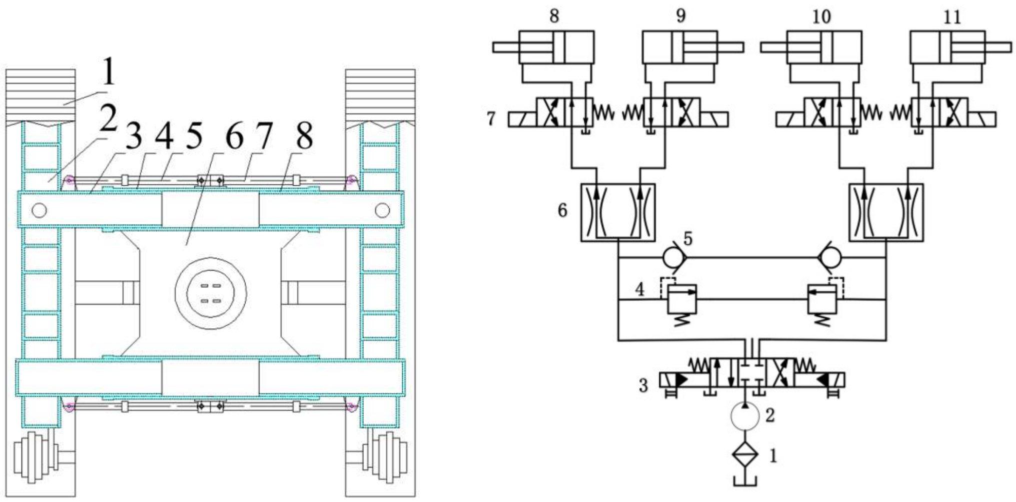
The above equation shows that when the left and right wheels are equally spaced out at the same time, that is, when $\Delta_1 = \Delta_2$, $K' = \frac{4h\sin\beta}{1+a+2\Delta_1}$, which indicates that the left and right wheels can be extended equally at the same time to reduce the load transfer rate of the left and right wheels. The safety of the whole harvester operation can be improved.

When the position of the low wheel remains unchanged, that is, when $\Delta_1 = 0$, $K' = \frac{2\Delta_2\cos\beta + 4h\sin\beta}{1+a+\Delta_2}$, it indicates that the high wheel is used to extend. The load transfer rate of the left and right wheels increases, which will reduce the safety of corn harvesting operations on slopes.

When the position of the high wheel remains unchanged, that is, when $\Delta_2 = 0$, $K' = \frac{4h\sin\beta - 2\Delta_1\cos\beta}{1+a+\Delta_2}$, it indicates that the low wheel is used to extend, which indicates that this method will significantly reduce the load transfer rate of the left and right wheels. It will significantly improve the safety of corn harvesting operations on slopes.

Adjustment Mechanism and Hydraulic Control System

As above, increasing the left and right track separately can reduce the load transfer rate and improve the safety of the whole machine operation. The principle of wheel spacing adjustment is to adopt the telescopic shaft structure with "H" distribution. The layout of the telescopic frame can be divided into two ways: opposed and misplaced. Among them, the misalignment distribution can increase the adjustment range of the wheel spacing. However, the misalignment distribution will not only increase the complexity of the transmission structure but also cause the misalignment of the rotating shaft. It will affect the smoothness of the transmission. While the opposed distribution has a small wheel track adjustment range, its structure is simple and stable. Furthermore, combined with the characteristics of small plots of slope land, this study adopted an opposed distribution structure with a smaller adjustment range (Gao & Wang, 2006, Figure 5A).



(a) (b)

(a) (1) track (2) Left walking beam (3) left telescopic frame (4) fixed frame (5) left telescopic cylinder (6) chassis base (7) right telescopic cylinder (8) right telescopic frame

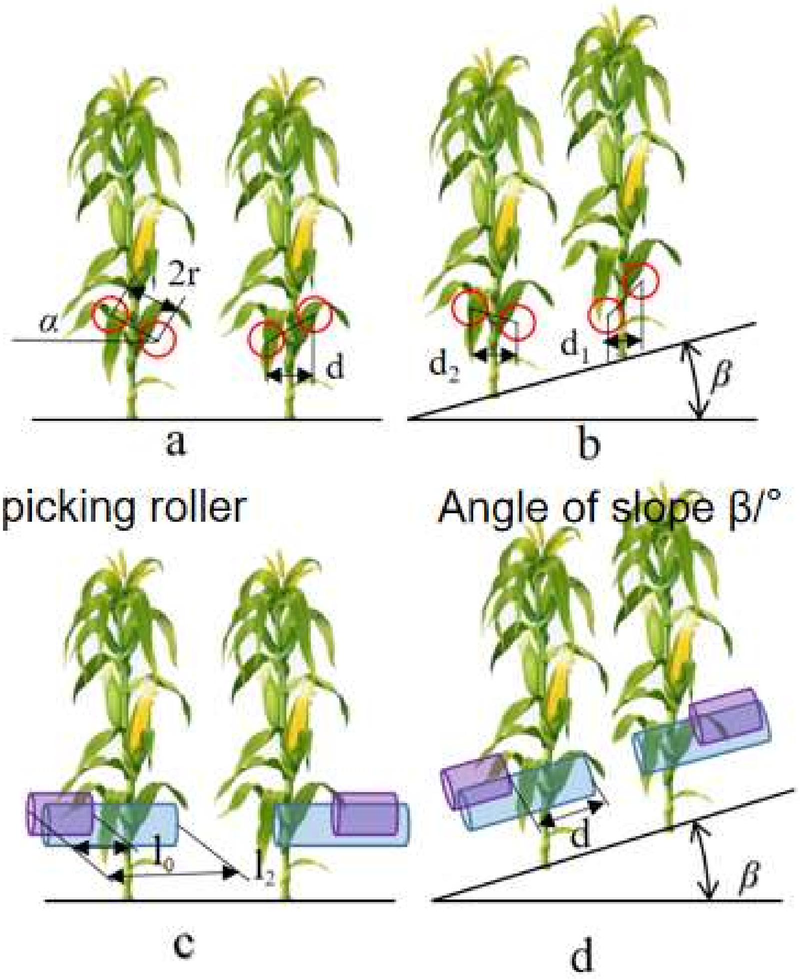
(b) (1) filter (2) hydraulic pump (3) three-way four-way solenoid valve (4) relief valve (5) check valve (6) diverter valve (7) two-way two-way solenoid valve (8) left rear wheel adjusting cylinder (9) left front wheel adjusting cylinder (10) right rear wheel adjusting cylinder (11) right front wheel adjusting cylinder

FIGURE 5. Diagram of crawler extension (a) Wheel spacing hydraulic adjustment control system (b).

Considering the weight of the machine and the complexity of the operating environment (Sun et al., 2019; Sun et al., 2020), the wheel spacing adjustment of the maize harvest adopts a hydraulic control system to adjust (Figure 5B).

Adaptation of Row Spacing in Maize Harvest

Corn ear picking is the separation of the ear and stalk in the pull-down process of the stalk under the action of a pair of relative inward rotating ear picking rollers. The prerequisite is that the stalk enters the gap between the ear picking rollers. Generally speaking, to reduce the biting injury of the picking roller on the ear of corn, the picking roller group usually adopts the layout structure of outer high and inner low (He, 2019; Zhang & Wu, 2019; Figure 6).



(a) Schematic diagram of the longitudinal roller picking structure for level ground operation
(b) Schematic diagram of the longitudinal roller picking structure on sloping ground
(c) Schematic diagram of the cross-roller picking structure on level ground
(d) Schematic diagram of the cross-roller spike picking structure on sloping ground

FIGURE 6. Adaptability analysis of row spacing on slopes.

It can be seen from Figure 6 that since the terrain is a slope with an inclination angle β, the entrance gap between the two pairs of ear-picking roller sets must change relative to the gap in the corn feeding direction. Suppose the original entrance gap between the two ear picking rollers is 2r and the angle between the center line of the inner and outer ear picking rollers and the horizontal plane is a. When the corn is harvested on flat ground, the entrance gap is:

$$d = 2r\cos\alpha \tag{10}$$

When the corn is harvested on a sloping field, the entry gap of the low picking roller is:

$$d_2 = 2r\cos(\alpha - \beta) \tag{11}$$

The entrance gap of the high picking roller is:

$$d_1 = 2r\cos(\alpha + \beta) \tag{12}$$

Obviously, for the low-position ear-picking roller group, the entrance gap is increased, which is conducive to row harvesting. However, it will affect the difficulty of removing the ears from the stalk, which increases the probability of ears being gnawed. For the high-position ear picking roller, the entrance gap will inevitably decrease. Although it is beneficial to remove the ears from the stalk and reduce the probability of ear gnawing, it will inevitably increase the difficulty of the corn plant entering the ear-picking roller group. In severe cases, it will lead to the probability of corn plants being blocked at the entrance of the picking roller group. Therefore, this study adopts the ear-picking structure of a horizontal roller, as shown in Figure 2B. Because the structure of this picking ear is short front roll and long back roll, the feeding inlet clearance in flat ground operation is:

$$d = l_2 - l_0 \tag{13}$$

When the maize harvest is operated on sloping ground, the picking rollers are parallel to the sloping ground surface. So, its clearance is:

$$d_2 = d_1 = (l_2 - l_0)\cos\beta \tag{14}$$

Obviously, the gap is significantly larger than the feed inlet gap of the traditional ear picking method. When working on slopes, the high and low gap changes are equal, which will not cause a significant change in the feed inlet gap. It is conducive to the entry of corn into the feed inlet. Secondly, due to the structure is a layout with a high front picking roller and a low rear picking roller, and the relative position is not affected by the slope angle, which can ensure the picked ears will stably slide off the picking rollers and reduce the probability of ear gnawing injuries. In addition to the harvesting process, the corn to be harvested is in front of the ear picking roller, which can effectively prevent the ears from falling out and reduce the loss of ears.

Forward and Reverse Operations

Due to the small area of the sloping land and the complex terrain, it is difficult to meet the turning requirements of the large turning radius corn harvester, and frequent turning around increases the operating time and safety hazards during the harvesting period (Jin & Du, 2016; Geng & Sun, 2021). Therefore, the working parts and the chassis in this study adopt a turntable structure, that is, when working on the ground, the corn harvesting device can be adjusted at a large angle without moving the chassis. Also, the corn harvesting device can achieve a 360° rotation function relative to the chassis (Figure 7), which provides convenience for the U-turn of the harvester.

FIGURE 7. Schematic diagram of forward and reverse operations.

Through field tests, it takes about 45 s to turn the machine around by the chassis travel device. However, with this forward and reverse turning control technology, it only takes about 7 s to complete the head turn. It greatly shortens the field turning time and increases the efficiency of the machine's head turn by more than 90%, significantly improving the machine's adaptability to small plots of land.

FIELD TRIAL

Test Conditions

Field trials of a hilly slope maize harvester were carried out in September 2020 on a maize test plot at Shandong Guofeng Machinery Manufacturing Co. The maize was planted in rows spaced 600 mm apart. The test plot was approximately 75 m long and 20 m wide, and the slope of the test plot was 0–25°. The physical characteristics of the maize variety tested were Zhengdan958 at harvest. The moisture content of the corn kernels and corn stalks was 32.5% and 88%, respectively. The cob droop rate is less than 5%, plant fall rate is less than 5%, and minimum cob height is more than 350 mm (Figure 8).

FIGURE 8. Field experiment.

Test Method

According to GBT21961-2008 'Corn Harvester-Test Method', GBT 21962-2008 'Corn Harvester-Technical Conditions', and NY/T645-2002 'Technical Specification for Quality Evaluation of Corn Harvester', the adaptability of the corn harvester on a slope is tested. The main measuring equipment used for ear loss rate includes: 0–30 m tape measure, TL-4 intelligent moisture tester, J9-2 electronic stopwatch, HCS-50 electronic crane scale, and JJ3000 electronic balance.

In the test area, collect the missed and fallen ears (including ear segments above 5 cm) and weighed them. The loss rate of ears was calculated by the following equation.

$$S_u = \frac{W_b}{W_z} \times 100\% \quad (15)$$

Where:

Su is the ear loss rate, %;

Wb is the weight of the ear lost in the measurement area, kg, and

Wz is the weight of the ear in the measurement area, kg.

Adaptability Test

Usually, when working on slopes, the whole machine itself encounters the slope of the road, causing the whole machine to tilt around the side of the crawler. In severe cases, it will roll over. The factors causing the tilting of the corn harvester are divided into internal factors and external factors. The internal factors are forward speed, steering centrifugal force, and change of center of gravity position. External factors refer to the influence of the intervention of the uneven surface under objective conditions on the tilting of the whole machine (Liu & Yang, 2013; Wang & Yang, 2019).

In order to verify the adaptability of the maize harvester to sloping land, plots with different slopes were firstly selected for operational harvesting to give full play to the effect of the wheel spacing adjustment on the sloping land adaptability. Secondly, when the maize harvester was harvested on flat land, the forward speed had an effect on the amount of feed that would lead to the effect of picking the ears. In the slope trials, therefore, forwarding speed was chosen as the test factor. As analysed above, different slope angles had a significant effect on the size of the feed inlet. So, different slope angles were selected for the harvesting operations to verify the effect of the whole machine on the harvesting results. Therefore, the test index selected for this validation test was the ear loss rate, and the test factors were forward speed, track wheel spacing, and slope angle. A test program was designed for the adaptation of a tracked chassis for lateral slope operation on hilly slopes with reference to the Optimised Test Design. The levels of parameters are shown in Table 3. The result of the multiple factor experiment results is shown in Table 4.

TABLE 3. Levels of parameters.

Levels	**Factors**		
	Forward speed X_1 /km/h	Track wheel spacing X_2 /mm	Angle of slope X_3 /°
-1	1.4	1300	6
0	2.1	1700	12
1	2.8	2100	18

TABLE 4. The result of the multiple-factor test.

Test number	**Levels**			the ear loss rate Y/%
	X_1	X_2	X_3	
1	-1	-1	0	2.32
2	1	-1	0	2.68
3	-1	1	0	1.87
4	1	1	0	2.16
5	-1	0	-1	1.85
6	1	0	-1	2.32
7	-1	0	1	2.88
8	1	0	1	3.23
9	0	-1	-1	1.95
10	0	1	-1	1.65
11	0	-1	1	3.12
12	0	1	1	3.06
13	0	0	0	2.15
14	0	0	0	2.35
15	0	0	0	2.20
16	0	0	0	2.22
17	0	0	0	2.19

RESULTS AND DISCUSSION

Regression model establishment and significance test of the ear loss rate

According to the test scheme and test results in Table 4, multiple regression fitting is carried out using the data analysis software Design-Expert.10. The regression model of the ear loss rate is shown in Eq. (15). The significance test of the equation is shown in Table 5.

$$Y = 2.22 + 0.18X_1 - 0.17X_2 + 0.57X_3 - 0.018X_1X_2$$
$$-0.03X_1X_3 + 0.06X_2X_3 + 0.08{X_1}^2 - 0.045{X_2}^2 + 0.27{X_3}^2 \tag{16}$$

Where:

X_1 is the operating speed, km/h;

X_2 is the track wheel spacing, mm, and

X_3 is the slope angle,° .

TABLE 5. ANOVA analysis for the rate of ear loss.

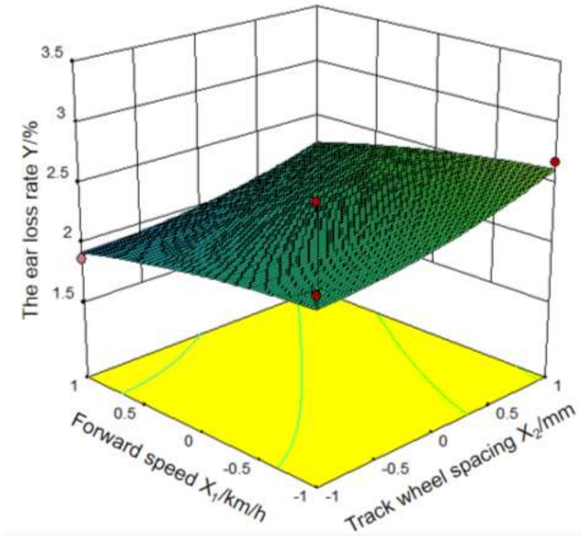
Variance Source	Sum of Squares of Deviations	Freedom f	F Value	p-Value
Model	3.41	9	21.30	0.0003 ***
X_1	0.27	1	15.20	0.0059 **
X_2	0.22	1	12.44	0.0096 **
X_3	2.55	1	143.70	< 0.0001 **
X_1 X_2	1.225E-003	1	0.069	0.8005
X_1 X_3	3.600E-003	1	0.20	0.6663
X_2 X_3	0.014	1	0.81	0.3980
X_1X_2	0.027	1	1.53	0.2566
X_2X_2	8.432E-003	1	0.47	0.5131
X_3X_2	0.30	1	16.98	0.0045
Residual	0.12	7		
Lack of Fit	0.10	3	5.85	0.0604
Pure Error	0.023	4		
Cor Total	3.53	16		

Note: X_1 is Forward speed /(km/h); X_2 is Track wheel spacing /(mm); X_3 is Angle of slope/(°);*** is extremely significant ($p < 0.001$) ; ** representative test factors are significant at 0.01 significance level; * representative test factors are significant at 0.05 significance level.

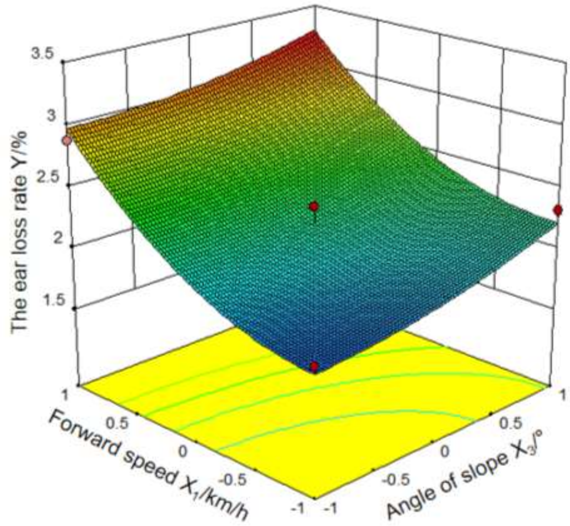
Table 5 shows that the regression model of the ear loss rate has $P < 0.01$, indicating that the model is extremely significant. The mismatch criterion $P > 0.05$ produces no mismatch factors, indicating that the regression model can be used to replace the real point of the test in order to analyze the results. The model determination coefficient $R^2 = 0.9648$ indicates that the model can reflect a change of 96.48% in the response value and that the regression model fits the sample points well. In this model, the P values of terms X_1, X_2, and X_3 are all less than 0.01, indicating that the confidence interval of the regression term is within 99%, while the impact on the angle of slope is extremely significant.

Response effect analysis of interactive factors on the ear loss rate

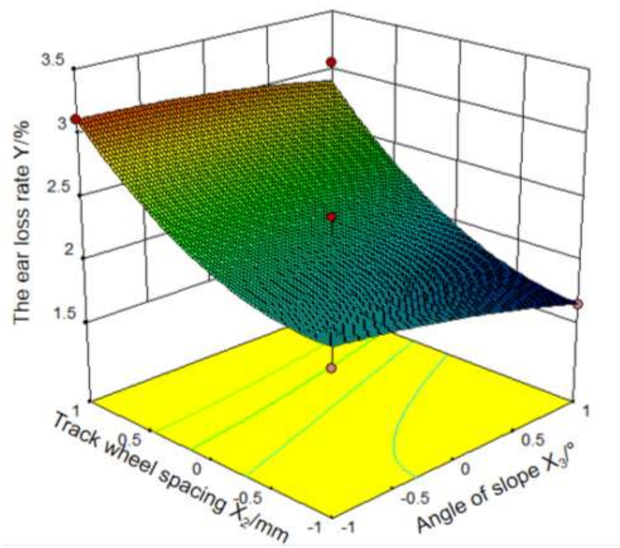
This section only analyzes the response effect between significant items and the ear loss rate, while non-significant terms are ignored. The response surface analysis is shown in Figure 9.



(a)



(b)



(c)

(a) Interaction of forward speed and track wheel spacing

(b) Interaction of forward speed and slope angle

(c) Interaction of track wheel spacing and slope angle

FIGURE 9. The influence of interaction factors on the ear loss rate.

The interaction between forward speed and track wheel spacing on the loss rate of maize cobs harvested on slopes was obtained when driving at a slope angle of 12° (Figure 9a). As the track wheel spacing increases, the loss rate of maize cobs is reduced because when the track wheel spacing increases, the lateral load transfer rate of the machine is reduced, which, as analysed above, makes the machine more stable and reduces the loss rate of cobs during operation. When the forward speed is low, the loss rate of maize ears is small; as the speed increases, the loss rate of ears tends to increase because as the operating speed of the harvester increases, the feeding volume of ears at the cutting table becomes larger, leading to congestion of ears at the picking roller, resulting in a larger loss rate of ears. The interactive effect of slope angle and track wheel spacing on the loss rate of harvested maize cobs on slopes was obtained when the forward speed was 2.1 km/h (Figure 9b). When the track wheel spacing is not extended, the loss rate of maize cobs is more influenced by the angle of the slope, and when the track is fully extended, the loss rate of maize cobs is less influenced by the angle of the slope compared to when it is not extended. This suggests that a telescopic track chassis can increase the adaptability of the maize harvester to sloping ground. When the track wheel spacing was 1700 mm, the interaction between the travel speed and slope angle on the loss rate of harvested maize cobs on sloping ground was obtained (Figure 9c). As the forward speed increased, there was a tendency for the loss rate of maize cobs to increase in all slope conditions. When the slope angle is 6°, an increase in forward speed can increase the efficiency of maize harvesting while keeping the loss rate low; when the slope angle is 18°, an appropriate reduction in forward speed can reduce the loss rate of maize cobs.

The analysis of the whole machine harvesting maize on the sloping ground shows that the order of the factors according to the ANOVA results is $X_3 > X_1 > X_2$, i.e., the order of influence of the test factors on the cob loss rate is: slope angle > forward speed > track wheel spacing. The results of the variance show that all three factors are the main factors influencing the loss rate of the whole machine on maize cob harvesting. The comprehensive test results show that the developed crawler-type slope maize harvester can effectively reduce the harvesting loss rate of ears when working on slopes, which increases the adaptability of the harvester to slope operations and can meet the needs of slope maize mechanised harvesting.

CONCLUSIONS

The load distribution and transfer of the left and right wheels during the slope operation of the whole harvester were analyzed. The strategy of lowering the load transfer with the extension of the low wheels was determined, and the safety performance of the whole machine operation was improved.

The horizontal roller picking mechanism reduces the longitudinal dimension of the whole machine by 500–700 mm, improving the adaptability of the whole machine to small plots. The consistency of the entrance gap of the picking roller group when the corn is harvested on sloping fields was ensured.

The forward and reverse two-way operation control systems meet the small-range U-turn requirements of the slope corn harvester in slope-field operations. The overall machine U-turn efficiency was increased by more than 90%.

The results of the field trials show that track wheel spacing, slope angle, and operating speed are the main factors affecting the coefficient of loss rate of the slope maize harvester. The effect of the interaction of the two factors on the cob loss rate was analyzed, and the results showed that the developed crawler-type slope maize harvester is highly adaptable to hilly and mountainous areas. All the indexes meet the relevant national standards and can meet the needs of hilly mountainous areas for maize mechanical harvesting.

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