Design and Experiment of Root Stubble Harvester for Corn*

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Abstract

Offset digging shovel and three-roller mechanism were developed to realize the complete working process of root stubble harvest, which included root stubble digging, picking up, stubble-soil separating and root stubble paving. Structural and kinematic parameters of a root stubble harvesting machine were determined by analyzing digging characteristics of the shovel and kinematics of the three-roller mechanism. In field tests, the offset digging shovel demonstrated competency of digging, and the three-roller mechanism showed capability of picking up, separating and paving. The stubble digging, picking up and paving rate of stubble harvest machine were more than 90%. Its work met the requirements of design and application.

Key words　Root stubble digging, Digging shovel, Three-roller mechanism, Stubble-soil separating, Root stubble harvesting machine

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Introduction

Compared to other crops' root stubble, root stubble of corn is thicker and heavier, and is a clean biomass fuel source with high calorific content. Acquisition of this root stubble is the first step to use its biomass energy. However, the traditional manual stubble excavating consumes large amount of labor and therefore is low in efficiency. To achieve the use of stubble in large-scale, mechanized harvesting methods must be implemented. At present, there is a popular method called stubble breaking and no-tillage operations to conduct mechanical harvesting of stubble, mechanical harvesting was seldom used on corn stubble. Therefore, it was necessary for a corn stubble excavation and root soil separation parts to be developed to meet the technical requirements of root stubble digging rate more than 90% and the effective paving.

In this study, a root stubble harvesting machine will be developed. It consists of the offset shovel and three-roller mechanism and could accomplish operations such as corn root stubble digging, picking up, stubble-soil separating and paving.

1　Materials and Methods

1.1　Structure Characteristic and Working Principle

The root stubble harvesting machine was composed of frame, transmission mechanism, offset digging shovel, three-roller mechanism (front picking roller, rear picking roller, upper hammering roller), retaining cover, paving plate and so on, as shown in Fig. 1.

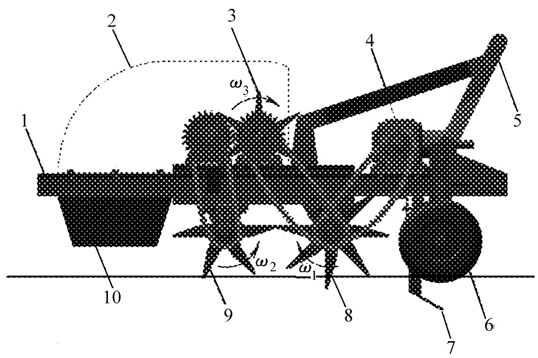

Fig. 1　Structure of root stubble harvesting machine
1. Frame　2. Retaining cover　3. Upper hammering roller　4. Transmission mechanism　5. Hitch bracket　6. Depth wheel　7. Offset digging shovel　8. Front picking roller　9. Rear picking roller　10. Paving plate

During operation, root stubble dug out of soil by offset digging shovel was first picked and flung up by the front picking roller and the rear picking roller

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rotating in forward (the same direction as the rotation of the tractor wheels) and reverse direction respectively. Then, the ascending stubble was struck and thrown backward by the upper hammering roller. The root stubble finally hit the retaining cover, fell on the paving plate and was paved in stripes along with the forward of the machine. After this process, stubble and soil were separated by the impact from the rollers, hence root stubble harvest was completed.

1.2 Design of Key Parts

1.2.1 Design of Root Stubble Digging Shovel

There are many types of digging components including plane shovel, surface shovel, chisel shaped shovel and so on[1]. Plane shovel is wildly applied because the structure was simple and its manufacture was relatively easy. Referring to details of triangular plane shovel[2], parameters of root stubble digging shovel as shown in Fig. 2 were researched and the optimum values were determined as: bevel of shovel edge $\gamma = 45°$, inclination angle $\alpha = 20°$, shovel length $L = 320$ mm and shovel width $B = 320$ mm.

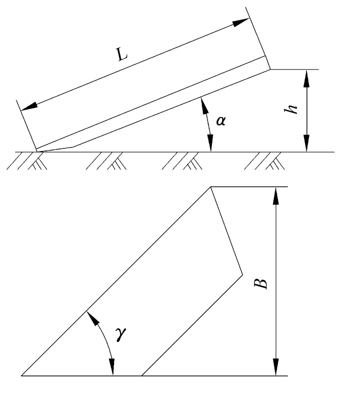

Fig. 2 Parameters of root stubble digging shovel

3-D model the shovel was shown in Fig. 3. In order to reduce the possibilities of impacts between root stubble and shovel handle, a offset digging shovel was proposed. Offset means that shovel handle's installation position deviates from the mid-point of blade edge for $e = 110$ mm. Thanks to the offset handle, the root-soil complex cut at the bottom of ridge-row by shovel blade could move backward smoothly along the shovel plane to the downside of front picking roller. If a pair of shovels were designed symmetrically (digging width of two rows), having the imposed opposing lateral forces cancelled out, the machine would be subject to traction resistance only and exhibit an excellent balance quality.

1.2.2 Design of Three-roller Picking up and Stubble-soil Separation Mechanism

Root stubble dug out of soil was first picked up

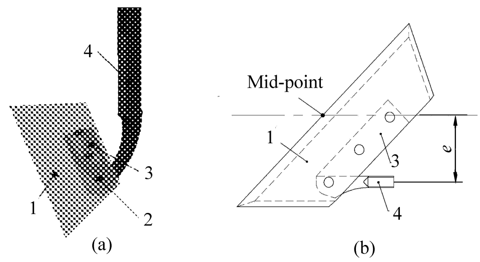

Fig. 3 3-D model and platform of the shovel

(a) 3-D model of the shovel (b) Platform of the shovel

1. Shovel blade 2. Connecting bolt 3. Support board 4. Shovel handle

and flung up by front picking roller and rear picking roller which were installed under the frame and were designed to rotate in opposite directions, then the root stubble was thrown backward by the upper hammering roller. Finally the root stubble flying backward hit the retaining cover and fell down on the paving plate. Three-roller mechanism was shown in Fig. 4. v_m was forward velocity, m/s; ω was angular velocity, rad/s.

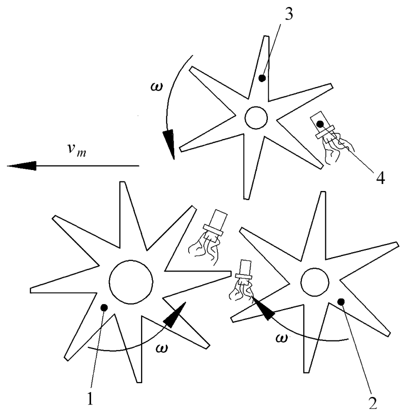

Fig. 4 Three-roller picking and soil separation mechanism

1. Front picking roller 2. Rear picking roller 3. Upper hammering roller 4. Root stubble

(1) Motion Analysis of Front Picking Roller

The motion any point on the rollers travels was a composed by the machine's forward motion and the rollers' rotational motion[3]. We defined that the front picking roller axis was the origin of the coordinate, the forward moving direction of the machine to be $+x$ direction, and the y axis was vertical upwards (Fig. 5). The parametric equations[3~5] which described the path of this point were

$$\begin{cases} x = R\cos\omega t + v_m t \\ y = R\sin\omega t \end{cases} \tag{1}$$

where, t—time, s

R—radius of roller, mm

For front picking roller rotating in forward direction, ω is negative; for rear picking roller rotating in reverse direction, ω is positive.

Velocity of x component can be calculated by the

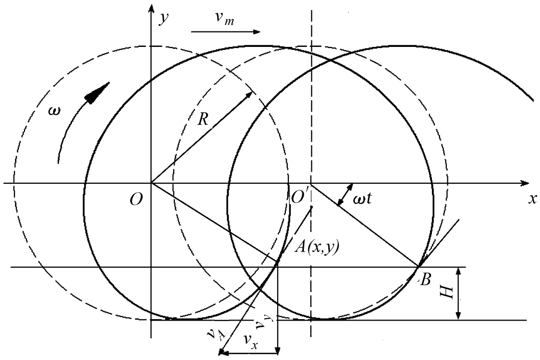

Fig. 5　Locus of a peripheral point on front roller

derivative of Eq. (1) with respect to time

$$v_x = \frac{dx}{dt} = v_m - R\omega \sin\omega t \quad (2)$$

v_x was a variable affecting picking performance. If $v_x > 0$, which means the x component of the velocity of this point was in the same direction with the machine's forward direction, instead of throwing backward root and soil or picking up root stubble, the front picking roller would push soil and root stubble forward. To ensure effective picking, v_x must be negative and its absolute value must be larger than a threshold value, that was

$$\begin{cases} v_x = v_m - R\omega\sin\omega t < 0 \\ |v_x| \geqslant v_p \end{cases} \quad (3)$$

where, v_p—a constant, defined as the minimum velocity the front picking roller must satisfy

During the soil cutting process, $|v_x|$ increased with time. This means that if at the moment of soil entry v_x complies with Eq. (3), it will continue to satisfy it in the complete process. Therefore, parameters at the moment of soil entry (point A in Fig. 5) must be analyzed. Suppose the cutting depth was H, from Fig. 5 and Eq. (1), it was known that

$$y = R - H = R\sin\omega t \quad (4)$$

then,

$$\sin\omega t = \frac{R-H}{R} \quad (5)$$

Eliminating v_x and $\sin\omega t$ by substituting Eq. (5) into Eq. (3), and rearranging yields

$$\omega \geqslant \frac{v_m + v_p}{R-H} \quad (6)$$

therefore,

$$n \geqslant \frac{30(v_m + v_p)}{\pi(R-H)} \quad (7)$$

where, n—rotational speed, r/min

If v_p is too large, root stubble may be smashed easily; however, if it is too small, it will cause the root stubble pushing. Considering that peripheral velocity of rotary tiller's rotor u was 3 ~ 8 m/s and straw smashing velocity of multi-function smashed straw machine v_s was 5.5 m/s, v_p here was set as $v_p = 3.5$ m/s. Given that $v_m = 1$ m/s, $R = 210$ mm and $H = 50$ mm, rotational speed n can be calculated as

$$n \geqslant \frac{30(v_m + v_p)}{\pi(R-H)} = 268.5$$

Rounded to $n = 270$ r/min, namely, ω was 28.3 rad/s, one-half of tractor PTO shaft's speed.

(2) Motion Analysis of Rear Picking Roller

Contrary to front picking roller, the rear picking roller's, in the soil cutting process, x component peripheral velocity v_x was always in the same direction with v_m. To the soil entry point, v_x was

$$v_x = v_m - R\omega\sin\omega t = v_m + |R\omega\sin\omega t| = v_m + \omega(R-H) = v_m + \frac{(R-H)\pi n}{30} \quad (8)$$

To realize picking, v_x must be greater than a threshold value, and satisfied the following inequality

$$v_x \geqslant v'_p \quad (9)$$

As root stubble has already been poked to ground surface by front roller, so cutting depth and radius of rear picking roller should be smaller than that of the front picking roller. $H = 30$ mm, and $R = 190$ mm was suitable here. Based on experience and the value of v_p, v'_p was set as $v'_p = 5$ m/s. So $n \geqslant 239$ r/min was obtained by substituting these values into Eq. (8) and Eq. (9).

To simplify manufacture, gears and chain sprockets of the same specification were recommended. So transmission ratio 1∶1 was selected, rear picking roller's speed was finally compromised at 270 r/min, the same with front picking roller.

(3) Motion Analysis of Upper Hammering Roller

Along the forward direction, the picked up root stubble acquired the same forward velocity with the machine. Therefore the upper hammering roller was doing uniform circular motion relative to root stubble, and throwing velocity was namely the peripheral velocity of the upper roller teeth, which could be calculated with the equation

$$v = \omega R = \frac{2\pi n R}{60} \quad (10)$$

If the roller's velocity is too high, root stubble may be smashed easily, however, if it is too low, it will not reach ideal throwing and striking effect. If the velocity is determined as the same with $v'_p = 5$ m/s and $n = 270$ r/min, R can be calculated as $R = 177$ mm from the above equation.

2　Field Experiments

To test performance of root stubble harvesting machine, field experiments were conducted in Huaiji County, Guangdong Province during July 2 ~4, 2011.

2.1 Experimental Conditions

In the field, soil type was light sandy loam, and corn was artificial planted with average row and plant spacing being 60 cm and 20 cm, respectively. After artificial removal of straw, the height of retained stubble was 25 cm, and average diameter was 1.95 cm. Conditions of soil surface before experiment was shown in Fig. 6. A tractor Dongfanghong − 504 was used to hitch the harvesting machine. The tractor was driven under gear Ⅰ at steady speed from 1 km/h to 3 km/h. The field operation was as shown in Fig. 7.

Fig. 6 Field before digging

Fig. 7 Field experiment

2.2 Performance Test and Results

Root stubble digging rate, picking up rate and paving under digging depth of 120 mm, 140 mm, and 160 mm were measured (each measurement distance was 20 m, each measurement distance repeated 3 times), and statistics were listed in the following Tab. 1. R_d means the digging rate, R_p means the picking up rate, and the R_{pa} means the paving rate in Tab. 1. They could be caculated as

$$R_d = N_d / N_t \quad R_p = N_p / N_d \quad R_{pa} = N_{pa} / N_p$$

where, N_d—numbers of digging out root stubble

N_t—total numbers of root stubble in measurement distance

N_p—numbers of picking up root stubble

N_{pa}—numbers of paving root stubble

Tab. 1 Root stubble digging rate and picking up rate

%

Working performance	Digging depth/mm		
	120	140	160
R_d	90	92	93
R_p	95	98	96
R_{pa}	100	100	100

Experimental results demonstrated that the mechanisms were able to meet the design and operation requirements while keeping root stubble's integrity at the same time.

3 Conclusions

(1) A offset root stubble digging shovel was developed based on determination of parameters: $\gamma = 45°$, $\alpha = 20°$, $L = B = 320$ mm and $e = 110$ mm. Slide cut way and offset handle made resistance smaller and miss-digging rate lower. Experimental results showed that the digging rate was higher than 90%, and root stubble miss-digging occurred mainly because the rows were not that straight as the corn was artificially planted.

(2) Three-roller mechanism was developed to conduct root stubble picking up (picking rate higher than 95%), soil separation and paving effectively. The concept of three-roller mechanism was put forward for the first time. Mechanism motion and picking up process were analyzed to determine rollers' working parameters including rotational speed, distances between front picking roller and rear picking roller, and roller diameters.

(3) Results of field experiment showed that the developed root stubble harvesting machine could accomplish root stubble digging, picking up, stubble-soil separation and paving in one round of operation. The stubble digging, picking up and paving rate of stubble harvest machine were more than 90%. Its work met the requirements of design and application.

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玉米根茬收获机设计与试验

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【摘要】　为了实现根茬的挖掘、捡拾、根土分离与放铺等联合收获作业，研制了一种偏置式挖掘铲刀和三辊机构。通过分析偏置式挖掘铲刀的挖掘特性，以及三辊机构的运动学特性，确定了工作部件的结构参数及运动参数。田间试验表明，偏置式挖掘铲刀挖掘根茬效果好，三辊机构具有较好的捡拾、根土分离和放铺能力，根茬收获机的根茬起挖率、捡拾率和放铺率均大于90%，满足设计和使用要求。

关键词： 根茬挖掘　挖掘铲刀　三辊机构　根土分离　根茬收获机
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