OPTIMUM DESIGN OF SEED HOLDING RING OF VERTICAL DISC SEED-METERING DEVICE
/
垂直圆盘排种器护种环的优化设计

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ABSTRACT
In this paper, the vertical disk mechanical seed-metering device is taken as the object to optimize the design of seed holding ring. The laboratory test is carried out with seed-metering test bench and high-speed camera system; and the influence law of starting and ending angle, front inclination angle and flexible buffer of seed holding ring on the seed filling performance is studied. The ending angle of seed holding ring shall be consistent with seed throwing angle of seed-metering device, and the starting angle of seed holding ring has a significant effect on seed filling performance. The quality of fill index will first increase and then decrease, reaching the maximum at 35.7°; while miss fill index will first decrease and then increase, and the multiple fill index will be 0% when the starting angle is greater than 50°; and seed damage index will first decrease and then increase. In order to improve seed filling performance, the front end of seed holding ring is treated with inner chamfering. The larger the angle is, the lower the quality of fill index, the higher the multiple fill index and the lower the miss fill index, but the seed damage index will also increase. By setting a flexible buffer in the front end of seed holding ring, the seed damage index can be effectively reduced. When the buffer is 60 mm, the seed can be cleaned smoothingly, and the seed damage index will be 0%.

摘要
本文以垂直圆盘机械式排种器为对象，对护种环进行优化设计。利用排种试验台和高速摄像系统进行室内试验；研究护种环的起止角度、前端倾斜角度、柔性缓冲区对充种性能的影响规律。护种环的终止角与排种器的投种角保持一致，护种环的起始角对充种性能具有显著影响，充种合格率先增大后减小，在35.7°时达到最大，漏充率先减小后增大，当起始角大于50°时重充率为0%，破碎率先减小后增大。为了提高充种性能，对护种环前端进行内倒角处理，角度越大，充种合格率越低、重充率越高、漏充率越低，但是破碎率也会增高。通过在护种环前部设置柔性缓冲区，可以有效降低破碎率，缓冲区60mm时，能够顺利清种，且种子破碎率为0%。

INTRODUCTION
Seed-metering device is the core component of seeder, and its performance has an important effect on seeding effect. At present, the pneumatic seed-metering device is adopted in the developed countries (*Cujbescu et al., 2019; St Jack et al., 2013*), including air suction type (*Yazgi et al., 2007*), air pressure type (*Yu et al., 2014*), air delivery type and other forms (*Correia et al., 2016; Dylan et al., 2013; Lei et al., 2021*). The pneumatic seed-metering device can adapt to high-speed operation with excellent performance and small seed damage (*Liao et al., 2018*), but the cost will be high; therefore, a large number of mechanical seed-metering devices is still used in some developing countries (*Ding et al., 2021; Shen et al., 2021; Yang et al., 2016*). The mechanical seed-metering device is low in cost, but high in the seed damage, and it is difficult to adapt to high-speed operation (*Yang et al., 2016*). According to the installation mode of planter plate and the seed filling direction, the mechanical seed-metering device can be divided into horizontal disc type (*Vianna et al., 2014*), inclined disc type, vertical disc type (*Liu et al., 2015*), spoon type, and other types of seed-metering device (*Wang et al., 2017*), among which the seeding operation of the spoon type and clamping type are mainly for corn, and the disk type is mainly for beans.

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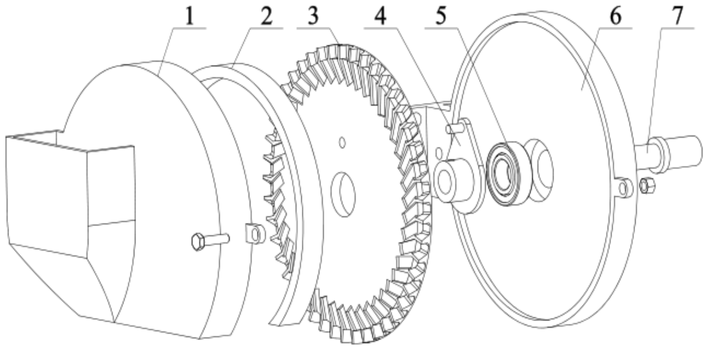
The vertical disk seed-metering device is a mechanical seed-metering device used for sowing beans (*Chen et al., 2021; Liu et al., 2015*). A number of seed collection holes open to the side is distributed in the circumferential direction of planter plate. When the planter plate passes through the population in the rotation process, the seed collection operation is completed with the seed collection holes. However, when seeds are taken from population by seed collection hole, they cannot be guaranteed to stay in the seed collection hole under the action of its own gravity and external vibration; therefore, the seed holding ring needs to be provided, so that a closed space will be composed of seed holding ring and seed collection hole and the seeds can be kept in the seed collection hole. The seed holding ring plays an important role in the operation process of seed-metering device. In this paper, the optimal design will be conducted for its structure.

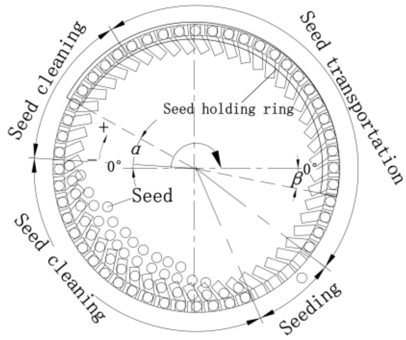
MATERIALS AND METHODS

Vertical disc metering device

The vertical disc seed-metering device consists of shell, disk, shaft, bearing, flange and seed holding ring which is installed inside the shell (Fig.1).



a. Structure of seed metering device



b. Principle of seed metering device

Fig. 1 - Structure and principle of vertical disc metering device

1. Shell; 2. Seed holding ring; 3. Disk; 4. Flange; 5. Bearing; 6. Base; 7. Shaft

The operation process of vertical-plate seed-metering device consists of four stages, i.e., seed filling stage, seed clearing stage, seed transportation stage and seed throwing stage. In the seed filling stage, the seeds will enter the seed collection hole by filling the space under the action of gravity and population internal force. In the seed clearing stage, the excess seeds will be removed by gravity before the seed collection hole reaches the seed holding ring. If there are still excess seeds in contact with the seed holding ring, the excess seeds will be removed continuously in the front end of the seed holding ring, but only one seed will be kept in the seed collection hole at last and it will enter into the coverage area of the seed holding ring. And then in the seed transportation stage, the seeds will move circularly after being kept in the seed collection hole under the protection of seed holding ring. At the seed throwing position, the seed holding ring disappears, so that the seed is no longer protected by the seed holding ring and will be thrown out under the action of gravity.

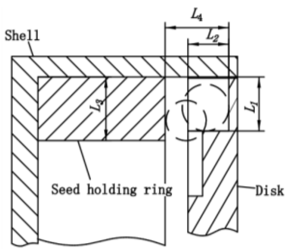


Fig. 2 - Schematic diagram of seed holding ring

In the previous study (*Chen et al., 2021; Jia et al., 2018*), the optimal experiment was carried out for the structural size of the seed collection hole, and the optimal length L_1 and thickness L_2 were 10.2 and 6.3 mm respectively. In order to ensure that the seeds would not fall off during seed transportation, the radial thickness L_3 of the seed holding ring should be larger than L_1, which is 12.0 mm in this paper, and the distance L_4 from the inner side of the seed holding ring to the bottom of seed collection hole should be within the range of d_{max} to $L_2+0.5d_{min}$, with L_4 of 10.0 mm in this paper.

The seed holding ring adopts PMMA processing and plays a role of seed holding and seed clearing at the same time, so that the starting angle of the seed holding ring has an important influence on the seed collection effect. The starting angle of seed holding ring is *α*, the horizontal negative direction is defined as 0°, and the clockwise direction is positive (Fig. 2); while the ending angle of seed holding ring is *β*, the horizontal positive direction is defined as 0°, and the clockwise direction is positive direction. The ending angle of the seed holding ring should cover the seed throwing position of the seed-metering device and be adjusted according to the seed throwing angle. After the previous test (*Chen et al., 2021; Jia et al., 2018*), the optimal seed throwing angle will be 39.5°, so that the ending angle of the seed holding ring is also 39.5°. In order to ensure that the seed clearing is smooth under the action of gravity and will not be slipped from the seed collection hole, the starting angle of seed holding ring should be as close as possible to the upper surface of the population, but space should be left for seed clearing under gravity at the same time. The starting angle of seed holding ring will be determined through experiments.

Prototype experiment

Laboratory bench test is a commonly used test method in the research process of seed-metering device (*Karayel et al., 2006; Zhang et al., 2015*). JPS-12 test bench for operation and performance of seed-metering device is used for laboratory test, and such test bench consists of the fixed device of seed-metering device, rotary conveyor belt and oil injection mechanism. During the test, the seed-metering device is fixed, but the conveyor belt moves, thus simulating the relative movement between the seed-metering device and the soil; meanwhile, oil is constantly sprayed to the conveyor belt to reduce the bouncing and displacement of seeds falling on the conveyor belt, so as to accurately detect the performance of the seed-metering device.

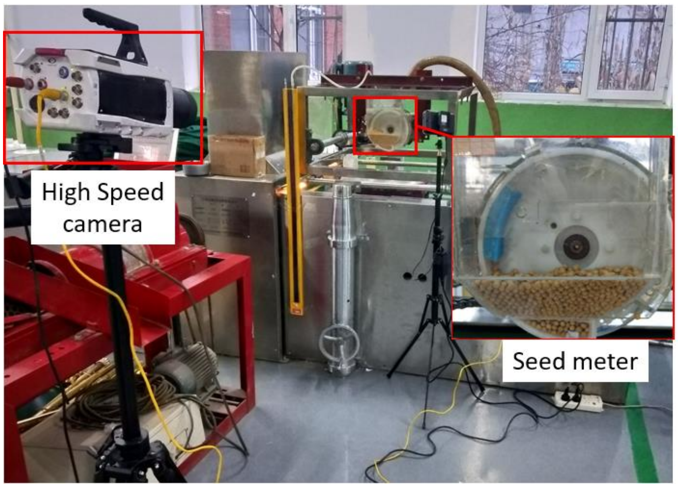
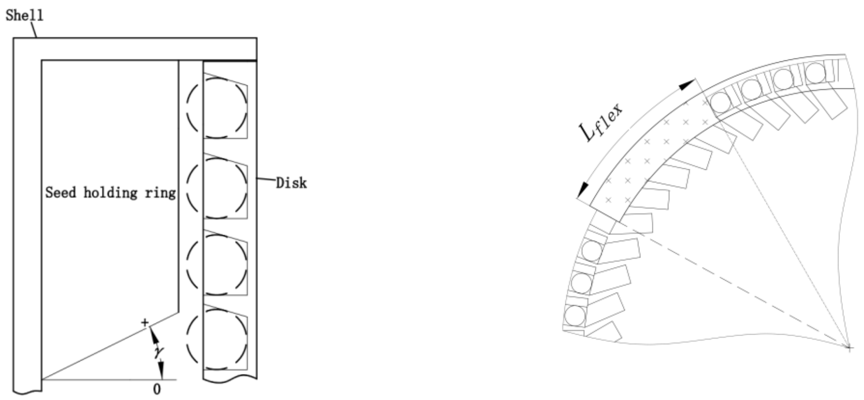


Fig. 3 - Physical prototype

In order to observe the instantaneous movement of seeds in the process of seed collection, a snapshot shall be made with a high-speed camera (Phantom V711) (*Karayel et al., 2006; Shen et al., 2021*), and the shooting frequency shall be set at 100 fps (Fig.3).



a. Front inclination of seed holding ring *b. Flexible buffer zone of seed holding ring*

Fig. 4 - Experimental factors of seed holding ring

The experimental study shall be conducted for the starting angle α, the front inclination angle γ and the length L_{flex} of the flexible buffer of seed holding ring through bench test (Fig.4), and different test levels shall be designed respectively (Table 1).

Table 1

Factors and codes of orthogonal rotation combination test

Level	Factors		
	α [°]	γ [°]	L_{soft} [mm]
1	0	30	5
2	10	45	10
3	20	60	15
4	30	75	20
.	…		…
.	90		40

Evaluating indicator

According to GB/T 6973-2005 test methods for single seed (precision) planter, and JB/T10293-2001 Specification for single grain (precision) planter, 250 seeds were collected for statistics in each group of experiments, and the test was repeated for 3 times, and the seed metering performance evaluation indexes were FA, FD, FM and P (*Chen et al., 2021; Lei et al., 2021*).

$$FA = n_1 / N \times 100\% \tag{1}$$

$$FD = n_2 / N \times 100\% \tag{2}$$

$$FM = 100\% - FA - FD \tag{3}$$

$$P = m_1 / m_2 \times 100\% \tag{4}$$

Where：

n_1 is the number of seed holes containing only one seed in the test; n_2 is the number of seed holes containing more than one seed in the test; N is the total number of seed holes recorded in the test; m_1 is the weight of broken seeds; m_2 is the total mass of seeds discharged by seed metering device.

RESULTS AND ANALYSIS

Effect of initial angle of seed holding ring on seed filling performance

In order to make clear the effect of α on seed filling performance, α shall be set as 0°, 10°, 20°... 90°, and seed filling test shall be carried out at the forward speed of 4 km/h (Table 2).

Table 2

Effect of initial angle on seed filling performance

α [°]	Seed filling performance			
	FA [%]	*FD* [%]	*FM* [%]	*P* [%]
0	85.64	5.62	8.74	3.24
10	86.32	4.83	8.85	2.86
20	87.45	5.14	7.41	1.52
30	91.74	2.15	6.11	0.93
40	92.68	1.04	6.28	0.86
50	90.52	0	9.48	1.85
60	82.63	0	17.37	2.43
70	56.84	0	43.16	3.68
80	34.65	0	65.35	3.24
90	16.83	0	83.17	3.43

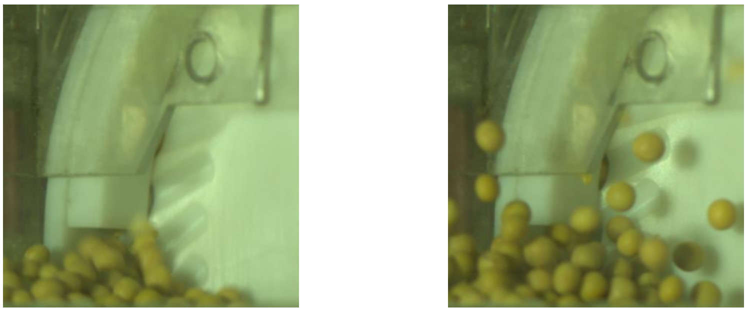
α has a significant effect on FA, and the change of FA is less obvious when the starting angle is from 0° to 20° When α is greater than 20°, FA increases gradually and reaches the maximum value, 92.68%, at 40°. When α is greater than 50°, FA decreases sharply, only 16.83% at 90°.

α has a significant effect on FD. With the increase of α, FD decreases gradually, and the maximum value of FD is 5.62% at 0°. When α is greater than 50°, multiple FD is 0.

α has a significant effect on FM. FM decreases gradually from 0° to 40°, reaching the minimum value, 6.11%, at 30°. When α is greater than 50°, FM increases greatly, reaching 83.17% at 90°.

α has a significant effect on P. With the increase of angle, P decreases first and then increases, and the minimum value is 0.86% at 40°. At 0° and 90°, P remains maximum value, 3.24% and 3.43%, respectively.

The high-speed camera shall be used to observe the process of seed damage. It is found that seed damage mainly occurs at the moment when seeds enter the seed holding ring, and the seeds are damaged under the extrusion between the seed collection hole and the front face of the seed holding ring; meanwhile, the enormous energy will be released, thus leading to the impact on the population and causing the failure of subsequent one or more seed collection holes to fill seeds successfully. Therefore, seed damage is often accompanied by miss fill (Fig.5).



a. Seed breaking *b. Seed group impact diffusion*

Fig. 5 - High speed camera picture of seed filling process

After excluding the data when α is 0° and 10°, regression analysis on the remaining data shows that the regression equation between FA and α is:

$$y = -0.027x^2 + 1.95x + 59.51, R^2 = 0.98 \quad (5)$$

Derivation of equation (5) shows that α at the maximum of FA is 35.7°. For convenience of design, α is set to 36° thereafter.

Effect of front-end inclination on seed filling performance

In order to reduce P, the front face of the seed holding ring is treated with inner chamfering, and the front inclination angle γ is set as 30°, 45°, 60° and 75° respectively. When the starting angle of seed filling is 36° and other conditions remain unchanged, the experiment shall be carried out again.

Table 3

Effect of front-end inclination on seed filling performance

γ [°]	Seed filling performance			
	FA **[%]**	***FD*** **[%]**	***FM*** **[%]**	***P*** **[%]**
30	93.52	1.66	4.82	0.91
45	86.32	12.28	1.40	1.88
60	84.65	14.03	1.32	2.25
75	82.73	16.64	0.63	3.05

The test results (Table 3) shows that FA is not improved in the design of inner chamfering at the front end of seed holding ring. When γ is 30°, FA is only 89.62% at maximum, which is smaller than that without inner chamfering. Meanwhile, the size of γ has a significant effect on seed filling performance. With the increase of γ, the lower FA, the higher FD, the lower FM, and the higher P are.

a. Successful seed filling

a. Seed crushing

Fig. 6 - High speed photography of seed filling process when the front was tilted

After observation for seed filling process after chamfering on the front face of the seed holding ring through high-speed camera, it is found that the fill index is improved after chamfering treatment, and some cases of seed damage or miss fill under the original conditions are alleviated. Some seeds have been separated from the seed collection hole before contact with the seed holding ring, but with the help of the inclination angle, the seeds return to the seed collection hole, and the seed filling is successfully completed.

However, at high speed, there are still more damage phenomena. Through high-speed camera observation, it is found that when half or bigger part of a seed is separated from seed collection hole, seed extrusion will still occur during the contact between the seed and seed holding ring, and even deformation of seed-metering device will be caused.

In conclusion, it is impossible to improve seed filling performance by changing the front inclination angle of seed holding ring.

Effect of flexible buffer length on seed filling performance

Through high-speed camera observation, it is found that the seed damage index is increased by seed holding ring. The main reason for seed damage is that both planter plate and seed holding ring are rigid materials. When the seeds contact with the seed holding ring, extrusion can be easily occurred, so that seeds will be damaged. Therefore, the seed holding ring shall be replaced with flexible material, and polyester sponge shall be chosen as the replacement material.

Table 4

Effect of the length of flexible buffer on seed filling performance

L_{flex} [mm]	Seed filling performance			
	FA [%]	*FD* [%]	*FM* [%]	*P* [%]
5	88.45	7.82	3.73	1.54
10	91.65	5.07	3.28	0.96
15	94.24	1.25	4.51	0.51
20	95.88	0	4.12	0
25	96.56	0	3.44	0
30	97.02	0	2.98	0
35	96.68	0	3.32	0
40	96.88	0	3.12	0

Polyester sponge belongs to vulnerable and consumable material and should be used as less as possible. The extrusion collision between seed and seed holding ring mainly occurs at the edge of seed holding ring; therefore, polyester sponge shall only be set at the front end of seed holding ring as a buffer. The length of flexible buffer is L_{flex}, and the rest of seed holding ring shall still adopt PMMA material.

When the flexible material contacts with the seed, it will tilt and the effective thickness will decrease; therefore, the buffer thickness will increase by 4 mm compared with that of the original seed holding ring.

In order to study the influence of L_{flex} on seed filling performance, the test shall be carried out (Table 4) when the forward speed is 4 km/h, and L_{flex} is 5, 10, 15... 40 mm respectively.

The test results (Table 4) show that L_{flex} has a significant effect on FA. With the increase of L_{flex}, FA gradually increases. When L_{flex} is larger than 25 mm, FA gradually remains at about 96%.

L_{flex} has a significant effect on FD, and as L_{flex} increases, FD decreases gradually, reaching 0% after length is 20 mm.

L_{flex} has no significant effect on FM because FM has a little change when L_{flex} increases. By observing the seed filling process with high-speed camera, it is found that the miss fill occurs at the moment when the seed contacts with the buffer. No matter how L_{flex} changes, there is no change in contact state between the seed and buffer; therefore, there is no significant change in miss fill.

It is found through high-speed camera observation that seed clearing operation under gravity cannot be completed due to the participation of seed holding ring and buffer, and the buffer plays a role of seed clearing. Most of the excess seeds are removed at the moment when the seed contacts with the buffer, and a small portion of seeds enter the buffer and move forward with the seed collection hole. In this process, some of the excess seeds are separated from the side of buffer to complete seed clearing. The effect of seed clearing will be determined by the length of buffer. When L_{flex} is less than 20 mm, partial seeds cannot be separated from the side and move to the position of seed holding ring. At this time, two situations will occur; first, when the size of seed and excess seed in the seed collection hole is small, the two seeds enter the seed holding ring at the same time; second, when the size of the two seeds is large, the fierce collision will occur between excess seeds and the seed holding ring, resulting in seed damage. Therefore, L_{flex} has a significant effect on FD and P.

Table 5

Effect of speed on seeding performance with flexible buffer

Forward speed [km·h^{-1}]	**Seed filling performance**			
	***FA* [%]**	***FD* [%]**	***FM* [%]**	***P* [%]**
1	96.83	0	3.17	0
2	95.52	0	4.48	0
3	96.33	0	3.67	0
4	96.88	0	3.12	0
5	96.22	0	3.78	0
6	94.61	0	5.39	0
7	93.66	0	6.34	0
8	92.75	0	7.25	0
9	91.33	0	8.67	0
10	90.25	0.51	9.24	0.86
11	87.64	0.83	11.53	1.25
12	85.32	1.25	13.43	1.68

When α is 36° (including buffer) and L_{flex} is 40 mm, seed filling performance tests shall be carried out at speeds ranging from 1 to 12 km/h (Table 5).

The test results (Table 5) show that the forward speed has a significant effect on seed filling performance. When the forward speed is less than 4 km/h, the seed filling performance is not sensitive to the forward speed. When the forward speed is greater than 4 km/h, with the increase of speed, FA gradually decreases and FM gradually increases.

When the forward speed is less than 9 km/h, both FD and P are 0. When the forward speed is more than 10 km/h, FD and P gradually increase. It is found through high-speed camera observation that the clearing distance of seeds into the buffer increases with the increase of speed (Fig. 7). When the speed is greater than 10 km/h, the clearing distance is greater than 40 mm; therefore, the seeds cannot successfully escape from the buffer, thus leading to the multiple fill and damage phenomenon.

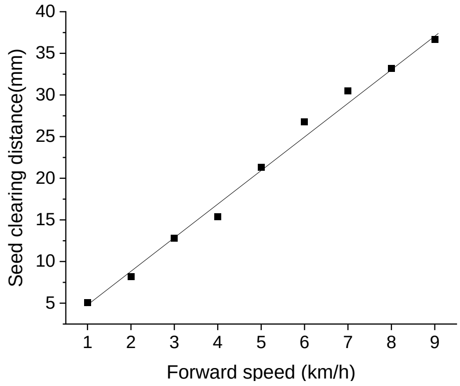


Fig. 7 - Effect of forward speed on seed clearing distance

Regression analysis is conducted on the forward speed and the distance of seed clearing, and the regression equation is obtained as,

$$y = 4.14x + 0.43, R^2 = 0.99 \tag{6}$$

According to the calculation of regression equation (6), when the forward speed is 12 km/h, the seed clearing distance is 50.1 mm. In order to ensure that the seed clearing can be completed, the buffer length is set to 60 mm for the verification test of seed filling performance.

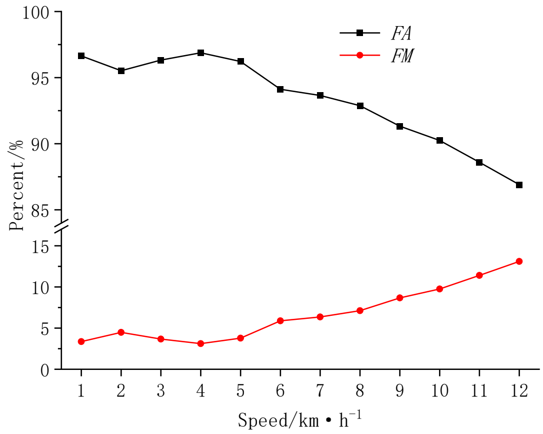


Fig. 8 – The result of verification experiment

The verification test results (Fig.8) show that the seed clearing effect is good when FD and P are reduced to zero after extending buffer. FA is further improved and FM is slightly decreased.

CONCLUSIONS

In this paper, the indoor seed-metering test bench and high-speed camera system are used to optimize the design of the seed holding ring of vertical-plate seed-metering device. With the seed filling performance as the evaluation index, the study on starting and ending angle, the front inclination angle and the flexible buffer is carried out.

(1) The starting angle of seed holding ring has a significant effect on seed filling performance. The regression equation shows that the best filling performance can be achieved when the starting angle is 35.7°, but the problem of high P always exists. The seeds are damaged under the extrusion between the seed collection hole and the front face of the seed holding ring, accompanied by the miss fill phenomenon.

(2) By setting the inner chamfer in the front section of seed holding ring, the seed filling performance is significantly affected. The higher γ is, the lower FA, higher FD and lower FM are. Although P is alleviated to a certain extent, it still fails to meet the qualified standard.

(3) In order to further reduce P, flexible buffer is added in the front section of seed holding ring. When L_{flex} is 60 mm, seed filling performance is better, and FD and P are 0%, which meets the requirements of precision seeding.

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