DESIGN OPTIMIZATION AND PERFORMANCE TEST OF MAGNETIC PICKUP FINGER SEED METERING DEVICE

磁力指夹式排种器优化设计及性能试验

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ABSTRACT

As the core part of precision seeder, the performance of pickup finger seed metering device directly affects the seeding quality. Aiming at the problem that the traditional pickup finger seed metering device can be easily affected by the performance of spring material, and the reliability of spring decreases with the increase of service time, a magnetic pickup finger seed metering device is designed to open and close the pickup finger by magnetic force, so as to improve the stability of seed metering performance. Through the design and optimization of permanent magnet structure, cam structure and seed taking pickup finger structure, the magnetic force distribution of ring magnet is analysed by using ANSYS Maxwell magnetic simulation software. Under the working speed of 3.9km/h, the vibration frequency, vibration amplitude and magnetic induction intensity were selected for orthogonal test. The experimental results show that the optimal combination of factors is vibration frequency 6Hz, vibration amplitude 3.1mm and magnetic induction intensity 316.34mT. Under the condition of the combination of operation parameters, the seed arrangement performance is 91.7% of the qualified rate, 6.2% of the replant rate and 2.1% of the missed rate, which meets the requirements of the national standard for the performance of the seeder. This study can provide a reference for the optimization of the structure and the improvement of the seed metering performance of the pickup finger seed metering device.

摘要

指夹式排种器作为精密播种机核心工作部件，其性能直接影响播种质量。针对传统指夹式排种器易受弹簧材料性能影响，随使用时间增加排种性能下降的问题，设计一种由磁力完成指夹开启与闭合的磁力指夹式排种器，提高指夹式排种器排种性能稳定性。通过设计优化永磁体结构、凸轮结构及取种指夹结构，应用 Ansys-Maxwell 磁力仿真软件分析环形磁铁磁力分布；在作业速度 3.9km/h 条件下，选取振动频率、振动幅值、磁感应强度 3 因素进行正交试验。试验结果表明：较优因素水平组合为振动频率 6Hz、振动幅值 3.1mm、磁感应强度 316.34mT；该组合作业参数条件下，排种合格率 91.7%、重播率 6.2%、漏播率 2.1%，满足国家标准对精密播种机性能要求。该研究可为指夹式排种器结构优化与排种性能提高提供参考。

INTRODUCTION

As a major corn planting region, the Inner Mongolia Autonomous Region is among the top regions in China in terms of corn planting area and output. The Inner Mongolia Region consists mostly of alpine arid areas where vibrations from machines and tools cause disturbances during the no-tillage surface operation in the case of heavy straw coverage. Therefore, suction-type and spoon-wheeled metering devices may exhibit poor metering performance (*Wang et al, 2019*; *Yang et al, 2016*). The pickup finger metering device is a mechanical precision metering device extensively used for precision seeding operation on no-tillage surfaces due to its stable metering performance and strong adaptability to operating environments (*Searle et al, 2008; Tang et al, 2020*).

In recent years, *Abdolahzare et al., (2018)*, used high-speed camera systems to study factors affecting the seed distribution uniformity, thereby reducing the seed spacing variation coefficient. *Cortez et al., (2020)*, studied the effect of seeding speed on operation quality and found that the seed spacing distribution stability decreases with the increase in the forward speed of the seeder, with an operating speed of 5 km/h providing an optimal operating performance.

Weidong et al., (*2004*), *Zhang et al.*, (*2020*) and *Yazgi et al.,* (*2014*), investigated the metering performance and miss-seeding monitoring system of precision metering devices for crops, such as corn, rape and rice. In addition, some researchers have studied the structure of the pickup finger precision metering device. For instance, Geng *et al.*, (*2016*), designed a telescopic pickup finger corn seed metering device.

Li et al., (*2018*), designed a pickup spoon precision broad bean seed metering device incorporating the advantages of a spoon-wheeled metering device and a pickup finger metering device; they studied the optimal operating parameters of seed pickup length, seed pickup width and bending angle, thereby improving the operating performance of the precision seeding of broad bean.

Wang et al., (*2019)*, optimized the design of the pickup finger precision corn seed metering device, simplifying the structure of the mechanical metering device and improving the operation quality. *Wang et al.*, (*2015; 2017)*, optimized the structure parameters of the precision corn seed metering device and improved the adaptability of the metering device to seeds*.

Zhou et al., (*2019*), performed tests on the operating performance of metering devices that use rubber and plastic as additional materials for the seed plate and reported that the operating performance of the metering device can be improved by changing the contact material.

Fu et al., (*2011)*, proposed a precision metering technique featuring mechanical forced gripping of corn, performed theoretical analysis of the metering process and built relevant mechanical models, providing the theoretical basis for improvement in the operating performance of metering devices. By optimizing the cleaning brush and jounce belt structures, the U.S. Kinze no-tillage seeder achieves decreased seed spacing, decreased re-seeding rates and improved seed metering accuracy. Precision Planting (*Trimont, Boston,* USA) designed a cushion device at the seeding opening of the metering device pickup finger, which prevents seed collision and rebounds miss-seeding when seeds enter the lead-in chamber.

Chinese and foreign scholars have studied the pickup finger, cam, seed plate, jounce belt and other structures through theoretical analyses, numerical simulations and experimental investigations, thereby improving the operating performance of metering devices. However, there are few studies on the performance of the helical compression spring in the pickup finger. It is impossible to avoid the effect of spring material performance on metering performance. Moreover, it is difficult to study the spring material performance stability in pickup finger metering devices. Therefore, the present paper designed a magnetic pickup finger-type precision metering device, in which the magnetic force enables the pickup finger to hold the seeds to avoid the poor metering performance resulting from the degradation of spring material.

MATERIALS AND METHODS
Structure and operating principle of the metering device

The structure of the magnetic pickup finger-type precision metering device is shown in Figure 1. During the seeding operation, seeds enter the metering chamber from the seed box, and the ground wheel powers the pickup finger pressure plate that drives the pickup finger to rotate through the seed filling area, seed guiding area, seed clearing area and seed charging area.
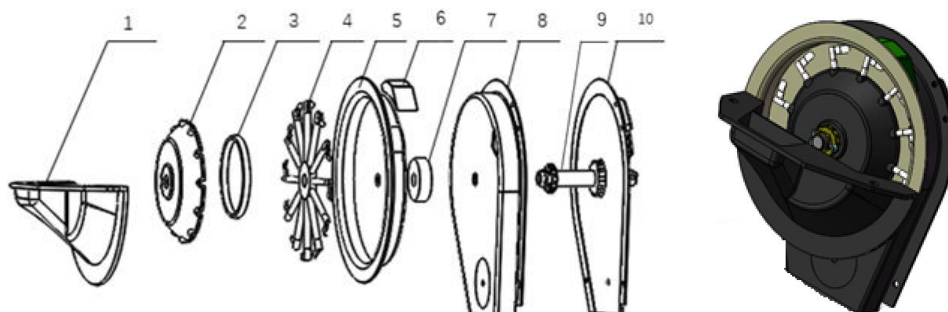

Fig. 1 - Structure of magnetic pickup finger seed metering device
1. Feeding inlet; 2. Refers to the pressure plate; 3. Permanent magnet; 4.Pickup finger; 5. Discharge plate; 6. Hairbrush;
7. Cam; 8. End cap; 9. Feed shaft; 10. Conductor shield

The permanent magnet attracts the pickup finger tail tab to a certain extent so that the pickup finger tab fits tightly on the surface of the seed plate. The pickup finger rotates around a fixed axis at the seed plate surface. A cam is placed under the seed plate, and the cam is designed with a pickup finger opening area and a pickup finger closing area. The pickup finger tail tab slides on the cam surface, and when the pickup finger rotates to the opening area of the cam surface, the supporting force of the cam surface for the pickup finger

tail tab overcomes the attraction of the permanent magnet. At this moment, the pickup finger opens and forms a definite opening angle with the seed plate, and the seeds enter the pickup finger to complete seed filling. When the pickup finger rotates to the closed area of the cam surface, the attraction of the permanent magnet to the pickup finger tail tab provides torque for the pickup finger, thus allowing it to clamp the seeds. The seeds rotate with the pickup finger to complete seed guiding. When the pickup finger tab holding the seeds passes through the seed clearing belt, the jounce belt vibrates slightly to remove excess seeds, which completes the seed clearing. When the pickup finger rotates to the seed exit, the magnetic action of the permanent magnet causes the pickup finger to push the seeds into the seed exit, and the seeds fall into the seed guide belt. All four seeding processes, i.e., seed filling, guiding, clearing and charging, are then completed.

Permanent magnet structure design and numerical simulation

In a pickup finger precision metering device, a fine-tuning spring provides the pickup finger tab with holding force, the stability of which has an immediate effect on the seed filling, seed guiding and seed clearing performance. Performance degradation of the spring material develops as time passes, which changes the spring stiffness coefficient, thereby impairing the stability of the metering performance. In the present paper, a permanent magnet is used to replace the fine-tuning spring, and the attraction of the permanent magnet to the pickup finger tail tab replaced the spring force for the pickup finger. Compared to the fine-tuning spring, the permanent magnet has a more stable force and a longer life span. Moreover, the permanent magnet is reusable. The structure of the designed permanent magnet is a ring with an outer diameter of 110 mm, an inner diameter of 93 mm, and a thickness of 6 mm. The magnetization direction is radial magnetization. Permanent magnet is a hard magnet, which is not easy to lose magnetism or magnetize. Ferrite material can maintain its original magnetism for a long time (*Hu et al, 2011; Hu et al, 2010*).

To identify the effect of the magnetic field distribution on the attraction to the pickup finger tail tab, Ansys-Maxwell software was used for computer simulation analysis of the magnetic induction intensity and the magnetic field intensity. Because the permanent magnet is circular with a symmetrically distributed magnetic field, the solution type is a static magnetic field when the axisymmetric 3D model is imported into Ansys-Maxwell. A permanent magnet is defined as a boundary condition under which the tangential component of the magnetic field intensity is always zero. The insulation boundary condition is used for the metering device housing, while the symmetric boundary condition is used for the cam. The cam material property is defined as steel, and the pickup finger material property is defined as iron. The simulation results of permanent magnet magnetic field are shown in Figure 2.
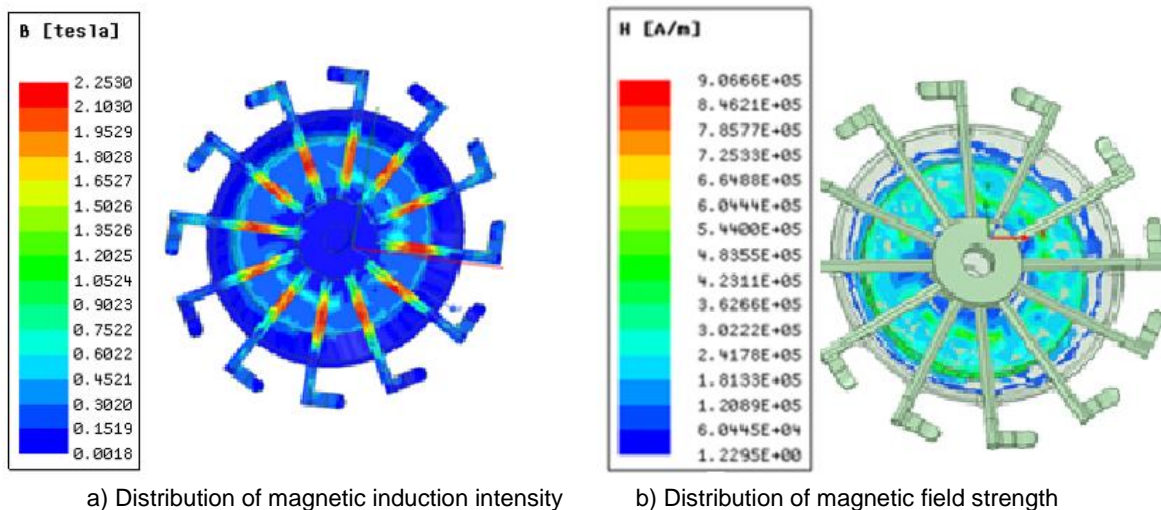

a) Distribution of magnetic induction intensity   b) Distribution of magnetic field strength

Fig. 2 - Magnetic field simulation results of permanent magnet

According to the cloud chart of the magnetic induction intensity numerical simulation result, the magnetic density at the yoke is larger and the distribution is more concentrated, and the magnetic density at the outer side is smaller. The uneven distribution of radial magnetization and material density results in uneven lateral yoke distribution, and the largest magnetic force occurs at the contact point between the permanent magnet and pickup finger. The change in permanent magnet shape significantly affects the peripheral flux density value characteristics, thereby affecting the attraction to the pickup finger tail tab.

Metering control mechanism design

The seed filling performance has an important effect on the overall operating performance of the magnetic pickup finger metering device. The seed filling performance is affected by the opening/closing time point and opening angle of the pickup finger as well as the tail tab attraction. The magnetic pickup finger metering device is designed with a cam mechanism that controls the opening/closing time point and opening angle of pickup finger and a permanent magnet that changes the attraction of the pickup finger tail tab. Thus, the operating angle of the cam has an immediate effect on seed filling performance. Based on the motion pattern desirable for the pickup finger, the cam working surfaces are divided into a constantly open plane, constantly closed plane, closed slope and progressively opened slope. Figure 3 shows the cam structure.

The pickup finger tail tab is in contact with the cam slope. When the pickup finger tail tab moves to the progressively opened slope of the cam, the supporting force of the progressively opened slope for the pickup finger tail tab is greater than the attraction of the permanent magnet to the pickup finger tail tab. As a result, the pickup finger opens, and the seeds enter the space formed by the pickup finger and seed plate to complete seed filling. Hence, the opening angle and structure of the pickup finger affect the seed filling quantity and stability. When the pickup finger tail tab moves to the closed slope of the cam, the attraction of the permanent magnet to the pickup finger tail tab causes the pickup finger to close, and the pickup finger holds the seeds for seed guiding and clearing. The closed slope and constantly closed plane of the pickup finger affect the seed guiding stability and seed clearing process. Both vibration frequency and vibration amplitude may significantly affect the seed filling performance, seed guiding stability and seed clearing process during the metering operation.

To effectively fill the seeds and keep them steady, the pickup finger opens and closes steadily in the filling area. The closed slope of the cam is smooth and stable, ensuring that the corn grains are accurately pushed to the guiding port. The maximum finger opening angle is 20°, the constant filling angle is 160°, the finger hold angle is 30°, and the finger push angle is 150°.
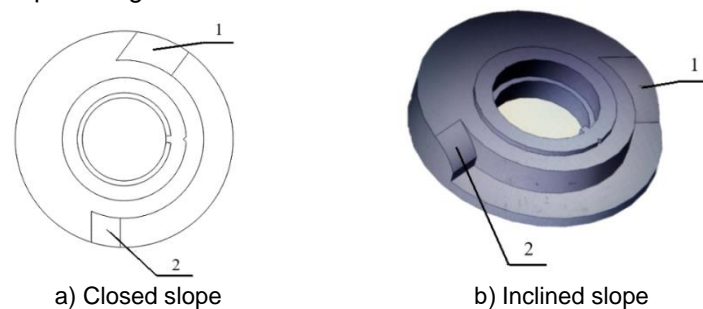

            a) Closed slope   b) Inclined slope

Fig. 3 - Cam structure

Pickup finger design

The pickup finger consists of a pickup finger tab, pickup finger lever, magnet and pickup finger tail tab. The pickup finger structure is shown in Figure 4. During operation of the metering device, the pickup finger rotates with the pickup finger pressure plate around a fixed axis under the driving force of the pickup finger lever to hold the seeds. The cam structure and permanent magnet control the pickup finger to complete seed filling, seed guiding, seed clearing and seed charging. The structure and motion pattern of the pickup finger affect the action of the pickup finger on seeds. Figure 5 shows the analysis of the force applied during the pickup finger holding.
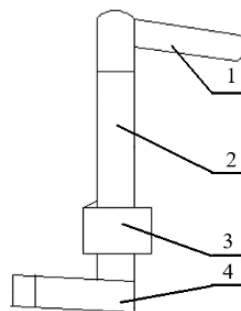

Fig. 4 - Seeding pickup finger structure diagram
1. Pickup finger; 2. Pickup finger pole; 3. Magnet; 4. Pickup finger tail

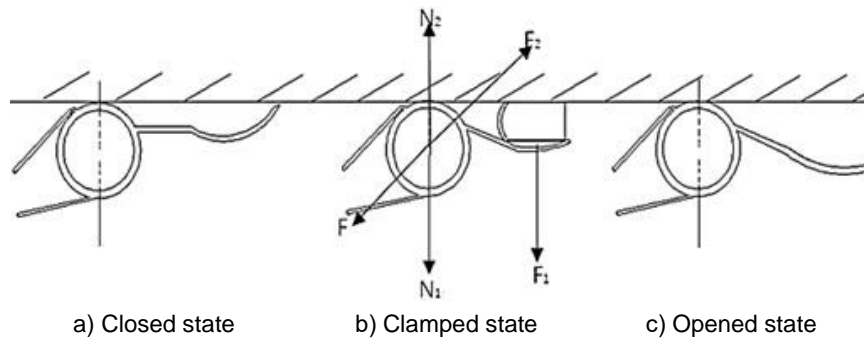a) Closed state   b) Clamped state   c) Opened state
Fig. 5 - Stress analysis of finger clamp

Because corn seeds cannot rotate in the process of carrying seeds, Equations (1), (2), (3) are reached.

$$\sum M = 0 \tag{1}$$

$$fr + F(u_1 + u_2) = F_1 b_1 \tag{2}$$

$$F_1 = \frac{fr + F(u_1 + u_2)}{b_n} \tag{3}$$

where: M is torque of the pickup finger pole axle centre, N·m;

f is friction between the planter plate and the finger clamp, N;

F_1 is clamping force of pickup finger, N;

F is magnetic of permanent magnet, N;

u_1 is force arm of the left magnetic force, mm;

u_2 is force arm of the right magnetic force, mm;

r is radius of pickup finger, mm;

b_n is width of the corn seeds that are clamped, mm.

Seed stress analysis indicated that the pickup finger holding force is associated with the magnetic force of the permanent magnet, the frictional force of the seed plate against the pickup finger lever, the pickup finger lever radius, the left magnetic force arm, the right magnetic force arm and the width of the held corn seed. In the condition of the pickup finger structure and seed plate material are invariants, the magnetic force of the permanent magnet significantly affects the holding force of the pickup finger.

Test method

The test was performed with Yulong-9 corn seeds with a moisture content of no more than 15.0%, a thousand grain weight of 288.48 g and a rest angle of 30.84°. The metering performance test was performed using a JPS-12 metering device performance test stand (developed by Heilongjiang Research Institute of Agricultural Machinery Engineering). The test unit was an optimized magnetic pickup finger-type precision metering device. A computer controlled the rotation speed of the pickup finger pressure plate and the seed bed belt velocity during the test. The seeds from the metering device fell onto viscous oil on the surface of the seed bed belt. The data were collected as per the Chinese National Standard (GB), and the metering performance index of the metering device was calculated.

According to above-noted structure optimization and theoretical analysis, the dominant factor affecting the metering performance was the vibration frequency of the metering device. The metering qualification index, re-seeding index and miss-seeding index were calculated based on the Chinese National Standard GB/T6973-2005 "Testing Methods of Single Seed Drills (Precision Drills)" with reference to the agronomic requirements on corn seeding.

RESULTS

In order to find a better parameter combination, three-factor and three-level orthogonal test was carried out on the three selected factors, and $L_9 (3^4)$ orthogonal table was used for the test and analysis. According to the single-factor test results in the early stage, the factors and horizontal setting are shown in Table 1, the test results of seeding performance are shown in Table 2, and the variance analysis of seeding performance is shown in Table 3.

Table 1

Factors and levels of orthogonal test

Level	Vibration frequency (Hz)	Vibration Amplitude (mm)	Magnetic induction intensity (mT)
1	5	2.4	316.34
2	6	3.1	226.48
3	7	3.7	200.36

Table 2

Test results of seed metering performance

Test number	Factors				Performance values		
	Vibration frequency (Hz) A	Vibration Amplitude (mm) B	Magnetic induction intensity mT C	Error D	Qualified rate (%)	Multiple rate (%)	Miss rate (%)
1	1	1	1	1	65.0	35.0	0
2	1	2	2	2	78.0	22.0	0
3	1	3	3	3	64.9	35.1	0
4	2	1	2	3	88.9	11.1	0
5	2	2	3	1	91.7	6.2	2.1
6	2	3	1	2	84.4	13.3	2.3
7	3	1	3	2	73.0	24.4	2.6
8	3	2	1	3	78.0	18.0	4.0
9	3	3	2	1	77.3	18.2	4.5
Qualified rate R	0.19	0.07	0.06	0.01			
Important order			A B C				
Optimization scheme			$A_2B_3C_1$				
Multiple rate R	0.62	0.24	0.15	0.05			
Important order			A B C				
Optimization scheme			$A_1B_3C_2$				
Miss rate R	0.07	0.04	0.02	0.03			
Important order			A B C				
Optimization scheme			$A_3B_3C_1$				

Table 3

Variance analysis of seeding performance

Test indexes	Sources	SS	df	MS	F	P-value	Significant
Qualified rate	A	558.162	2	279.081	254.224	99	**
	B	97.549	2	48.774	44.430	19	**
	C	55.582	2	27.791	25.316	9	*
	Error e	2.196	2	1.098			
Multiple rate	A	630.500	2	315.250	130.809	99	**
	B	113.540	2	56.770	23.556	19	*
	C	48.080	2	24.040	9.975	9	（*）
	Error e	4.820	2	2.410			
Miss rate	A	20.829	2	10.414	23.001	18	**
	B	3.376	2	1.688	3.728	6.94	
	C	0.649	2			4.32	
	Error e	1.162	2				
	New error e	1.811	4	0.453			

According to the outcome of the range analysis, the factors affecting the grain spacing qualification index were vibration frequency, vibration amplitude and magnetic induction intensity. The grain spacing qualification index was quite favourable at a vibration frequency of 6 Hz, an amplitude of 3.7 mm and a magnetic induction intensity of 316.34 mT.

Variance analysis indicated that vibration frequency significantly affected the grain spacing pass rate, re-seeding rate and miss-seeding rate. The vibration amplitude also significantly affected the abovementioned metering performance indicators, and the magnetic induction intensity imposed a relatively weak effect on the metering performance indicators. These facts further indicated that the magnetic pickup finger metering device does not require the permanent magnet to have high magnetization performance, which, to some extent, helps reduce the cost of this type of metering device, making it suitable for wide promotion.

Integration of the range and variance analyses and the analysis shown in Table 3 indicated that the three factors affecting the metering performance were as follows, in decreasing order: vibration frequency > vibration amplitude > magnetic induction intensity. The optimal operation parameter combination is vibration frequency 6Hz, vibration amplitude 3.1mm and magnetic induction intensity 316.34MT. Under the conditions of the combined operation parameters, the performance of the seeding operation was 91.7%, 6.2% and 2.1% respectively.

CONCLUSIONS

This study presents a novel magnetic pickup finger-type precision metering device and analyses and optimizes its primary structure and operating parameters. This study also investigates the dominant factors affecting metering performance through the orthogonal test. The findings are shown below.

(1) The stress analysis for the pickup finger in the operating state indicates that its metering performance is associated with the magnetic field distribution and the coefficient of friction between the seed plate and pickup finger.

(2) According to the numerical simulation outcome of the permanent magnet, the magnetic field is strong at both ends and weak in the middle. The material density distribution and magnetizing direction of the permanent magnet affect the magnetic induction intensity. The RbFeB permanent magnet offers evenly distributed magnetic induction and a favourable metering result.

(3) The magnetic induction intensity has a less significant effect on metering performance indicators, and the magnetic pickup finger metering device does not require the magnetization performance of the permanent magnet to be high, which reduces the cost of the metering device.

(4) The orthogonal test for metering performance indicates that the parameter combination offering optimal metering performance consists of a vibration frequency of 6 Hz, an amplitude of 3.7 mm and a magnetic induction intensity of 316.34 mT.

ACKNOWLEDGEMENTS

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