Article

Design Evaluation and Performance Analysis of the Inside-Filling Air-Assisted High-Speed Precision Maize Seed-Metering Device

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Abstract: In view of the problems of a poor seed-filling state and poor seed-cleaning effect of a precision metering device under high-speed working conditions, an inside-filling air-assisted high-speed precision maize seed-metering device was designed, fabricated, and evaluated. The overall structure and working principles of the seed-metering device are explained. Theoretical analysis and parametric design of the key parts, such as the horizontal stirring notch seed-metering plate and the wheel seed-cleaning mechanism, were carried out. The main factors that produce multiple seeding problems were studied. The forward speed (FS) and working pressure (WP) of the seed-metering device are determined as the main factors affecting the seeding performance. A quadratic orthogonal rotation combination experiment was designed. The relationship between influencing factors and performance indexes was constructed using the Design-Expert 10.0.7 software. The response surface method was used to optimize the experimental results. The results of the bench validation experiments showed that the seeding performance of the seed-metering device was excellent when the FS of the seed-metering device was 13.10 km/h and the WP of the seed-metering device was 4.75 kPa. The results of the bench comparison showed that the seeding performance of the designed seed-metering device was better than that of the conventional air-suction precision seed-metering device. This study provides theoretical and practical references for the optimized design of a pneumatic precision seed-metering device and the sustainable development of grain.

Keywords: field machinery; maize; seed-metering device; precision agriculture

1. Introduction

With the advancement of science and technology and the strengthening of agricultural policies, there has been great growth and progress in agricultural development. However, there is still a large food gap, especially for strategic crops, which affects the national economy and compromises food security. Self-sufficiency can be achieved only by preserving the existing natural resources and achieving the highest production efficiency [1]. Maize is one of the most important grain crops and plays an important role in ensuring world grain production security and sustainable agricultural development [2–4]. Under the background that the demand for grain output is constantly increasing, but the planting area cannot be increased, the overall yield can only be increased by increasing the yield rate per unit area.

Mechanized precision seeding plays an important role in increasing maize yield per unit area [5]. The agronomic requirements of maize precision seeding are to ensure the consistency of seed-spacing and row spacing (the seed-spacing of maize ranges from 200 to 300 mm, and the row spacing of maize ranges from 500 to 600 mm in the Northeast of China [6]). Precision seeding is defined as the process of using a precision seeder to make a single seed fall accurately into a reserved position in the soil according to certain agronomic requirements [7]. Combining with the maize planting working in the...
Northeast Plain of China, the high-speed precision seeding refers to the FS of the seed-metering device, which is greater than 10 km/h [8]. The seed-metering device is key in high-speed precision seeding, and its performance is one of the most important factors that affect the seeding quality. According to its working principle, these devices can be mechanical or pneumatic [9]. The pneumatic seed-metering device is widely used for its high-speed operation and its low mechanical damage rate, which is the current development trend of high-speed precision seeding. It is also a focus and hotspot of domestic and foreign scholars.

At present, many experts and scholars are carrying out studies on pneumatic seed-metering devices. Nal et al. [10] expounded on the seeding mechanism of the pneumatic seed-metering device through fluid mechanics and established a regression model of seed-spacing. Dizaji et al. [11] designed a pneumatic seed-dropping device of the pneumatic precision seed-metering device and studied the influence of the rotating speed of the seed-metering plate and the airflow speed of the seed-dropping device on the seed breakage rate, seed-filling rate, and seedling emergence rate. Yang et al. [12] designed an auxiliary air-suction precision seed-metering device to improve the seed-filling rate, aiming at the problem that the effect of seed-filling was not good when the FS of the air-suction precision seed-metering device was increased. However, the serrated seed-cleaning mechanism easily caused mechanical damage to the seeds at high speed. Zhang et al. [13] designed a variable particle size double-plate air-suction precision seed-metering device, which could realize the precision seed-metering plate of different particle sizes without replacing the seed-metering plate, improving the universality of the seed-metering device. Shi et al. [14] designed a pneumatic maize precision seed-metering device with combined holes. By combining airflow and the mechanical hole, the seeds were more easily absorbed to the hole by the airflow, and the probability of seed-filling was improved.

In conclusion, the pneumatic precision maize seed-metering device has problems, such as a poor seed-filling state, a poor seed-cleaning effect, and unstable seed-unloading under high-speed working conditions. This study focused on the design, analysis, and evaluation of a new precision metering device to improve the seeding performance and stability of the metering device under high-speed working conditions. The hole of the seed-metering plate used positive pressure to absorb the seeds. The fluidity of the seeds was increased, and the seed-filling performance of the seed-metering device was improved. The seed-cleaning process was completed by the wheel seed-cleaning mechanism. The seed-cleaning performance of the seed-metering device was improved. Through the pressure relief wheel and seed-unloading tube, the process of initiative pressure relief and seed-unloading was completed, which made the seed-unloading process run smoothly.

The objectives of this study were to design, fabricate, and evaluate an inside-filling air-assisted high-speed precision maize seed-metering device. The working principle of the seed-metering device was analyzed. Theoretical analysis and parametric design of the key parts, such as the horizontal stirring notch seed-metering plate and the wheel seed-cleaning mechanism, were carried out. Additionally, the effects of the FS and the WP on the seeding performance of the precision seed-metering device were investigated. The best combination of working parameters was determined and verified. Finally, the seeding performance was compared with that of the conventional air-suction precision seed-metering device. This study provides technical references for the innovative design of maize precision seed-metering devices and provides an important machine innovation for the sustainable development of agriculture.

2. Materials and Methods
2.1. Structure and Working Principle of Seed Metering Device
2.1.1. Structure of Seed Metering Device

An inside-filling air-assisted high-speed precision maize seed-metering device was composed of seed-metering device cases, an initiative pressure relief wheel, a matching seat, seed-cleaning wheels, a curved blocking board, a seed-unloading tube, a seed-ejecting
wheel, and so on, as shown in Figure 1. The horizontal stirring notch seed-metering plate and the wheel seed-cleaning mechanism were the key components of the seed-metering device. The rationality of the design of the key parts directly affected the seeding quality. The seed-metering plate and matching seat tightened the assembly, ensuring a steady seed-filling process. The initiative pressure relief wheel and the seed-ejecting wheel were installed on the front case, completing the respective processes of the initiative pressure relief and ejecting seed. The seed-unloading process was carried out steadily to avoid blocking the holes of the seed-metering plate. The wheel seed-cleaning mechanism was assembled on the rear case, completing the seed-cleaning process. The effect of seed-cleaning was artificially controlled by adjusting the adjustable knob. The seed-cleaning wheel is made of rubber material to avoid damage to the seeds during the seed-cleaning process. A curved blocking board was located below the wheel seed-cleaning mechanism to prevent the cleaned seeds from entering the seed-unloading zone and avoid multiple seeding problems. The rear case was designed with a seed inlet, an air inlet, and a seed-unloading outlet in a clockwise direction.

Figure 1. Overall structure of the seed-metering device: (a) expanded view; (b) side view. 1. Front case; 2. fixed nut; 3. initiative pressure relief wheel; 4. matching seat; 5. seed-cleaning wheel; 6. driving gear; 7. adjustable knob; 8. seed adjustable board; 9. rear case; 10. curved blocking board; 11. seeding shaft; 12. seed-unloading tube; 13. seed-metering plate; 14. seed-ejecting wheel; 15. air inlet; 16. seed inlet.

2.1.2. Working Principle of the Seed Metering Device

According to different functions and working sequences, the working zone of the precision seed-metering device was divided into a seed-filling zone (I), a seed-cleaning zone (II), a seed-carrying zone (III), and a seed-unloading zone (IV), as shown in Figure 2. The working process of the seed-metering device was mainly divided into the four stages of the seeding process: seed-filling, seed-cleaning, seed-carrying, and seed-unloading. When the seed-metering device is in operation, an external fan was attached to the upper air inlet of the rear case and provided stable positive pressure airflow. The maize seeds entered the seed-filling zone of the device from the seed box through the seed inlet. The number of seeds in the seed-filling zone was controlled by an adjustable seed board, which ensured the dynamic balance of the number of seeds in the seed-filling zone. The driving motor transmitted power to the seeding shaft and drove the seed-metering plate to rotate in a counter-clockwise direction. Under the agitation of the horizontal stirring notch and the airflow, one or more seeds were usually filled in the hole of the seed-metering plate by the pressure when the hole of the seed-metering plate moved to the seed-filling zone. The angle of the seed-filling zone in this process was set to 120°. With the rotation of the seed-metering plate, the hole filled with the seeds entered the seed-cleaning zone. Multiple unstable seeds were removed by the seed-cleaning wheel in the seed-cleaning zone. The cleaned seeds fell back to the seed-filling zone. The angle of the seed-cleaning zone was set to 60°. The single seed rotated along with the seed-metering plate and reached the seed-unloading zone after the seed-cleaning process was completed. The initiative pressure
relief wheel cut off the pressure so that the seeds smoothly entered the seed-unloading tube. The process of initiative pressure relief and seed-unloading was jointly completed. The stability of the seed-unloading process was ensured. A seed-ejecting wheel was arranged below the initiative pressure relief wheel to avoid blocking the hole of the seed-metering plate. In the end, the maize seeds were accurately put into the soil at zero speed using initiative airflow, and precision seeding was achieved.

![Figure 2](image_url)

**Figure 2.** Working zone and seed-unloading process of the seed-metering device: (a) working zone; (b) seed-unloading process. I. Seed filling zone; II. seed-cleaning zone; III. seed-carrying zone; IV. seed-unloading zone.

### 2.2. Structural Design and Theoretical Analysis of the Seed Metering Device

#### 2.2.1. Design of the Horizontal Stirring Notch Seed Metering Plate

Seed filling is an important part of the seeding process. A reasonable seed-filling state and stirring effect on maize seeds can improve seed-filling stability and the seed-filling rate [15]. According to the seed-filling process and the high-speed camera analysis, the state of seed-filling can be divided into horizontal, longitudinal, and vertical seed-filling, as shown in Figure 3. When the WP of the seed-metering device is unchanged, and the filling state of the seeds is horizontal, the adsorption area in the hole of the seed-metering device is largest, and the pressure is also largest at this time [16]. Therefore, the horizontal seed-filling state is the most stable. The longitudinal seed-filling state leads to an increase of the required WP and the problem of missing seeding and multiple seeding. At the same time, the accumulation of maize seeds in the seed-filling zone decreases the activity of the seeds and leads to missing seeding [17,18]. The horizontal stirring notch seed-metering plate was designed in this study, as shown in Figure 4. The analysis shows that when the seed-metering plate and the WP rotating speed are unchanged, the larger the adsorption area of the seeds in the hole of the seed-metering plate is, the larger the pressure is, and the better the filling performance and adsorption stability of the seeds are. When the seeds are in the horizontal seed-filling state, the adsorption area is larger compared with when the seeds are in the other two seed-filling states (the longitudinal and vertical seed-filling states), the force is relatively stable, and the seed-filling quality and efficiency are high. At the same time, the seeds to be filled are stirred through the horizontal stirring notch seed-metering plate to improve the effect of seed-filling. The horizontal stirring notch corresponds to the hole of the seed-metering plate one to one. The design of structural parameters is based on the random size of the maize seeds. The main designed parameters are the length of the notch (m), the width of the notch (n), and the angle of the notch (θ).
To improve the seed-filling adaptability and quality of the horizontal stirring notch seed-metering plate, the characteristic physical parameters of maize seeds were statistically analyzed [19]. Combined with the geometric size of maize seeds, the basic parameters of the horizontal stirring notch should be satisfied as follows:

\[
\begin{align*}
    d_L & \leq m \leq 1.5d_L \\
    h & \leq n \leq 1.5h
\end{align*}
\]  

(1)

where \(d_L\) is the average length of maize seeds, mm; \(h\) is the average thickness of maize seeds, mm; \(m\) is the length of the horizontal stirring notch, mm; and \(n\) is the width of the horizontal stirring notch, mm.

The horizontal stirring notch of the seed-metering plate rotates at a constant speed, and the seeds are forced in the rotating horizontal stirring notch. When the horizontal stirring notch of the seed-metering plate rotates to the angle (\(\delta\)), the center of mass of the maize seeds in the horizontal stirring notch is taken as the coordinate origin \(O\), and the spatial rectangular coordinate system \(xyz\) is established, as shown in Figure 5. The forces on the seeds are analyzed. The seeds are subjected to the centrifugal force of the horizontal stirring notch (\(T\)), the gravity (\(G\)), the supporting force of the horizontal stirring notch (\(F_{N2}\)), the sidewall thrust of the horizontal stirring notch (\(F_{N3}\)), the supporting force of the seeds (\(F_{N4}\)), the frictional force of the seeds (\(F_f2\)), the frictional force of the horizontal stirring notch (\(F_f3\)), and the flow resistance (\(F_D\)).

Figure 3. Seed filling state.

Figure 4. Horizontal stirring notch seed-metering plate: (a) seed-metering plate; (b) partial enlargement.
Figure 5. Force analysis of the seed in the horizontal stirring notch: (a) force analysis in $xOy$; (b) force analysis in $yOz$.

In the $yOz$ plane, the area relation of the seed in the stirring notch is as follows:

$$\begin{cases}
a = \left(\frac{m-1}{m}\right)^2 \\
M_1 = A - a \\
M_2 = S - M_1 \\
A = \frac{1}{2} m^2 \tan \theta
\end{cases}$$

(2)

where $A$ is the side area of the inner wall of the notch, mm$^2$; $a$ is the area of the inner wall of the notch not touching the seed, mm$^2$; $S$ is the total side area of the maize seed, mm$^2$; $M_1$ is the area of the maize entering the notch, mm$^2$; $M_2$ is the area of the maize not entering the notch, mm$^2$.

By simplifying Equation (2), the relation of $M_1$ and $\theta$ can be shown as follows:

$$M_1 = \left( ml - \frac{1}{2} l^2 \right) \tan \theta$$

(3)

From the analysis of Equation (3), $\tan \theta$ increases accordingly when $\theta$ increases. When $\theta$ increases, the area of the seed in the stirring notch increases, and the frictional force increases. The effect of the horizontal seed-filling is good, so the maximal angle of the notch ($\theta$) determines the rate of the horizontal seed-filling and the stirring effect of the seeds.

The force analysis on the seeds is carried out in the $xOy$ plane, and the seeds with proper agitation can be better filled. Equation (4) must be satisfied to increase the rate of horizontal seed-filling and stir the seeds.

$$\begin{cases}
x axis : F_{f1} + F_{f2} + F_{N4} \cos \delta < F_{N3} \\
y axis : G \cos \delta > F_{N2}
\end{cases}$$

(4)

where $m_e$ is the mass of maize seeds, $g$; $F_{f1} = F_{N1} \mu_1$, $F_{f2} = F_{N4} \mu_2$, $F_{f2} = G + F_{N1} \sin \theta = S^{-1} M_1 G$, $F_{N3} = m_e \omega R$, $F_{N4} = S^{-1} M_2 G$, $\omega$ is the angular velocity of the seed-metering plate, rad/s; $\mu_1$ is the coefficient of friction between the maize seed and the stirring notch; $\mu_2$ is the coefficient of friction between the maize seeds.

Combining Equations (3) and (4), the relationship between the angle of the notch ($\theta$) and the angular velocity of the seed-metering plate are simplified as

$$\tan \theta \leq \frac{S m_e \omega^2 R}{k G (\mu_1 - \mu_2 - \cos \delta)} + S$$

(5)

where $k = (ml - 1/2l^2)$.

The analysis of Equation (5) shows that the maximal angle of the notch ($\theta$) increases when the rotating speed of the seed-metering plate increases. The larger the angle of the notch ($\theta$) is, the better the effect of horizontal seed-filling and stirring. Therefore, the FS is the main factor that affects the maximal angle of the notch. According to the reference [20] and the common FS and WP range of the pneumatic seed-metering device.
(8 km/h ≤ V ≤ 14 km/h, 3 kPa ≤ P ≤ 6 kPa), the structural parameters of the designed seed-metering device were designed with an FS of 12 km/h and a WP of 4 kPa. The analysis shows that the rate of horizontal seed-filling increased with the increase of the angle of the horizontal stirring notch, but the greater the notch’s angle, the greater the thickness of the seed-metering plate was. The range of the angle of the notch was calculated according to Equation (5) (0° ≤ θ ≤ 15°). Combined with the reference and the thickness of the seed-metering plate [21], the angle of the horizontal stirring notch was determined as 10°. The range of the length and width of the horizontal stirring notch was calculated according to Equation (1) (12.35 mm ≤ m ≤ 18.53 mm, 9.24 mm ≤ n ≤ 13.86 mm). The length and width of the horizontal stirring notch were determined as 16 mm and 8 mm, respectively.

The range of the length and width of the horizontal stirring notch was calculated according to Equation (1) (12.35 mm ≤ m ≤ 18.53 mm, 9.24 mm ≤ n ≤ 13.86 mm). The length and width of the horizontal stirring notch were determined as 16 mm and 8 mm, respectively.

The longer the hole of the seed-metering plate stays in the seed-filling zone, the better the seed-filling performance in the process of seed-filling. According to the analysis of the seed-filling process and reference [22], the seed-filling time is only related to the number of holes in the seed-metering plate and the radian of the seed-filling zone under the constant conditions of the FS and seed-spacing and has nothing to do with the diameter of the seed-metering plate [23]. However, the diameter of the seed-metering plate directly affects the overall size of the seed-metering device. The position radius of the hole refers to the distance from the center of the hole to the center of the seed-metering plate. The diameter of the hole is twice the radius of the hole. The diameter of the hole directly affects the linear velocity of the hole position and the centripetal force of the seed. Therefore, if the position diameter of the hole of the seed-metering plate is too large, the linear velocity and centripetal force of the seeds are large [24]. High centrifugal force in the seed-filling zone is not conducive to seed-filling at high speed. If the position diameter of the hole of the seed-metering plate is too small, the number of seed-metering plate holes is reduced. Therefore, the position diameter of the hole is determined as 176 mm after comprehensive consideration. At present, the diameter of the seed-metering plate is 140–260 mm at home and abroad. Combining this with the analysis of relevant reference [25], the diameter of the seed-metering plate (D) should be larger than the position diameter of the hole of the seed-metering plate and has a suitable outer edge. At the same time, the diameter of the seed-metering plate is not too large or too small, and the diameter range of the seed-metering plate is obtained according to the overall structure design requirements of the seed-metering device (176 mm < D < 260 mm). The diameter of the seed-metering plate is determined as 250 mm.

The holes’ parameters are mainly divided into the number of the holes, the structure of the holes, and the diameter of the holes, which directly affects the seed-filling process, seed-carrying process, and seed-unloading process of the seed-metering device. This is the key to the design of the seed-metering device:

\[ Z = \frac{60V}{NL} \]  

where \( N \) is the rotating speed of the seed-metering plate, r/min; \( L \) is the seed-spacing, mm; \( Z \) is the number of holes in the seed-metering plate; and \( V \) is the FS of the seed-metering device, m/s.

Based on the analysis of Equation (6), the greater the number of holes (Z) is, the lower the rotating speed (N) is under constant conditions of the FS and seed-spacing. However, the seeding performance does not increase with the number of holes in the seed-metering plate. According to the conclusion of [26], the optimal number of holes in a seed-metering plate in most maize seed-metering devices is 26. To meet the requirement of precision seeding of maize under high-speed conditions, a reasonable increase in the number of holes in a seed-metering plate means that the seed-metering plate will need to rotate for one week to absorb more seeds, thereby increasing the speed and efficiency of the operation of the seed-metering device. The final number of holes in the seed-metering plate is determined as 29. At the same time, the diameter of the holes of the pneumatic maize seed-metering device is generally 4–5.5 mm [27], and the size of the holes was determined to be 5 mm.
2.2.2. Analysis of Multiple Seeding Process

According to the precision seeding requirements, the seeding quantity should be consistent. When the precision seed-metering device is in operation, there should only be one seed per hole. However, due to the irregular size of the seed, it is difficult to completely seal the hole when pressing the seeds by the airflow, and the phenomenon of multiple seeding often occurs [28].

When the horizontal stirring notch of the seed-metering plate rotates through the seed-filling zone, the hole adsorbs steadily one or more seeds under the action of the pressure. Each seed occupies a different area of the hole, and the dominant seed occupies a larger area. Since the radii of the hole and the seed are small, the adsorption area \((S_i)\) of the seed can be approximated as follows:

\[
S_i = \pi \left(\frac{a_1}{2}\right)^2
\]

where \(a_1\) is the length of the seed along the direction of the position diameter of the hole, mm.

The single seed is absorbed into the hole of the seed-metering plate by the airflow in the seed-filling zone. The rotating center of the seed-metering plate is the origin of coordinate \(O\). The spatial rectangular coordinate system \(xyz\) is established, as shown in Figure 6. Force analysis was carried out on the seeds. Under the combined action of gravity \((G)\), the centrifugal force \((T)\), the flow resistance \((F_D)\), and the frictional force \((F_f)\), a single seed moves in a uniform circular motion in the seed-metering device. The flow resistance is the resistance of the object when the viscous fluid flows around the object, and its direction is consistent with the direction of the fluid streamline. The equation for calculating flow resistance is as follows:

\[
F_D = C_D B \frac{\rho v_f^2}{2}
\]

where \(C_D\) is the coefficient of the flow resistance; \(B\) is the projected area of the maize seeds, \(m^2\); \(\rho\) is the density of the fluid, \(\text{kg/m}^3\); and \(v_f\) is the velocity of airflow at seed position, \(\text{m/s}\).

\[\text{(8)}\]

Figure 6. Force analysis was carried out on the seeds. Under the combined action of gravity \((G)\), the centrifugal force \((T)\), the flow resistance \((F_D)\), and the frictional force \((F_f)\), a single seed moves in a uniform circular motion in the seed-metering device. The flow resistance is the resistance of the object when the viscous fluid flows around the object, and its direction is consistent with the direction of the fluid streamline. The equation for calculating flow resistance is as follows:

\[\text{(8)}\]

On this basis, if the maize seeds are ensured to carry a uniform circular motion, the force should be balanced along the normal and tangent directions of the motion of the seed, the seeds will not roll and slide, and the force balance equation (Equation (9)) should be satisfied:

\[
\begin{align*}
T \cos \eta + F_D \cos \alpha &= F_f \cos \beta \\
G + F_D \sin \alpha &= T \sin \eta + F_f \sin \beta
\end{align*}
\]

where \(\eta\) is the angle between \(T\) and \(x\)-axis, in degrees; \(\alpha\) is the angle between \(F_D\) and \(x\)-axis, in degrees; \(\beta\) is the angle between \(F_f\) and \(x\)-axis, in degrees; \(T = m_i \omega r\), \(F_f = F_N \mu\), \(F_N = PS\mu\), and \(\mu\) is the friction coefficient between the seed and the hole of the seed-metering plate.
Equation (10) is obtained by combining and simplifying Equations (8) and (9).

\[ S_i = \frac{2m_i\omega^2 r \cos \eta + C_D \rho v^2 r \cos \alpha}{2P \mu \cos \beta} \]  

(10)

According to Equation (10), the adsorption area \( (S_i) \) is related to the FS and the WP. The higher the seeds’ weight, the faster the linear speed of the seed-metering plate is, and the higher the required adsorption area \( (S_i) \) is. When the WP is higher, the adsorption area \( (S_i) \) is smaller. When the WP is unchanged, the area of the hole occupied by the seeds is larger, and the compressive force is greater. The migration of the seeds is more stable. The minimum area for the stable migration of the seeds can be calculated as \( S_1 \approx 6.93 \text{ mm}^2 \) by Equation (10).

It can be seen that, since the adsorption area is smaller than the total area of the hole, the hole adsorbs one or more seeds. The essence of the multiple seeding problem is that the hole cannot be filled during the seed-adsorbing process, leading to the phenomenon of multiple seeding. The seed-cleaning process can be understood as gradually increasing the adsorption area \( (S_i) \) of a certain seed. Although the unstable and disadvantaged seeds are cleaned up under the combined action of gravity, centrifugal force, and air current, there is still a stable migration of multiple seeds. Therefore, a reasonable design of the seed-cleaning mechanism can improve the performance of the seed-cleaning, reducing the multiple seeding problem and improving the seeding performance of the seed-metering device in the high-speed range.

2.2.3. Design of the Wheel-Seed-Cleaning Mechanism

It is known from the preparation experiment and [29] that the position of the seed-cleaning mechanism should ensure sufficient clearance between the sizes of adjacent holes in the horizontal position. It is ensured that the cleaned seeds do not interfere with the seeds in a normal state and return to the seed-filling zone smoothly. It is concluded that the angle of the installed position of the seed-cleaning mechanism should be greater than 52°. The installed position of the wheel seed-cleaning mechanism is shown in Figure 7. The seed-metering device fills seeds on the back and transports seeds in a counter-clockwise direction. The first quadrant angle of the installed position of the wheel seed-cleaning mechanism is determined as 75°.

![Figure 7](image-url)  

Figure 7. Position of wheel seed-cleaning mechanism: (a) position of seed-cleaning mechanism; (b) partial enlargement.

The wheel seed-cleaning mechanism is important for improving the single seed precision seeding ability of the seed-metering device. Single seed precision seeding can be realized through a wheel seed-cleaning mechanism [30,31]. According to the characteristics of maize seeding, the wheel seed-cleaning mechanism is designed to remove multiple seeds. The seed-cleaning wheel is trial-produced with rubber material. The frontal impact of the seeds can be reduced, and the seeds can be avoided by being damaged when the seed-cleaning wheel is in operation, achieving the purposes of a stable seed-cleaning. The wheel seed-cleaning mechanism comprises rubber seed-cleaning wheels, wheel seed-cleaning brackets, double-row teeth supporting plate, an adjustable knob, driving gears,
and driven gears, as shown in Figure 8. The rubber seed-cleaning wheels are installed on the wheel seed-cleaning bracket, and the double-row teeth supporting plate is installed on the rear case. According to the analysis of the preliminary experiment, increased the number of seed-cleaning wheels increases the continuous force on the seeds, making it easier to remove multiple seeds. Considering the space inside the seed-metering device and the effect of seed-cleaning, the optimum number of seed-cleaning wheels for seed-cleaning was determined to be three.

![Figure 8. Wheel-seed-cleaning mechanism: (a) structural diagram; (b) simplified diagram. 1. Adjustable knob; 2. double-row teeth supporting plate; 3. wheel seed-cleaning bracket; 4. rubber seed-cleaning wheel; 5. driving gears; 6. driven gears.](image)

The driving gear rotates to drive the driven gears with the same modulus, the number of teeth, and the pressure angle through the cleaning adjustment knob, and a double-row teeth supporting plate is finally controlled. The adjustable function of the seed-cleaning effect of the wheel seed-cleaning mechanism is completed. The wheel seed-cleaning mechanism is simplified in the process of regulation. The number of initiative components in the mechanism is 5, the number of low pairs of gears rotating on the contacting point is 4, and the number of high pairs of gears or racks on the contacting point is 6. The overall degree of freedom of the mechanism is 1, based on the analysis and calculation. The mechanical movement meets the requirements of the adjustment effect of seed-cleaning. The kinematic rationality of the mechanism is verified, and the stability of the process of seed-cleaning and seed-cleaning adjustment is ensured.

The seeds are blocked by the rotating seed-cleaning wheel and collide when the seeds are adsorbed on the holes rotating with the metering plate. The inferior seeds break out of the hole and fall to the seed-filling zone under the action of impact force. The purpose of seed-cleaning is completed, and the cleaned seeds are ensured that can fall back to the seed-filling zone smoothly when the seed-cleaning wheel cleans the seeds. The angle between the cleaning wheels should be greater than the angle between the holes, avoiding continuous seed-cleaning. The space size in the seed-metering device and the sliding friction between the edge of the seed-cleaning wheel and the seed should be considered. The angle (β) between the seed-cleaning wheels was determined as 16°, and the radius of the seed-cleaning wheel (r) as 15 mm.

The position radius of the seed-cleaning wheel refers to the distance from the center of the seed-cleaning wheel to the center of the seed-metering plate. The area distribution of the hole of the seed-metering plate should be determined in the stable adsorbing migration of multiple seeds. Thus, the position radius of the cleaning wheel was determined. The seed-cleaning effect was improved. The spatial rectangular coordinate system xyz was set up with the rotating center of the seed-metering plate as the coordinate origin O when the seed-metering plate steadily carried multiple seeds, as shown in Figure 9. The seeds were mainly affected by the combined effects of the gravity (G), the centrifugal force (T), the flow resistance (F_D), the frictional force of the seed-metering plate (F_τ), the supporting force of the lower seed (F_N1), and the frictional force of the lower seed (F_a). When multiple seeds are adsorbed and rotate in a uniform circular motion, the force should be balanced.
along with the normal and tangent directions of the seed movement. No rolling or sliding of multiple seeds should occur, and the force balance equations should be as follows:

\[
\begin{align*}
\begin{cases}
T \cos \eta + F_f \cos \alpha + F_{N1} \cos \eta + F_{f1} \cos \epsilon &= F_f \cos \beta \\
G + F_f \sin \alpha + F_{f1} \sin \epsilon &= F_f \sin \beta + F_{N1} \sin \eta + T \sin \eta
\end{cases}
\end{align*}
\]

where \( \epsilon \) is the angle between \( F_{f1} \) and \( x \)-axis, in \(^{\circ}\); \( F_{f1} = F_{N1} h_2 \).

![Figure 9. Force analysis of multiple seeds: (a) force analysis in \( xOy \); (b) force analysis in \( yOz \).](image)

Equation (11) analysis shows that the lower seed gives the upper seed-supporting force and frictional force, and the adsorption area will change relatively when the hole moves multiple seeds. Therefore, when the combined force of the supporting force and the frictional force is in a positive direction, the required adsorption area will become smaller. The minimum adsorption area for the stable migration of seeds can be calculated as \( S_2 \approx 5.91 \text{ mm}^2 \) by Equation (11).

According to the analysis of the multiple seeds carrying an area distribution and the seed-cleaning process, the position radius of the first seed-cleaning wheel (\( R_1 \)) is the largest when the minimum adsorption area of the upper seed is \( S_2 \). The maximum position radius of the second seed-cleaning wheel (\( R_2 \)) is at the middle value of the position radius of the first and third seed-cleaning wheel. The centrifugal force mutation is avoided. The maximum position radius of the third seed-cleaning wheel (\( R_3 \)) occurs when the maximum adsorption area of the seeds. A dominant seed is retained for stable migration under the action of the seed-cleaning wheels. Equation (12) can be used to calculate the position radius of the seed-cleaning wheels. The position radius of the seed-cleaning wheels are calculated as \( R_1 \) is 99.5 mm, \( R_2 \) is 97 mm, and \( R_3 \) is 94.5 mm by Equation (12).

\[
\begin{align*}
\begin{cases}
R_1 &= r_1 + d_w + r - (S_2 / \pi)^{\frac{1}{2}} \\
R_3 &= r_1 + d_w / 2 + r \\
R_2 &= (R_1 + R_3) / 2
\end{cases}
\end{align*}
\]

Here, \( r_1 \) is the radius of the hole of the seed-metering plate, mm; \( r \) is the radius of the seed-cleaning wheel, mm; \( d_w \) is the average width of the maize seeds, mm; \( R_1 \) is the position radius of the first seed-cleaning wheel, mm; \( R_2 \) is the position radius of the second seed-cleaning wheel, mm; and \( R_3 \) is the position radius of the third seed-cleaning wheel, mm.

2.2.4. Design of the Seed Unloading Device

The position of the seed-unloading device is the beginning of the seed-filling and seed-unloading process, which directly affects the stability and uniformity of seeding performance. The seed-unloading device is divided into seed-unloading (I) and seed-ejecting (II). The seed-unloading device comprises an initiative pressure relief wheel and a seed-unloading tube, as shown in Figure 10. The initiative pressure relief wheel is installed on the front case and is tangent to the front face of the seed-metering plate. The seed-unloading tube is installed on the rear case and is tangent to the back of the seed-metering plate. With the rotation of the seed-metering plate, the initiative pressure relief wheel fits
with the hole of the seed-metering plate when the seed-unloading device is in operation. The initiative pressure relief wheel cuts off airflow and completes the initiative pressure relief and seed-unloading process with the seed-unloading tube. The smooth operation of the seed-unloading process is thus ensured.

![Figure 10. Seed unloading device and seed-ejecting device: (a) seed-unloading device; (b) seed-ejecting device. 1. Initiative pressure relief wheel; 2. seed-ejecting wheel; 3. seed-metering plate; 4. seed-unloading tube; 5. mounting seat; 6. seed-ejecting wheel connecting part; 7. telescopic spring.](image)

After the process of seed-unloading, a seed-ejecting wheel device is arranged in front of the seed-filling zone to avoid impurities or to prevent fine particles from blocking the mold hole, causing continuous missing broadcast problems, as shown in Figure 10b. It is mainly composed of a seed-ejecting wheel, a seed-ejecting wheel connecting part, a mounting seat, and a telescopic spring. Under the action of spring force, the teeth of the seed-ejecting wheel mesh with the hole of the seed-metering plate when the seed-ejecting wheel is in operation. It ensures that the hole is not filled into the seed-filling zone. The specific design refers to [32] to optimize the configuration.

### 2.3. Experimental Materials and Equipment

The experimental site was the Seeding Performance Laboratory of Northeast Agricultural University. The experimental material was Demeiya no. 1, produced by the Heilongjiang Kenfeng Seed Industry Company (Harbin, China). Manual grading and cleaning ensured that test seeds were of a uniform shape, plump, without damage or insect pests. The geometric size and the 1000-grain weight of the tested variety were measured (the average length, width, and thickness of maize seeds were 12.35, 9.24, and 4.70 mm. The 1000-grain weight of the maize seeds was 331.08 g). The experimental device was mainly composed of an inside-filling air-assisted high-speed precision maize seed-metering device and a JPS-12 type seeding performance experiment bench developed by the Heilongjiang Agricultural Machinery Engineering Research Institute, as shown in Figure 11.

![Figure 11. Seeding performance experiment bench. 1. Inside-filling air-assisted high-speed precision maize seed-metering device; 2. fuel injection pump; 3. DC power supply; 4. image acquisition and processing system; 5. installed bench; 6. motor controller.](image)
2.4. Experimental Methods and Performance Indexes

According to the agricultural requirements of Northeast China, the seed-spacing of maize ranges from 200 to 300 mm. The seed-spacing of maize was set to 200 mm in this study. The length and width of the seedbed were 1900 mm and 70 mm, respectively. The experimental bench can simulate the field experiment, and the seeding performance of the seed-metering device was tested. According to the previous theoretical analysis, the main factors affecting the seeding quality and the performance of the precision seed-metering device were the FS and the WP on the premise that the structural parameters of the precision seed-metering device were determined. Therefore, the FS and WP were selected as experimental factors.

According to the agronomic requirements of maize seeding working and the National Standard of P.R.C. (GB/T 6973-2005 Testing Methods of Single Seed Drills (Precision Drills)) [33], the qualified index (QI) and coefficient of variation (CV) among seed-spacing were selected as performance indexes to evaluate the working quality and stability of the seed-metering device. The related calculation equations are as follows:

$$Q = \frac{n_0}{N} \times 100\% \quad (13)$$

$$C = \sqrt{\frac{\sum(x - \bar{x})^2}{(n' - 1)x^2}} \times 100\% \quad (14)$$

where $Q$ is the qualified index of seed-spacing, as a percentage; $C$ is the coefficient of variation of seed-spacing, as a percentage; $n_0$ is the seeding number of a single seed; $N$ is the theoretical number of seeding, and the theoretical number of seeding in each experiment was 250; $n'$ is the total number of sample seed-spacing; $x$ is the theoretical seed-spacing of seeding, in millimeters, and was set to 200 mm; $\bar{x}$ is the average distance between sample points, in millimeters, and was measured automatically by the image acquisition system of the experimental bench.

A multifactor orthogonal rotation combination experiment and a comparison experiment were carried out. To improve the operability and accuracy of the experiment, the FS of the seed-metering device was controlled by adjusting the rotating speed of the motor, and the WP of the air inlet of the seed-metering device was controlled by adjusting the frequency of the external fan on the experimental bench.

The actual seeding working requirements and the various controllable factors’ effective ranges were combined to test the working quality of the seed-metering device and the best combination of working parameters. To analyze the seeding performance of the seed-metering device intuitively, the FS of the seed-metering device and the rotating speed of the seed-metering plate were transformed into each other through a certain proportion. Combining the requirements of high-speed precision seeding (an FS greater than 10 km/h), the field preparation experiment, and the theoretical analysis, an FS range of 12–14 km/h (the corresponding rotating speed of the seed-metering plate was 34.48–40.23 r/min) and a WP range of 3–6 kPa were selected to highlight the seeding performance of the seed-metering device. An orthogonal rotation combination experiment of two factors and five levels was carried out using the Design-Expert 10.0.7 software. The coding of experimental factors was set, as shown in Table 1.
Experimental factors coding table.

| Level  | Experimental Factors |
|--------|-----------------------|
|        | FS \( x_1 \) km/h\(^{-1} \) | WP \( x_2 \) kPa |
| 1.414  | 14.00                 | 6.00               |
| 1      | 13.71                 | 5.56               |
| 0      | 13.00                 | 4.50               |
| −1     | 12.29                 | 3.44               |
| −1.414 | 12.00                 | 3.00               |

During the experiment, the seed-metering device was securely installed on the experimental bench. The air inlet of the seed-metering device was connected to the external fan of the experimental bench, providing a stable positive pressure for the seed-metering device. The belt of the seedbed moved in the opposite direction relative to the seed-metering device. The actual advanced state of the seeding machine was simulated. The fuel injection pump sprayed viscous oil on the belt of the seedbed. The maize seeds fell from the seed-metering device onto the oil-coated seedbed. The real-time detection and data acquisition were carried out by the image acquisition and processing system of the experimental bench to accurately determine the performance indexes of the seeding. The experimental bench has a statistical function and can automatically deal with the seed-spacing after seeding by the image acquisition and processing system. The QI and the CV were thus obtained. Each experiment was repeated five times. The 250 seeds were continuously recorded when the seed-metering device worked steadily on the seedbed, and other parameters were kept constant. The average value of the data was taken as the experimental results.

The experimental results of the orthogonal rotation combination experiment of two factors and five levels were processed by Design-Expert 10.0.7. The multiobjective variable optimization method was adopted by combining the range of factor levels and following high-speed precision seeding. Multiobjective parameter optimization (the numerical optimization module of Design-Expert 10.0.7) was used to analyze and solve the mathematical model. The best combination of working parameters was obtained. The performance of the designed seed-metering device was compared with that of the conventional air-suction seed-metering device in the best combination of working parameters.

3. Results and Discussion

3.1. Experimental Design and Results

The orthogonal rotation combination experiment of two factors and five levels was carried out. To obtain the best combination of working parameters of the seed-metering device, the influence factors were analyzed for significance. A comparison was carried out in the best combination of working parameters. The experimental results of the FS and the WP of the seed-metering device were analyzed. The specific experimental design scheme and results are shown in Table 2.
Table 2. Experimental design scheme and results.

| NO. | Experiment Factors | Performance Indexes |
|-----|--------------------|---------------------|
|     | FS    | WP    | QI%  | CV%  |
| 1   | x₁    | x₂    | 91.01 | 13.52 |
| 2   | 1     | -1    | 89.26 | 16.12 |
| 3   | -1    | 1     | 93.81 | 15.45 |
| 4   | 1     | 1     | 91.76 | 16.08 |
| 5   | -1.414| 0     | 95.12 | 10.78 |
| 6   | 1.414 | 0     | 90.15 | 17.23 |
| 7   | 0     | -1.414| 86.92 | 14.34 |
| 8   | 0     | 1.414 | 93.21 | 16.56 |
| 9   | 0     | 0     | 90.79 | 13.92 |
| 10  | 0     | 0     | 91.58 | 12.13 |
| 11  | 0     | 0     | 92.24 | 11.53 |
| 12  | 0     | 0     | 90.94 | 12.41 |
| 13  | 0     | 0     | 91.57 | 11.61 |
| 14  | 0     | 0     | 92.34 | 13.17 |
| 15  | 0     | 0     | 90.28 | 11.62 |
| 16  | 0     | 0     | 91.64 | 12.71 |

Note: FS = forward speed; WP = working pressure; QI = qualified index; CV = coefficient of variation.

3.2. Effect of Interaction Factors on Seeding Performance

The regression analysis of experimental data through Design-Expert 10.0.7 software. Analysis of factor variance was carried out, and more significant influence factors were screened out. The regression equations between the performance indexes and the experimental factors were as follows:

\[
Q = 91.42 - 1.35x_1 + 1.77x_2 - 0.075x_1x_2 + 0.63x_1^2 - 0.65x_2^2
\]  \hspace{1cm} (15)

\[
C = 12.39 + 1.54x_1 + 0.63x_2 - 0.49x_1x_2 + 0.95x_1^2 + 1.67x_2^2
\]  \hspace{1cm} (16)

The response surface was obtained using Design-Expert 10.0.7 to visually analyze the relationship between performance indexes and experimental factors under predetermined working performance indexes to meet the requirements of precision seeding. The influence rule of each factor was analyzed. According to the correlation regression equations and the contour distribution density of the response surface graph, the interaction between the FS and the WP of the seed-metering device had significant effects on the QI and the CV. As indicated by Figure 12, when the FS was unchanged, the QI increased first with the increase of the WP. When the WP was unchanged, the QI decreased with the increase of the FS. When the FS changed, the range of the QI changed greatly, so the FS was the main factor affecting the QI. As indicated by Figure 13, when the current FS was unchanged, the CV decreased first and then increased with the increase of the WP. When the WP was unchanged, the CV increased with the increase of the FS. When the FS changed, the variation range of the CV was large, so the FS was the main factor affecting the CV.
3.3. Parameter Optimization

To obtain the optimal combination of working parameters of the experimental factors, a parameterized mathematical model was established to optimize the design. Combining this with the conditions of the factors boundary and following the principle of high-speed precision seeding, the regression equations of the QI and CV were analyzed by the multiobjective variable optimization method [34–36]. Multiobjective parameter optimization was used to analyze and solve the mathematical model. The nonlinear programming parameter model is as follows:

\[
\begin{align*}
\text{max} Q \\
\text{min} C \\
\text{s.t.} \\
12.00 \text{ km/h} & \leq x_1 \leq 14.00 \text{ km/h} \\
3 \text{ kPa} & \leq x_2 \leq 6 \text{ kPa} \\
0 & \leq Q(x_1, x_2) \leq 1 \\
0 & \leq C(x_1, x_2) \leq 1
\end{align*}
\]  

(17)
The mathematical model was analyzed and solved based on multiobjective parameter optimization. When the FS and the WP of the seed-metering device were, respectively, 13.10 km/h and 4.75 kPa, the performance of the seed-metering device was excellent. The QI and the CV were, respectively, 91.62% and 12.86%. The bench validation experiments were carried out according to the optimized results. The QI and the CV were, respectively, 91.18% and 12.32% when the FS and the WP of the seed-metering device were 13.10 km/h and 4.75 kPa. The results of the bench validation experiments were consistent with the optimized results.

### 3.4. Comparison Experiment

Under the condition of the optimal combination of working parameters, the performance was compared with that of the conventional air-suction precision seed-metering device on the domestic market. The experiments were repeated five times, a certain number of maize seeds mixed evenly was ensured, and the data were then processed. The results of the bench comparison showed that the QI of the designed inside-filling air-assisted high-speed precision maize seed-metering device was 91.21% when the FS and the WP were 13.10 km/h and 4.75 kPa. The QI of the conventional air-suction precision metering device was 88.56%. Analysis of the comparison showed that the seeding quality of the inside-filling air-assisted high-speed precision maize seed-metering device was higher than the conventional air-suction precision seed-metering device. The QI was increased by 2.56%. The high-speed precision seeding requirements were thus satisfied.

### 3.5. Discussion

This study focused on designing, analyzing, and evaluating an inside-filling air-assisted high-speed precision maize seed-metering device. Theoretical analysis and parametric design of key components, along with a seeding performance optimization experiment and a comparison experiment, were carried out. In a future study, the seed-metering device will be installed on the precision seeder to carry out a field production experiment, focusing on a comparative study of the germination rate of the maize seeds after seeding in the actual production process. The actual seeding quality and production efficiency of the seed-metering device will be evaluated. At the same time, the relationship between seeding quality and agricultural production will be discussed. Such a study would provide an important reference for improving and optimizing precision seeding components and providing a machinery guarantee for sustainable agricultural development.

### 4. Conclusions

1. Precision seed-metering devices under high-speed working conditions suffer from a poor seed-filling state and a poor seed-cleaning effect. Problems of multiple and missing seeding occur during the working process of the device. Thus, an inside-filling air-assisted high-speed precision maize seed-metering device was designed, fabricated, and evaluated. The overall structure and working principle of the seed-metering device were explained. Theoretical analysis and parametric design of the key parts, such as the horizontal stirring notch seed-metering plate and the wheel seed-cleaning mechanism, were carried out. The seeding performance of the seed-metering device was improved.

2. FS and the WP were selected as the main influential factors of the experiment. QI and CV were selected as the performance indexes of the experiment. The optimum combination of working parameters of the seed-metering plate was determined by an orthogonal rotation combination experiment of two factors and five levels. The results of the bench validation experiments showed that the optimal performance of the seed-metering device was obtained when the FS and the WP of the seed-metering device were 13.10 km/h and 4.75 kPa. The QI and the CV were 91.18% and 12.32%.

3. Under the optimal combination of working parameters, a performance comparison was carried out with the conventional air-suction precision seed-metering device. The
results of the bench comparison showed that the seeding quality of the inside-filling air-assisted high-speed precision maize seed-metering device was higher than that of the conventional air-suction precision seed-metering device. The QI was increased by 2.56%. The high-speed precision seeding requirements were thus satisfied.

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