



Design and Experimental Study of a Combined Pneumatic Plot Seed-metering Device for Cotton

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ABSTRACT

This study presents a combined pneumatic seed-metering device (SMD) that could not only fill, carry, and meter seeds, but also switch quickly between seed-metering and seed-cleaning modes, and clean seeds thoroughly and rapidly. The seed-filling, seed-carrying, and seed-metering modes of the SMD were analyzed based on a theoretical kinematic model. Furthermore, a three-factor, three-level orthogonal test was conducted by using a performance test bench arranged for the SMD as well as Design-Expert software. The combination of parameters that led to the lowest mis-seeding rate (0.59%) was as follows: an air pressure of 2.67 kPa, a slot width of 2.83 mm, and a seed-metering speed of 20 r/min. The optimized scheme that resulted in a relatively low multiple-seeding rate (4.3%) and met other requirements at the same time was as follows: an air pressure of 2.35 kPa, a slot width of 2.78 mm, and a seed-metering speed of 20 r/min. A field test was subsequently performed by using a combined pneumatic plot cotton planter prototype. While the mis-seeding and re-seeding rates obtained from the field test were both somewhat higher than those obtained from the laboratory bench test, they still met precision planting requirements. The field test validated the accuracy of the theoretical analysis and bench test and served as a foundation for future prototype production and popularization.

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NOMENCLATURE

d	Width of the guide slot on the guide slotted disk (m)	G	Force of gravity exerted on each cotton seed (N)
l	Distance between the center of gravity of the seed and the guide slotted disk (m)	g	Gravitational acceleration (m/s^2)
Q	Resultant force of G , F , and J (N)	v	Distance between the cotton seed and the center (m)
P	Suction force generated by the seed-suction hole on the seed (N)	λ	Comprehensive seed friction coefficient
F	Sliding friction force between the seed and the guide slot (N)	K_1	Seed suction reliability coefficient ($K_1=1.8-2.0$)
N	Force (i.e., the sum of N_1 and N_2) exerted by the air-suction hole on the seed (N)	K_2	External conditions influence coefficient ($K_2=1.6-2.0$)
S	Area of the air-suction hole (m^2)	K_3	Seed moisture content influence coefficient ($K_3=1.1-1.2$)
H	Critical degree of vacuum in the SMD air-suction hole (Pa)	μ	Dynamic friction coefficient
		m	Seed group weight (kg)

1. INTRODUCTION

The cotton industry plays an important role in agricultural production system of China. Cotton is closely linked to daily life. In 2019, the total cotton planting area in China was 3,339,200 ha, which was 15,200 ha smaller than in 2018. This represents a 0.5% decrease. In 2019, China's total cotton production

reached 5,889,000 tons, which is 213,000 tons or 3.5% less than in 2018. (data from the National Bureau of Statistics of China). Cotton breeding substantially affects the cotton planting area and the production quality. Plot breeding is an important step in the selection and breeding of new cotton cultivars. Due to the large number of cotton cultivars and seeds available for selection, cotton is planted across many plots during cotton selection and breeding. Strict requirements are applied to cotton selection [1].

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Cotton planting in plots differs from that in fields. When cotton is planted in a plot, there are strict position requirements for the start and end of planting. In addition, precise row and plant spacings and planting depths are required. Moreover, rapid, thorough seed cleaning is required after cotton planting is completed and seeds are rapidly discharged in the subsequent plot.

Currently, plot planters are used in China primarily for crops such as wheat, maize, and soybeans. The 2BJ-2 planter developed by Hebei Suning Agricultural Machinery Research Institute is used primarily to plant wheat in plots [2]. Li et al. [3] designed an automatic control system based on a conical compartment tray-type seed-metering device (SMD). Xu et al. [4] designed a conical canvas belt-type plot planter for wheat. Shang's team studied plot planting of wheat extensively during the project termed "Development and Demonstration of Precision Planting and Harvesting Equipment for Plots of Crop Varieties—an Industrial Science and Technology Project of China". Li et al. designed a precision plot planter for maize [5]. Huang et al. designed a precision plot planter for soybeans [6]. Cotton seeds differ from wheat, maize, and soybean seeds. Therefore, it is necessary to further explore and design machinery for breeding and planting cotton in plots using planters similar to those currently used in China.

Internationally, enterprises that have been somewhat successful in crop breeding machinery development, including Wintersteiger in Austria, Haldrup in Germany, Almaco in the United States, and Baural in France, have all manufactured various plot planter models for various crops [7-10]. The agricultural parameters (e.g., plant and row spacings and planting depths) used with cotton differ from those for wheat, maize, and soybeans. Therefore, it is necessary to design precision plot planters for cotton that can accurately meter and rapidly and thoroughly clean seeds. These plot planters must be relatively easy to operate within the agricultural requirements of cotton [11-13].

According to the needs of cotton planting, we have designed a combined air suction cotton planter (Figure 1). This machine is mainly composed of seed metering device, opener, vacuum fan, air pump, waste seed recovery room, etc. The seed meter is the most critical component. Therefore, this paper combines the agricultural material characteristics of cotton seeds to design the structure of the combined air-suction seed meter and study the optimal working parameters.

2. STRUCTURE AND OPERATING PRINCIPLE OF THE COMBINED PNEUMATIC SMD FOR COTTON PLOT PLANTERS

The components of the SMD included a seed-metering shell, a drive disk, a guide slotted disk, a suction disk, a

forced seed-metering disk, and a seed-storage shell. The seed-metering shell could be fixed onto a furrow opener using bolts. The drive disk could rotate via a bearing when driven by the drive sprocket. The guide slotted disk was fixed onto the guide slotted disk via a positioning slot. The air-suction disk and the forced seed-metering disk rotated together with the drive disk across three slots that were evenly distributed on the drive disk. As demonstrated in Figure 2(b), seeds that are intended for planting are discharged through the seed-discharge opening during seed metering. Guided by the seed-guide tube, the seeds fall into the seed-storage shell. The vacuum fan provides vacuum, which is transferred to the air-suction disk via the guide slotted disk.

Figure 3(a) shows a schematic of the approximately rectangular air-suction holes formed by the combination of the guide slotted disk and the air-suction disk.

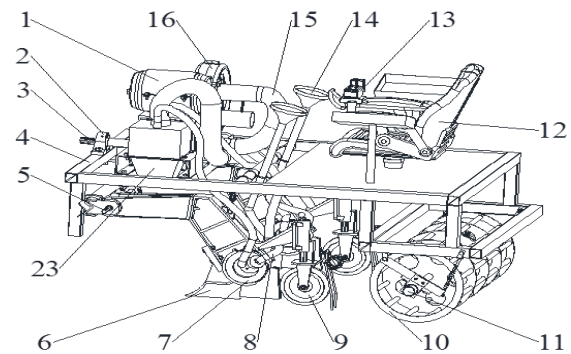


Figure 1. 3D drawing of seeder

1. Air pump 2. Bearing 3. Power input shaft 4. frame 5. Spline shaft 6. Opener 7. Seed metering device 8. Guided seed tube 9. Press wheel 10. Land wheel 11. Encoder 12. Work platform 13. Electromagnetic valve 14. Aid seed funnel 15. Vacuum tube 16. Vacuum fan 23. Wasteseed seed recovery room

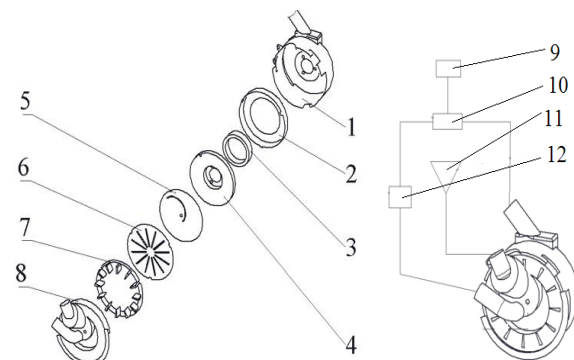


Figure 2. Structure of the combined pneumatic SMD (a) Exploded-view drawing (b) Assembly drawing

1. Seed-metering shell 2. Drive disk 3. Rolling bearing 4. Guide slotted disk-fixing device 5. Guide slotted disk 6. Air-suction disk 7. Forced seed-metering disk 8. Seed-storage shell 9. Vacuum fan 10. Three-way switch valve 11. Seeding funnel 12. Waste seed-recycling chamber

The figure also shows cotton seeds. Cotton seeds move towards the circumference of the air-suction disk as it rotates. The air-suction disk is in the front in the photograph in Figure 3(b).

Upon reaching the circumference of the air-suction disk, a seed enters the closed space formed by the three surfaces of the seed-storage shell, the two sides of the forced seed-metering disk, and the bottom surface of the air-suction disk, as shown in Figure 4. The seed rotates in the closed space with the forced seed-metering disk. Upon moving to the bottom, gravity causes the seed to fall through the opening at the bottom of the seed-metering shell to the furrow opened by the furrow opener. Thus, seed metering is completed.

After the planting in one cotton plot was completed, a three-way switch valve was controlled via an air system to direct vacuum to the waste-seed recycling chamber and transfer vacuum to the seed-suction opening. As a result, the seeds were sucked back to the waste seed-recycling chamber. This ensured that no seeds intended for the previous plot were stored in the SMD. When planting the subsequent plot, seeds were again discharged via the seed-discharge opening.

3. THEORETICAL FORCE ANALYSIS OF THE SEED-FILLING STAGE OF THE SMD

3. 1. Description of the Seed-filling, Seed-Carrying, and Seed-metering Stages of the SMD

The combined pneumatic SMD relies primarily on the negative pressure provided by vacuum to individuate single cotton seeds from a cotton seed group and arrange them into a uniform, orderly seed flow that rotates with the air-suction disk. The SMD carries and meters seeds via this mechanism. During this operation, the SMD is affected by factors such as disturbances from the seed group, negative pressure, the centrifugal force, and gravity. Here, a cotton seed force model is preliminarily established for each stage to facilitate force analysis. Based on the motion of and forces on a

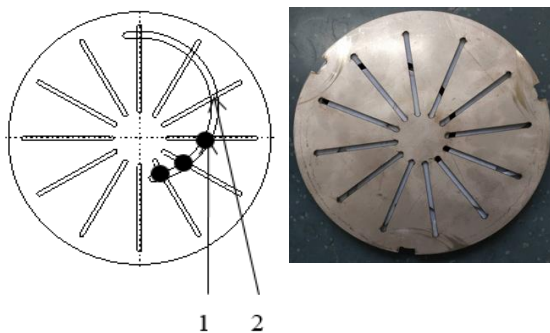


Figure 3. Air-suction holes formed by the combination of the guide slotted disk and the air-suction disk; (a) Two dimensional graph (b) Prototype; 1. cotton seed 2. air-suction holes

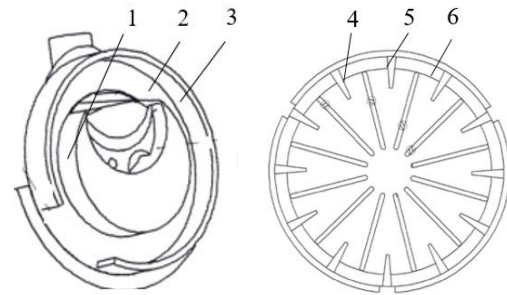


Figure 4. The closed space (a) Seed-storage shell (b) Air-suction disk and forced seed-metering disk

cotton seed, the seed-metering operation of the SMD is divided into three stages, as shown in Figure 5.

As the air-suction disk starts to rotate counterclockwise, the suction holes between approximately 0° and 60° on the seed-metering disk are under negative pressure. Under the negative pressure provided by the fan, the cotton seeds inside the seed storage chamber are sucked onto the suction holes and rotate with them as a seed group. This is the seed-filling stage. Between approximately 60° and 180° on the seed-metering disk, the air-suction holes are under vacuum. Under the negative pressure provided by the fan, the cotton seeds are sucked onto the suction holes, where they rotate synchronously with the seed-metering disk.

This is the seed-carrying stage. Between approximately 180° and 270° on the seed-metering disk, the suction holes are no longer under vacuum, the negative pressure provided by the fan disappears, and gravity causes the cotton seeds to fall into the closed space formed by the forced seed-metering disk and the seed-storage shell. The seeds rotate synchronously with the forced seed-metering and air-suction disks. The seed-metering operation is complete when the seeds eventually rotate to the opening at the bottom of the seed-storage shell. This is the seed-metering stage.

The following assumptions are made to facilitate analysis of the three stages of seed-metering operation:

(1) Cotton seeds are ideal, rigid ellipsoidal bodies with a uniform and consistent shape and size and do not

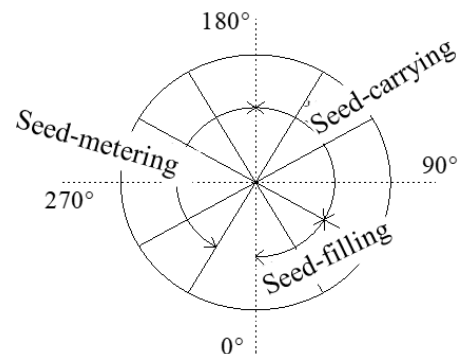


Figure 5. Three stages of the SMD

undergo elastic deformation. In addition, all external forces to which each cotton seed is subject act on its centroid.

- (2) The seed-metering disk rotates at a uniform, constant speed.
- (3) During seed-metering, the negative pressure difference provided by the fan is uniform and stable.

3. 2. Force Analysis of the Seed-filling Stage of the SMD

Seed-filling performance is a key factor in seed-metering that directly affects the seed-metering quality index [14-16]. Figure 6 shows a force diagram of a single cotton seed during the seed-filing stage. The diagram was produced based on the suction position of the cotton seed and a theoretical analysis of the vertical-disk air suction-type SMD. The air-suction hole is formed by the combination of the guide slot and a straight air-suction slot. As this combined air-suction hole moves continuously, the magnitudes and angles of the forces from centrifugal inertia and sliding friction on the seed that is sucked onto the air-suction hole also change continuously. The forces on the seed are complex and varied.

Therefore, it is necessary to make several assumptions to facilitate the subsequent force analysis [17-19]:

- (1) The distance between seed-suction holes is greater than their length and width. In addition, the dimensions of each seed-suction hole are smaller than the projected seed dimensions in all directions. This ensures that each seed-suction hole can suck and hold exactly one seed. The forces on a cotton seed at a seed-suction hole were investigated.
- (2) During operation, the air-flow field in the closed vacuum chamber inside the SMD is uniform, and its parameters are set to steady-state values.

Figures 6(a) and 6(b) analyze the forces on a seed sucked onto the guide slot within the horizontal and vertical planes, respectively, during seed-metering. In Figure 6, G is the gravitational force on the seed sucked onto the guide slot, J is the centrifugal inertial force

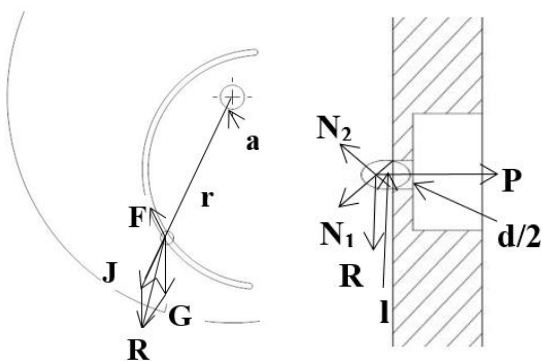


Figure 6. Force analysis of a cotton seed (a) The horizontal direction (b) The vertical direction

generated by of rotation of the seed (which is held onto the guide-slotted disk by suction) with the air-suction disk. The direction of J changes with the angle of rotation α . F is the sliding friction force generated by movement of the cotton seed on the guide slot during rotation of the air-suction disk and R is the resultant force from gravity and the centrifugal inertial force. In the force analysis shown in Figure 6, P is the suction force generated by the air chamber inside the SMD, while N_1 and N_2 are the reaction forces generated by the suction force on the guide slot. The suction force is itself generated by the SMD air chamber.

For a cotton seed to be sucked onto an air-suction hole, stably rotate with the air-suction disk, and undergo no sliding movement [20,21], the following force balance conditions should be satisfied at any location on the guide slot [22, 23]:

$$P \frac{d}{2} \geq Ql \quad (1)$$

The minimum pressure can be determined from the relationship between P and the degree of vacuum:

$$H = \frac{P}{S} \quad (2)$$

To suck and hold one cotton seed, an air-suction hole must at least meet the following condition:

$$P = \frac{2lQ}{d} \quad (3)$$

The critical degree of vacuum in an air-suction hole can be determined based on Equations (2) and (3):

$$H = \frac{2lQ}{Sd} \quad (4)$$

Q can be determined using the parallelogram rule of forces. First, one uses the parallelogram rule of forces to determine R , which is the resultant force of G and J :

$$R = \sqrt{G^2 + J^2 + 2GJ \cos \alpha} \quad (5)$$

Then, Q , which is the resultant force of R and F , is determined:

$$Q = \sqrt{R^2 + F^2 + 2RF \cos \beta} \quad (6)$$

Substituting Equations (5) and (6) into Equation (4) produces:

$$H = \frac{2lQ}{Sd} \sqrt{G^2 + J^2 + 2GJ \cos \alpha + F^2 + 2\sqrt{G^2 + J^2 + 2GJ \cos \alpha} F \cos \beta} \quad (7)$$

In ideal conditions, when $\cos \alpha = 1$ and $\cos \beta = 1$, Equations (2)-(7) produces:

$$H = \frac{2K_1 K_2 K_3 l G}{Sd} \left(1 + \frac{1}{g} \frac{v^2}{r} + \lambda\right) \quad (8)$$

The cotton seed dynamic friction coefficient was measured experimentally. The combined mass of the tested seed group and the shell was 435.38 g. The mass of the shell was 51 g. The mass of the weights used to pull the shell such that it moved horizontally was 275 g. F could be determined using the following equation:

$$F = mg\mu \quad (9)$$

Thus, μ could be determined using the following equation:

$$\mu = \frac{F}{mg} \quad (10)$$

Equation (10) was used to determine that μ was 0.72. The Shandong Cotton-37 cotton cultivar was used in the test. The cotton seed weight was set to 95.35 g/1000 seeds. The seed diameter was set to 5.3 mm and the area of each air-suction hole was set to 12 mm² (i.e., the width of the guide slot and the width of the air-suction straight slots were set to 4 mm and 3 mm, respectively). θ was set to 36.1°. K_1 , K_2 , and K_3 were set to 2.0, 1.8, and 1.1, respectively. The comprehensive coefficient was set to 7.2. The rotational speed of the air-suction disk was 15 r/min. Thus, the critical degree of vacuum was calculated to be 2180.89 Pa. When the air-suction disk rotated at a speed of 25 r/min, the critical air pressure was 2157.3 Pa. The calculation results of these theoretical values can provide numerical reference for subsequent experimental design.

4. SMD PERFORMANCE TEST

4.1. Test Material and Methods Based on the operating principle of the combined pneumatic SMD, the degree of vacuum (i.e., air pressure) in each combined hole, the air-suction disk slot width, and seed-metering rotational speed of the air-suction disk are the primary parameters that affect seed-metering quality [24]. Seed-metering quality includes multiple-seeding and mis-seeding rates. Test data were obtained using a JPS-12 test bench and subsequently analyzed using Design-Expert software. The effects of each parameter on seed-metering performance were analyzed. Thus, a partially optimized combination of seed-metering parameters was selected to further improve planting precision in cotton plots.

During the test, the vacuum required for the SMD was provided by a vacuum tube on the test bench. The degree of vacuum was altered by controlling the rotational speed of the vacuum fan via the test bench control system [25]. The SMD air-suction disk slot width was varied by using previously designed air-suction disks with various slot widths. SMD rotation was powered by a drive motor. The rotational speed was controlled by a pulse signal from the control system.

The control system was designed primarily to allow the SMD to be installed on real-world cotton plot planters. When used on the test bench, the seed-bed belt speed was set to mimic the advancing speed of a planter operating in a field [26]. Thus, all of the dependent variables (i.e., the degree of vacuum, slot width, and seed-metering speed) associated with the SMD during operation could be controlled. Figure 7 shows the test bench configuration and seed-metering results.

Tests were performed at the Seed-metering Performance Laboratory at the College of Mechanical and Electronic Engineering, Shandong Agricultural University. A Shannongmian-37 cotton cultivar was used. The following cotton seed parameters were measured: weight of 1000 seeds—96.7 g; density—0.886 g/cm³; angle of repose—19°; angle of sliding friction—25.3°; average length—9.66 mm; average thickness—5.22 mm.

During the tests, analytical and statistical models were established using Design-Expert software to investigate the effects of the air pressure, slot width, and rotational speed on multiple-seeding and mis-seeding rates. Air pressure, slot width, and rotational speed test values were determined based on previous kinematic analyses and the pre-testing. In addition, a three-factor, three-level central composite design (CCD) was developed, as shown in Table 1. In Table 1, X_1 , X_2 , and X_3 represent the air pressure, slot width, and rotational speed, respectively. In the data analysis, Y_1 and Y_2 represent the multiple-seeding and the mis-seeding rates, respectively.

The CCD parameters in Table 1 were imported into Design-Expert [27-29]. Based on the response-surface test design scheme, the software automatically generated 20 CCD schemes. Tests were performed

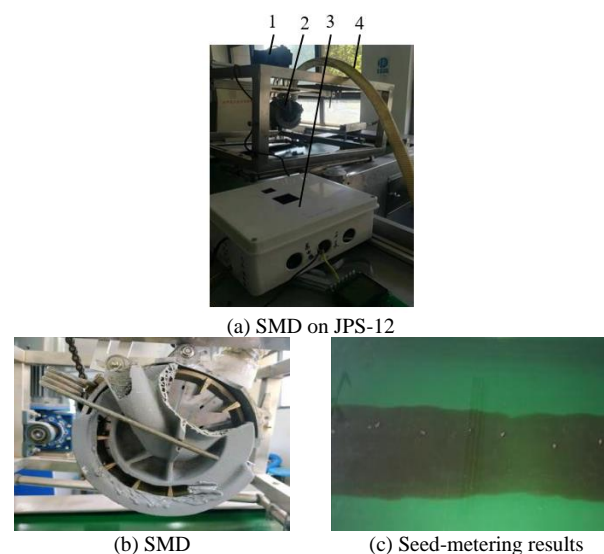


Figure 7. SMD performance test, 1. Drive motor 2. SMD 3. Control system 4. Vacuum tube

based on these CCD schemes. The results were subsequently imported into the Design-Expert software and the effects of each factor on the multiple-seeding and mis-seeding rates were analyzed. A suitable combination of parameters was determined by comprehensively considering multiple-seeding and mis-seeding rates. During the test, the SMD rotated approximately 12 times and theoretically metered approximately 240 seeds under the parameters corresponding to each number. The numbers of seeds corresponding to multiple seeding and missed seeding, respectively, were recorded when approximately 240 seeds were metered. Table 2 summarizes the CCD schemes and results.

TABLE 1. Test factor code

Code	Factors		
	X ₁ /kPa	X ₂ /mm	X ₃ /(r/min)
-1.414	3.7	3.24	46.82
-1	3.2	3.1	40
0	2.6	2.9	30
1	2.0	2.7	20
1.414	1.5	2.56	13.18

TABLE 2 Response-surface test schemes and results

Testing No.	Factor			Result	
	X ₁ /kPa	X ₂ /mm	X ₃ /(r/min)	Y ₁ %	Y ₂ %
1	2.6	2.9	30	3.71	1.299
2	1.5	2.9	30	3.64	1.54
3	2.0	3.1	20	4.1	4.25
4	2.6	2.9	30	3.24	4.58
5	2.6	2.56	30	3.65	2.52
6	3.2	3.1	40	2.3	4.08
7	2.6	2.9	30	3.34	1.64
8	2.6	2.9	30	2.41	3.54
9	2.6	3.24	30	4.53	2.13
10	3.2	3.1	20	2.3	3.25
11	2.6	2.9	30	2.1	2.54
12	2.6	2.9	13.18	1.62	4.21
13	2.0	2.7	20	1.3	1.54
14	2.0	2.7	40	3.62	1.2
15	3.2	2.7	20	1.36	1.47
16	3.2	2.7	40	1.4	1.87
17	2.6	2.9	46.82	1.45	2.03
18	2.6	2.9	30	1.63	1.89
19	2.0	3.1	40	1.42	1.96
20	3.7	2.9	30	1.36	1.54

4. 2. Test Results and Analysis

4. 2. 1. Mis-seeding Rate Data and Analysis

The test data were subject to analysis of variance using Design-Expert. Table 3 summarizes the regression equation significance test results. The mis-seeding rate (Y₁) goodness-of-fit is significant (P<0.01), whereas the lack-of-fit is insignificant (P=0.1006). This suggests that there are no other principal influencing factors. Air pressure exerts the most significant impact on the quality index, followed by rotational speed and slot width. The following multivariate quadratic response surface regression model was obtained via a quadratic response-surface regression analysis performed using Design-Expert (Version 8.0.6):

$$Y_1(\%)=78.93728-10.97592X_1-40.64099X_2-0.18529X_3-0.38541X_1X_2-0.02812X_1X_3-0.011875X_2X_3-2.324X_1^2+7.17705X_2^2+0.004X_3^2 \quad (11)$$

TABLE 3. Mis-seeding rate processing results

Source	Sum of square	df	Mean square	F	P
Model	16.95	9	1.88	3.36	0.0363**
X₁	3.55	1	3.55	6.33	0.0306**
X₂	0.0758	1	0.0758	0.1351	0.7208
X₃	0.0609	1	0.0609	0.1085	0.7486
X₁X₂	0.0171	1	0.0171	0.0305	0.8648
X₁X₃	0.2278	1	0.2278	0.4062	0.5382
X₂X₃	0.0045	1	0.0045	0.0080	0.9303
X₁²	10.09	1	10.09	18.00	0.0017
X₂²	1.19	1	1.19	2.12	0.1762
X₃²	3.59	1	3.59	6.40	0.0298
Residual	5.61	10	0.5608		
Lack of Fit	5.56	5	1.11	109.10	0.053
Pure Error	0.0509	5	0.0102		
Cor total	22.56	19			

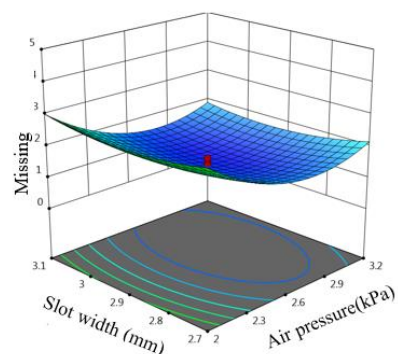


Figure 8. The slot width and air pressure impacts on the mis-seeding rate

The P-value of the model is 0.0363, which suggests that the model is significant. The X_1 , X_2 , X_3 , X_1^2 , and X_3^2 in the model are all significant terms. The lack-of-fit in this test is insignificant ($P=0.053$) and can be used to analyze data.

As demonstrated in Table 3, the slot width and air pressure each exert significant impacts on the mis-seeding rate. Thus, the effects of interactions between the slot width and air pressure on the mis-seeding rate were analyzed. To a certain extent, an increase in the slot width results in a lower mis-seeding rate (Figure 8). An increase in the air pressure also decreases the mis-seeding rate. However, the effects on the multiple-seeding rate should also be considered. Thus, the first scheme provided by the software is optimized and meets requirements. The optimized parameters that produce the lowest mis-seeding rate (0.59%) are as follows: an air pressure of 2.67 kPa, a slot width of 2.83 mm, and a seed-metering speed of 20 r/min.

4. 2. 2. Multiple-seeding Rate Data and Analysis

The test data was subjected to analysis of variance using Design-Expert [30-32]. Table 4 summarizes the significance test results for the regression equation. The goodness-of-fit of the mis-seeding rate (Y_2) is significant ($P<0.0001$) and the lack-of-fit (0.1551) is insignificant. This suggests that there are no other principal influencing factors. The slot width exerts the most significant impact on the quality index, followed by air pressure and rotational speed. A quadratic response-surface regression equation for the multiple-seeding rate was obtained via a response-surface analysis of the multiple-seeding rate using Design-Expert (Version 8.0.6):

$$Y_2(\%)=102.77096-8.21243X_1-78.23229X_2+1.22112X_3+0.446875X_1X_2+0.060188X_1X_3-0.463187X_2X_3+1.1267X_1^2+16.14963X_2^2-0.000669X_3^2 \tag{12}$$

The P-value of the model is less than 0.0001 suggests that the model is significant. In this model, X_1 , X_2 , X_1X_3 , X_1^2 , and X_2^2 are all significant terms. The F-value of the lack-of-fit is 0.1551. This suggests that the lack-of-fit is insignificant, the goodness-of-fit is high, and the original data are reasonably accurate. The coefficient of adjusted determination is 0.9586. This suggests that 95.86% of the multiple-seeding rate is related to the three test factors, that the goodness-of-fit is high, and that the equation is satisfactorily simulated. However, 4.14% of the total multiple-seeding rate cannot be explained using the established surface model.

As demonstrated in Table 4, the slot width and air pressure each exert significant impacts on the multiple-seeding rate. Thus, the effects of the interaction between the slot width and air pressure on the multiple-seeding rate were analyzed. As demonstrated in Figure 9, increasing the slot width results in an increase in

TABLE 4. Multiple seeding data processing results

Source	Sum of square	df	Mean square	F	P
Model	16.95	9	1.88	3.36	0.0363**
X₁	2.56	1	2.56	26.28	0.0004
X₂	3.99	1	3.99	40.90	< 0.0001
X₃	0.0155	1	0.0155	0.1595	0.6980
X₁X₂	0.0230	1	0.0230	0.2360	0.6376
X₁X₃	1.04	1	1.04	10.70	0.0084
X₂X₃	6.87	1	6.87	70.42	< 0.0001
X₁²	2.35	1	2.35	24.10	0.0006
X₂²	6.01	1	6.01	61.69	< 0.0001
X₃²	0.0570	1	0.0570	0.5847	0.4622
Residual	0.9749	10	0.0975		
Lack of Fit	0.7071	5	0.1414	2.64	0.1551
Pure Error	0.2677	5	0.0535		
Cor total	23.53	19			

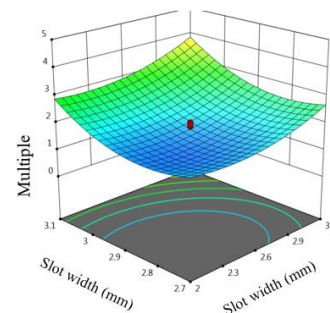


Figure 9. The slot width and air pressure impacts on the multiple-seeding rates

multiple-seeding rate to a certain extent. Increasing the air pressure also increases the multiple-seeding rate. Thus, the multiple-seeding rate data produces the following scheme optimized to produce the lowest multiple-seeding rate of 4.3%: an air pressure of 2.35 kPa, a slot width of 2.78 mm, and a seed-metering speed of 20 r/min.

5. FIELD TEST

In June of 2019, a field test was performed using a prototype machine at the Agricultural Test Station on the south campus of Shandong Agricultural University (shown in Figure 10). During the test, the planter was driven by a Lovol 350 tractor (power: 26 kW). The field soil consisted of loam and had a moisture content of 23.2%. The primary equipment used in this test included



Figure 10. Field test 1. Tractor 2.Waste seed-recycling chamber 3. Control system 4.Encoder 5.SMD

TABLE 5. Field test results

	First group	Second group
Mis-seeding rate (%)	1.53	4.96
Multiple-seeding rate (%)	1.69	5.34

a cotton planter, straight rulers, a stopwatch, and a moisture meter. The test results show that the planter is able to complete the relevant processes, exhibits good seed-planting performance, and can plant single seeds precisely. In addition, the distances between the seeds planted by this planter are reasonably consistent.

The parametric settings for the first test group are as follows: a vacuum of 2.67 kPa, a slot width of 2.83 mm, and a seed-metering speed of 20 r/min. The mis-seeding and multiple-seeding rates for the first test group are 1.53 and 4.96%, respectively. The parametric settings for the second test group are as follows: a vacuum of 2.35 kPa, a slot width of 2.78 mm, and a seed-metering speed of 20 r/min.

6. CONCLUSION

This study presented a combined pneumatic SMD design. This SMD could fill, carry, and meter seeds and could switch rapidly between seed-metering and seed-cleaning modes. In addition, this SMD could meter seeds precisely and thoroughly and rapidly clean seeds. Thus, this SMD could improve the accuracy and speed of cotton planting in plots.

The seed-filling, seed-carrying, and seed-metering modes of the SMD were analyzed theoretically based on a theoretical kinematic model. The results provided a basis for identifying SMD structural and motion parameters. The critical air pressure for stable seed suction was calculated to be 2,161.6 Pa. This data provided support for subsequent bench and field tests.

A three-factor, three-level orthogonal test was performed using a performance test bench arranged for

the SMD and Design-Expert software. SMD parameters that produced relatively good performance were determined during the test and used as a source of parameters for the field planting test. The combination of parameters that led to the lowest mis-seeding rate (0.59%) was as follows: an air pressure of 2.67 kPa, a slot width of 2.83 mm, and a seed-metering speed of 20 r/min. The optimized scheme that led to a relatively low multiple-seeding rate of 4.3% and otherwise met requirements was as follows: an air pressure of 2.35 kPa, a slot width of 2.78 mm, and a seed-metering speed of 20 r/min.

A field test was performed using a combined pneumatic cotton plot planter prototype. While the mis-seeding and multiple-seeding rates obtained from the field test were both somewhat higher than those obtained from the laboratory bench test, they still met precision planting requirements. The results of bench test and field test verify the accuracy of theoretical analysis. This validated provided a foundation for subsequent prototype production and popularization. The combined pneumatic cotton plot planter designed in this study could precisely meter and rapidly and thoroughly clean seeds. This design could meet cotton plot planting requirements.

7. REFERENCES

1. Karayela, D., Wieshoffb, M., Özmerzia, A., Muller, J. "Laboratory measurement of seed drill seed spacing and velocity of fall of seeds using high-speed camera system". *Computers and Electronics in Agriculture*, Vol. 5, No. 2, (2006), 89-96. DOI: 10.1016/j.compag.2005.05.005
2. Vianna, L. R., Reis, A. V., Machado, A. L. T. "Development of a horizontal plate meter with double seed outlets". *Revista Brasileira De Engenharia Agricola E Ambiental*, Vol. 18, No. 10, (2014), 1086-1091. DOI: 10.1590/1807-1929/agriambi.v18n10p1086-1091
3. Correia, T. P., De Sousa, S. F., Silva, P. R., Dias, P. P., Gomes, A. R.. "Sowing performance by a metering mechanism of continuous flow in different slope conditions". *Engenharia Agricola*, Vol. 36, No. 5, (2016), 839-845. DOI: 10.1590/1809-4430-Eng.Agric.v36n5p839-845/2016
4. Ghosal, M. K., Din, M. "Design and development of cup in cup feed metering seed drill for seed pattern characteristics study of paddy seeds". *Ama-Agricultural Mechanization in Asia Africa and Latin America*, Vol. 47, No. 3, (2016), 54-59. DOI: 10.5829/IJE.2019.32.12C.13
5. Li, Y., He, X. T., Cui, T., Zhang, D. X., Shi, S., Zhang, R., Wang, M. T.. "Development of mechatronic driving system for seed meters equipped on conventional precision corn planter". *International Journal of Agriculture and Biological Engineering*, Vol. 8, No. 4, (2015), 1-9. DOI: 10.3965/j.ijabe.20150804.1717
6. Wang, J. W., Han, T., Wang, J. F., Li, X., Hang, H. N. "Optimization design and experiment on ripple surface type pickup finger of precision maize seed metering device". *International Journal of Agriculture and Biological Engineering*, Vol. 10, No. 1, (2017), 61-71. DOI: 10.3965/j.ijabe.20171001.2050

7. Horabik, J., Molenda, M., Parafiniuk, P. "Discharge of rapeseeds from a model silo: Physical testing and discrete element method simulations", *Computers and Electronics in Agriculture*, Vol. 97, (2013), 40-46. DOI: 10.1016/j.compag.2013.06.008
8. Luo, X. W., Ou, Z., Jiang, E.C., Li, Z.W., Huang S. X.. "Experimental research on precision rice direct-seeder with hill sowing". *Transactions of the Chinese Society for Agricultural Machinery*, Vol. 36, No. 9, (2005), 37-40. DOI: 10.3969/j.issn.1000-1298.2005.09.010
9. Yu, J. J., Ding, Y. C., Liao, Y. T., Cong, J. L., Liao, Q. X.. "High-speed photography analysis of dropping trajectory on pneumatic metering device for rapeseed". *Journal of Huazhong Agricultural University*, Vol. 33, No. 3, (2014), 103-108. DOI: 10.13300/j.cnki.hnlkxb.2014.03.018
10. Searle, C. L., Kocher, M. F., Smith, J. A., & Blankenship, E. E.. "Field slope effects on uniformity of corn seed spacing for three precision planter metering systems". *Applied Engineering in Agriculture*, Vol. 24, No. 5, (2008), 581-586. DOI: 10.13031/2013.25270
11. Barr, J. B., Desbiolles, J. M. A., "Fielke John M. Minimising soil disturbance and reaction forces for high speed sowing using bentleg furrow openers". *Biosystems Engineering*, Vol. 151, (2016), 53-64. DOI: 10.1016/j.biosystemseng.2016.08.025
12. Kocher, M. F., Coleman, J. M., Smith, J. A., & Kachman, S. D. "Corn seed spacing uniformity as affected by seed tube condition". *Applied Engineering in Agriculture*, Vol. 27, No. 2, (2011), 177-183. DOI: 10.13031/2013.36484
13. Brosh, T., Kalman, H., Levy, A., Peyron, I., Ricard, F.. "DEM-CFD simulation of particle comminution in jet-mill". *Powder Technol*, Vol. 257, (2014), 104-112. DOI: 10.1016/j.powtec.2014.02.043
14. Yuan, G. Z., Zhang, T., Liu, Y. Q., . "Design of a Spoon Wheel Type Seed Metering Device and Simulation of Soybean Seeds By Discrete Element". *Journal of Agricultural Mechanization Research*, Vol. 11, (2017), 25-29. DOI: 10.13427/j.cnki.njyi.2017.11.004
15. Liu, T., He, R. Y., Lu, J., Zou, Y., Zhao, M. M.. "Simulation and verification on seeding performance of nest hole wheel seed-metering device based on EDEM". *Journal of South China Agricultural University*, Vol. 37, (2016), 126-132. DOI: 10.7671/j.issn.1001-411X.2016.03.020
16. Shi, S., Zhang, D. X., Yang, L., Cui, T., Li, K. H., Yin, X. W.. "Simulation and verification of seed-filling performance of pneumatic-combined holes maize precision". *Transactions of the Chinese Society of Agricultural Engineering*, Vol. 31, No. 3, (2015), 62-69. DOI: 10.3969/j.issn.1002-6819.2015.03.009
17. Safari, M., Joudaki, J., Ghadiri, Y.. "A Comprehensive Study of the Hydroforming Process of Metallic Bellows: Investigation and Multi-objective Optimization of the Process Parameters", *International Journal of Engineering, Transactions B: Applications*, Vol. 32, No. 11, (2019) 1681-1688. DOI: 10.5829/IJE.2019.32.11B.19
18. Kazemian, M. E., Gandjalikhan, Nassab, S. A., "Thermodynamic Analysis and Statistical Investigation of Effective Parameters for Gas Turbine Cycle using the Response Surface Methodology", *International Journal of Engineering, Transactions B: Applications*, Vol. 33, No. 5, (2020), 894-905. DOI: 10.5829/IJE.2020.33.05B.22
19. Patel, S. S., Prajapati, J. M., "Experimental Investigation of Surface Roughness and Kerf Width During Machining of Blanking Die Material on Wire Electric Discharge Machine", *International Journal of Engineering, Transactions A: Basics* Vol. 31, No. 10, (2018), 1760-1766. DOI: 10.5829/ije.2018.31.10a.19
20. Wang, J. W., Tang, H., Wang, Q., Zhou W. Q., Yang, W. P., Shen, H. G.. "Numerical simulation and experiment on seeding performance of pickup finger precision seed-metering device based on EDEM". *Transactions of the Chinese Society of Agricultural Engineering*, Vol. 31, No. 21, (2015), 43-50. DOI: 10.11975/j.issn.1002-6819.2015.21.006
21. Cao, X. Y., Liao, Y. T., Cong, J. L.. "Design and Experiment on Metering Hole Structure of Centrifugal Precision Metering Device for rapeseed". *Transactions of the Chinese Society for Agricultural Machinery*, Vol. 45, (2014), 40-46. DOI: 10.6041/j.issn.1000-1298.2014.S0.007
22. Ding L., Yang L., Zhang D.X., Cui T. G., Xiao J., "Design and experiment of seed plate of corn air suction seed metering device based on DEM-CFD". *Transactions of the Chinese Society for Agricultural Machinery*, Vol. 50, No. 5, (2019), 50-60. doi: 10.6041/j.issn.1000-1298.2019.05.006
23. Shi S., Zhou J.L., Liu H., Fang H.M., Jian S.Ch., Zhang R.F., "Design and experiment of pneumatic precision seed-metering device with guided assistant seed-filling". *Transactions of the Chinese Society for Agricultural Machinery*, Vol. 50, No. 5, (2019), 61-70. doi:10.6041/j.issn.1000-1298.2019.05.007
24. Kamgar, S., Eslami, M. J., Maharlouie, M. M.. "Design, development and evaluation of a mechatronic transmission system to improve the performance of a conventional row crop planter". *International Journal of Agronomy and Plant Production*, Vol. 4, No. 3, (2012), 480-487. DOI: 10.13031/2013.41987
25. Yang, L., Yan, B. X., Cui, T., Yu, Y. M., He, X. T., Liu, Q. W., Liang, Z. J., Yin, X. W., Zhang, D. X.. "Global overview of research progress and development of precision maize planters". *International Journal of Agricultural and Biological Engineering*, Vol. 9, No. 1, (2016), 9-26. DOI: 10.3965/j.ijabe.20160901.2285
26. Wang, X. Y.. "Improve design and experiment on spoon of spoon precision seed metering device". *Journal of Northeast Agricultural University*, Vol. 46, No. 12, (2015), 79-85. DOI: 10.19720/j.cnki.issn.1005-9369.2015.12.012
27. JB/T10293-2001 "Single grain (precision) planter technical conditions". *People's Republic of China machinery industry standard*, (2001). DOI: 10.3969/j.issn.1002-6819.2014.08.005
28. Shi, L. R., Wu, J. M., Sun, W., Zhang, F. W., Sun, B. G., Liu, Q. W., Zhao, W.Y.. "Simulation test for metering process of horizontal disc precision metering device based on discrete element method". *Transactions of the Chinese Society of Agricultural Engineering*, Vol. 30, No. 8, (2014), 40-48. DOI: 10.3969/j.issn.1002-6819.2014.08.005
29. Singh, R.C., Singh, G., Saraswat, D.C.. "Optimisation of design and operational parameters of a pneumatic seed metering device for planting cottonseeds". *Biosystems Engineering*, Vol. 92, No. 4, (2005), 429-438. DOI: 10.1016/j.biosystemseng.2005.07.002
30. Xu, D. "Research and Application of Wheat Precision Seeding Machinery". *Agricultural Science & Technology and Equipment*, Vol. 6, (2015), 79-80. DOI: 10.16313/j.cnki.nykjz.2015.06.030
31. Wang, J. W., Tang, H., Wang, J. F.. "Analysis and Experiment of Guiding and Dropping Migratory Mechanism on Pickup Finger Precision Seed Metering Device for Corn". *Transactions of the Chinese Society for Agricultural Machinery*, Vol. 8, No. 1, (2017), 29-37. DOI: 10.6041/j.issn.1000-1298.2017.01.005
32. Lei, X. L., Liao, Y. T., Liao, Q. X.. "Simulation of Seed Motion in Seed Feeding Device with DEM-CFD Coupling Approach for Rapeseed and Wheat". *Computers and Electronics in Agriculture*, Vol. 131, (2016), 29-39. DOI: 10.1016/j.compag.2016.11.006

Persian Abstract

چکیده

این مطالعه یک دستگاه اندازه‌گیری پنوماتیکی ترکیبی (SMD) دانه (بذر) را ارائه می‌دهد که نه تنها می‌تواند ظرف بذر را پر، حمل و اندازه‌گیری کند، بلکه می‌تواند سریعاً بین حالت‌های اندازه‌گیری و تمیز کردن بذر تغییر عملکرد دهد و دانه‌ها را به‌طور کامل و سریع تمیز کند. حالت‌های تمیز کردن، انتقال و روش‌های اندازه‌گیری بذر در SMD بر اساس یک مدل سینماتیکی نظری انجام شد. علاوه بر این، یک آزمون سه‌عاملی و سه‌سطحی متعامد با استفاده از یک میز آزمون عملکرد تنظیم‌شده برای SMD و نرم افزار Design-Expert انجام شد. ترکیبی از پارامترهایی که منجر به کمترین میزان بذرپاشی نادرست (۰.۵۹٪) شد، فشار هوای ۲.۶۷ کیلو پاسکال و عرض شکاف ۲.۸۳ میلی‌متر بود. طرح بهینه‌شده که منجر به سرعت کاشت بذر چندگانه‌ی نسبتاً پایین (۴.۳٪) و در عین حال برآورده کردن سایر نیازها شد به شرح زیر است: فشار هوای ۲.۳۵ کیلو پاسکال، عرض شکاف ۲.۷۸ میلی‌متر و سرعت اندازه‌گیری بذر از ۲۰ r/min. سپس، یک آزمایش میدانی با استفاده از یک نمونه آزمایشی بذرپاش پنبه ترکیبی پنوماتیکی انجام شد. با این که میزان کاشت بذر نادرست و جوانه‌زنی مجدد در آزمایش میدانی هر دو تا حدودی بالاتر از مقادیری بود که از آزمایش میز آزمایشگاهی به دست می‌آمد، اما هنوز هم نیازهای کاشت دقیق را برآورده می‌کردند. آزمون میدانی صحت تحلیل نظری و آزمون میز آزمایشگاهی را تأیید کرده و به عنوان پایه‌ای برای تولید نمونه اولیه و مقبولیت آن عمل می‌کند.