DESIGN AND EXPERIMENT OF SEED AGITATOR FOR VERTICAL DISK SEED METERING DEVICE
/
垂直圆盘排种器搅种装置的设计与试验

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ABSTRACT

In order to improve the seed filling performance of mechanical hole type seed metering device with high speed, a vertical disc metering device was designed with seed agitator to improve the seed filling probability. Discrete element simulation method and physical prototype bench tests were used to simulate and analyse the seed metering process. The structure parameters of the seed agitators were optimized by the quadratic orthogonal rotation central composite design test. The results showed that: 1) the addition of seed agitator had a significant influence on the MIS (miss index), among which the concave type had the lowest MIS, and it was the highest without agitator; 2) for concave type agitator, the optimal value of depth and angle were 3.1 mm and 60.5°, respectively; 3) the physical prototype tests showed that the QFI (quality of feed index) was more than 95% under the speed of 2-10 km/h, and the MIS was less than 1%, which meets the requirements of precision sowing.

摘要

为了提高机械式排种器的高速作业性能，设计了一种垂直圆盘排种器，通过搅种装置提高种子填充率。采用离散元仿真和台架试验对排种过程进行仿真和分析。采用二次正交旋转中心组合设计试验对搅种装置的结构参数进行优化分析。结果表明：1）搅种装置对漏播指数有显著影响，其中凹式搅种槽的漏播率最低，没有搅种槽时漏播率最高；2）凹式搅种槽的最佳深度和倾角分别为3.1mm和60.5°；3）台架试验表明，在2～10km/h转速下，排种器的合格率大于95%，漏播率小于1%，满足精量播种的要求。

INTRODUCTION

Precision seeding is one of the most important research branch of smart agriculture. Seed metering device is the core mechanism of the planter (*Yang et al., 2016*). Mechanical metering device was the firstly developed and also the most popular precision metering device in the past decades (*Liu et al., 2015; Vianna, Reis, & Machado, 2014; Wang et al., 2017*). Compared with pneumatic seed metering devices, mechanical seed metering devices still occupies an important proportion in the field of sowing at home and abroad because of its simple structure, low cost and convenient operation (*Singh, Singh, & Saraswat, 2007*). But the mechanical seed metering device cannot complete the filling operation smoothly because of its poor filling performance under high-speed.

To improve the seed filling performance of the metering device under high-speed conditions, some scholars have carried out a lot of research work. Researchers designed linear and guided stirring teeth on the metering plate to make the seeds flip to improve the seed fluidity and to reduce the probability of missing filling (*Zhang et al., 2014*). A kind of convex table seed metering disk was designed to support the seeds while stirring the seed group, which can assist to fill seed and to improve the high-speed operation performance of seed metering device (*Ding et al., 2018*). Aiming at the horizontal disc wheat seed metering device, a cone surface diversion scheme was proposed. Influence of guide strip type, number of holes, cone speed and cone angle on seed filling performance was studied.

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The results showed that the guide seed metering device was better than the original seed metering device in seed metering performance and crushing rate (*Liu et al., 2018*). It was found that the internal friction force between seeds would be reduced by stirring the seed group, thus, to improve the seed filling affection (*Shi et al., 2019*). A self-disturbance inner filling corn precision metering device was designed (*Du et al., 2019*), in which the involute type stirring strip was added on the inner surface of the inner filling metering device to improve the kinetic energy of the seed group. The optimized stirring strip can effectively improve the seed metering performance.

The literature review results show that reasonable disturbance to the seed group can effectively improve the seed filling performance. A lateral filling device of vertical disc was designed to improve the seed filling performance while the stirring groove was designed to stir the seeds. Theoretical analysis, key parameters optimization and simulations of the seed filling and agitator of the seed metering device were carried out. After that the theoretical results were verified by bench tests, which provides a useful exploration for the high-speed adaptive design and development of mechanical precision seed metering device.

MATERIALS AND METHODS
Vertical disc metering device

The vertical disc metering device was composed of shell, flexible unit, metering plate, flange, bearing, base, shaft and other parts (Fig. 1). The outer ring of the metering plate was evenly distributed with multiple seed taking holes while the inner side of the seed taking hole was designed with a seed agitator.
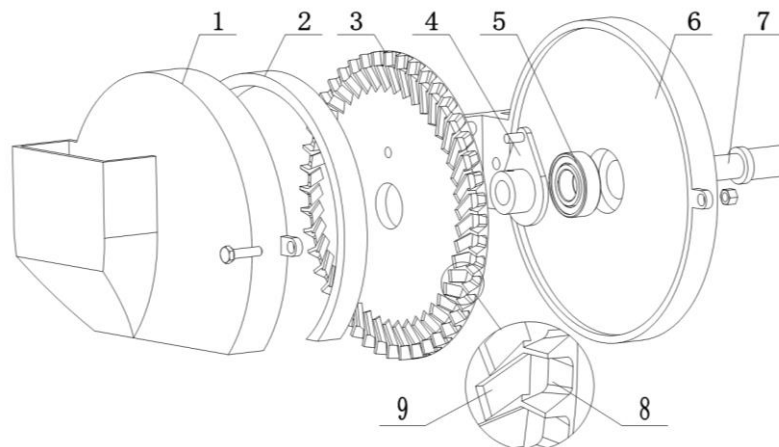
1. Shell; 2. Flexible seed cleaning part; 3. Disk; 4. Flange; 5. Bearing; 6. Base; 7. Shaft; 8. Hole; 9. Seed agitator

Fig. 1 - Structure diagram of seed metering device

During operation, seeds will be sent to the seed chamber surrounded by the disk and the shell through the seed inlet on the shell. The disk makes a circular movement under the drive of the main shaft to complete the seed metering operation. The working process can be divided into four stages: seed filling, seed cleaning, seed transportation and seeding. When the hole enters the seed group, the filling process will be started by. The seeds will be sent to the seed hole by the lateral component of the internal force of the seed group. When the seed hole overlaps with the flexible unit, the flexible unit starts to clean seeds until only one seed stayed in the reasonably designed hole. The seed hole and the seed in it continue to move under the flexible unit. At this time, the flexible unit plays a role to maintain the seed preventing the seed to separate from the hole, and the seed is transported to the seed dropping area. When the hole leaves the flexible unit, it starts the seed dropping process, and the seeds are separated from the hole under the action of gravity and centrifugal force.

A number of seed taking holes were evenly designed on the edge of the seed disk.

According to the design experience (*Liu et al, 2015*), the radius of the seed hole of the seed metering device was set as follows:

$$d = l_{max} + (1 \sim 1.5) \text{ [mm]}$$

(1)

where l_{max} is the maximum size of seed.

Here, the radius of disk was set as 100 mm. Forty holes were drilled on each disk with radius of 4mm.

The relationship between the rotation speed of disk and the forward speed of planter was shown as follows:

$$n = \frac{v}{60k \cdot s} \ [\text{r/min}] \tag{2}$$

where:

n is the speed of disk, [r/min];

v is the forward speed of planter, [m/s];

k is the number of seed holes on the disk;

s is the plant spacing of sowing and the plant spacing of soybean is designed as 0.05m.

Seeds accumulated under the action of gravity in the seed chamber and it was easily to form a nearly linear force chain at the bottom of the seed group. The force chain was linked to each other and generated arching. This reduces the activity of the seed group and easily leads to miss filling (*Ding et al., 2018*).

To activate the seed group, an agitator was designed on the inner side of the hole in the disk to break the force chain of the seed group. At the same time, the agitator was used to guide the seeds above the hole to the direction of the hole, so as to increase the probability of seed filling.

Two kinds of seed agitator were designed (Fig. 2). The first was concave type, which was lower than the inner surface of disk. The second was convex type, which was higher than the inner surface of disk. The number of two kinds of seed agitator were the same as the number of seed holes. The position was one-to-one corresponding to the seed taking hole. The preset length *l₁* of the seed stirring structure was 20 mm, the depth or height *h* was 2 mm, and the inclination angle *β* was 60°.
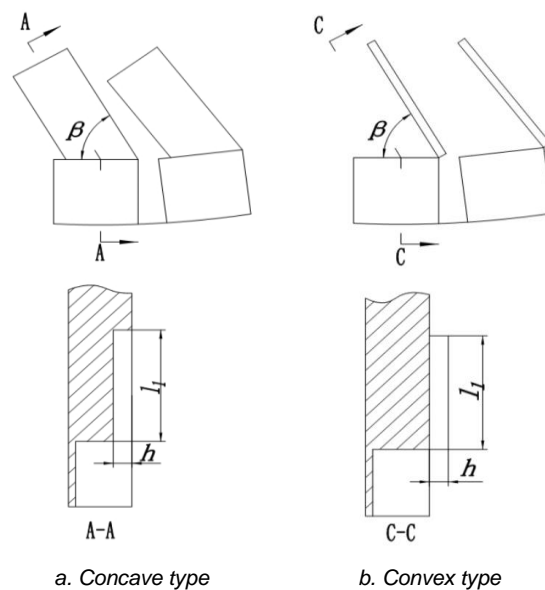

a. Concave type   *b. Convex type*

Fig. 2 - Schematic diagrams of concave and convex agitators

Discrete element simulation design

Seed is a typical discrete material. Discrete element method is widely used in the research of seed metering device (*Khatchatourian, Binelo, & Lima, 2014; Yu et al., 2014*).

EDEM is a mature commercial discrete element simulation software (*Wang et al., 2015*) and version 11.0 of EDEM was used for virtual simulation test in this paper.

During the simulation, the seed metering device was simplified by removing the shaft and flexible seed cleaning part, and only the disk and shell were remained. The disk and shell were made of PMMA (polymethyl methacrylate), a transparent material.

Soybean used in this paper was Jiyu202 (Table 1), which was widely planted in Northeast the major soybean production region of China.

Physical properties of soybean

Physical property	Mean	Standard error
L [mm]	7.21	0.32
W [mm]	6.11	0.31
T [mm]	6.32	0.44
D [mm]	6.52	
Φ [%]	91.88	
Thousand seed mass (g)	180.55	0.21

Note: L average length; W average width; T average Thickness; D means of geometrical diameter and calculated as $D = (LWT)^{1/3}$ respectively. ϕ means of sphericity and calculated as $\phi = \dfrac{(LWT)^{1/3}}{L} \times 100$.

The discrete element simulation model of soybean seed consisted of three spherical particles with a diameter of 6.0 mm (Fig. 3). According to the measured values of triaxial size of seeds, the length, width and thickness were set to 7.2 mm, 6.1 mm and 6.3 mm, respectively.
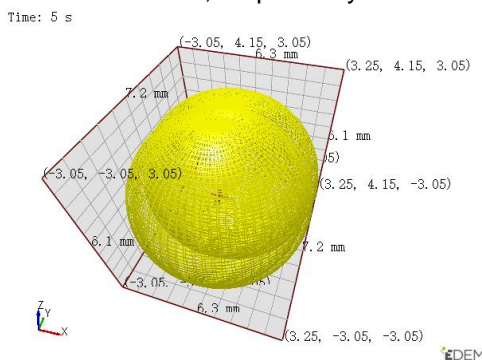

Fig. 3 - Discrete element simulation model of soybean seed

Since there was no adhesion on the surface of soybean seeds, the Hertz-Mindlin non-sliding contact model was adopted. The global parameters used in the simulation were obtained by reference (*Li et al., 2013; Zhang et al., 2017*) (Table 2).

Table 2

Parameters used in simulation

Property	Soybean	PMMA	Property	Soybean-Soybean	Soybean-PMMA
Poisson's ratio	0.4	0.33	Collision recovery coefficient	0.6	0.5
Shear modulus [Pa]	1.1×10^7	8×10^7	Static friction coefficient	0.5	0.3
Density [kg/m^3]	1053	1190	Rolling friction coefficient	0.01	0.09

Through the simulation test, the better agitator was selected, and the simulation optimization design was carried out on the depth or height and inclination angle of the agitator. The simulation test adopts two factors and five levels orthogonal rotation combination central composite design (Table 3) (*Yazgi, & Degirmencioglu, 2007*). To meet the requirements of high-speed operation, the tests were carried out when the forward speed was 10 km/h.

Table 3

Factors and codes of orthogonal rotation combination test

Code	Factors	
	H [mm]	B [°]
-1.414	1.6	45.9
-1	2	50
0	3	60
1	4	70
1.414	4.4	74.1

Prototype experiment

The simulation test results were verified by the indoor test bench (*Karayel et al, 2006; Zhao et al, 2010*). The physical prototype seed metering performance test was carried out on JPS-12 seed metering device performance test system (Fig. 4).

The test system is composed of seed metering device, conveyor belt, industrial camera, fuel injection device, computer, electronic control system and two frequency modulation motors.
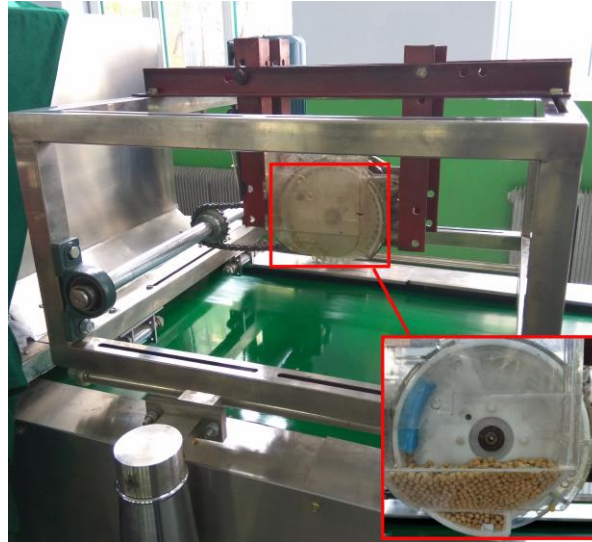

Fig. 4 - Physical prototype

Evaluating indicator

According to GB / T 6973-2005 test methods for single seed (precision) planter, 250 seeds were collected for statistics in each group of experiments, and the test was repeated for 3 times, and the seed metering performance evaluation indexes were *MUL* (multiple index), *MIS* and *QFI* (*Mao et al, 2015; Zhang et al, 2015*).

$$MUL = N_1 / N \times 100\%$$
(3)

$$MIS = N_2 / N \times 100\%$$
(4)

$$QFI = (1 - MIS - MUL) \times 100\%$$
(5)

where:

N_1 is the number of seed holes containing multiple seeds in the simulation test, and the number of seeds whose distance between adjacent seeds is less than 0.5 times the theoretical spacing in physical test.

N_2 is the number of seed taking holes that are not filled in the simulation test, and the number of seeds whose distance between adjacent seeds is greater than 1.5 times of the theoretical spacing in the physical test.

N is the total number of seed holes recorded in the simulation test, and the total number of seeds in the physical test.

RESULTS AND ANALYSIS
Optimization test of seed agitator device

The simulation experiments were carried out under three conditions of concave type agitator, convex type agitator, and without agitator. The filling conditions were recorded. Since the leakage of filling was the biggest impact on the sowing effect, this paper mainly studies the *MIS* (Fig. 5a).

Under three different conditions, the *MIS* increases significantly with the increase of rotating speed. When the speed was 16.7 r/min, the difference of the *MIS* under the three kinds of agitator was not significant. With the increase of the speed, the *MIS* of without agitator increases significantly at the speed of 16.7 and 33.3 r/min, which was significantly higher than that of the concave and convex type.

When the speed reached 66.7 r/min, the *MIS* of convex type increased significantly, and it was significantly higher than that of concave type.

To further analyse the influence of the seed agitator on the seed movement, the seed velocity near the agitator was recorded (Fig. 5b).
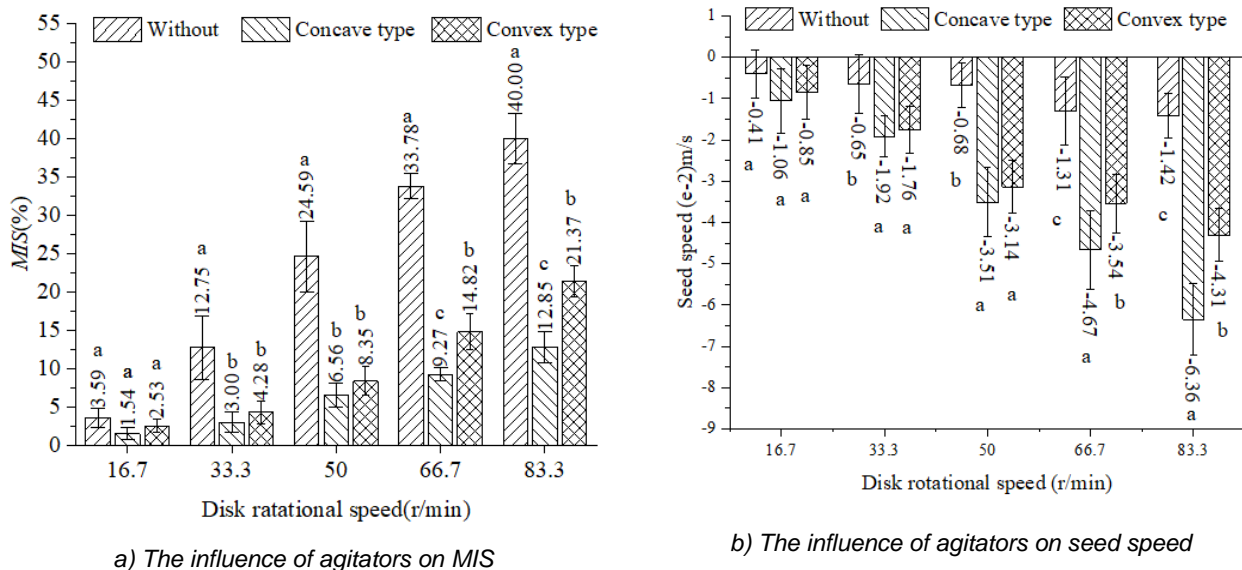
a) The influence of agitators on MIS

b) The influence of agitators on seed speed

Fig. 5 - The influence of agitators on *MIS* and seed speed

Note: At the same speed, different lowercases indicate that agitators have significant influence on MIS and seed speed (p<0.05).

It can be concluded that the seed stirring mechanism has a significant inhibitory effect on the *MIS*. With the increase of rotating speed, the decreasing trend was more and more significant. The concave type agitator has little difference with the convex seed stirring mechanism at low speed. With the increase of speed, the advantage of concave seed filling was more significant.

Therefore, the concave type was selected as the seed stirring mechanism, and its structure was further optimized.

The depth and angle of the concave type agitator were taken as experimental factors.

The simulation experiment of two factors and five levels orthogonal rotation combined central composite design tests was carried out (Table 4).

Table 4

Results of quadratic regression orthogonal rotating experiment

	h / x_1 [mm]	B / x_2 [°]	QFI [%]	MIS [%]	MUL [%]
1	2	70	84.9	15.1	0
2	3	60	98.9	1.1	0
3	4.4	60	83.3	0	16.7
4	3	60	97.3	0.5	2.2
5	3	74.1	92.4	2.2	5.4
6	3	60	98.4	0	1.6
7	3	45.9	90.5	2.5	7
8	4	50	85.1	1.1	13.8
9	4	70	89.1	0	10.9
10	1.6	60	81.1	18.9	0
11	3	60	97.3	0.5	2.2
12	3	60	98.2	0	1.8
13	2	50	89.7	10.3	0

The regression analysis of central composite design test results showed that the regression model was as follows.

$$QFI = -7.82x_1^2 - 0.03x_2^2 - 0.22x_1x_2 + 34.04x_1 + 3.19x_2 - 50.04 \tag{6}$$

$$MIS = 4.69x_1^2 + 0.01x_2^2 - 0.15x_1x_2 - 25.71x_1 - 0.89x_2 + 74.08 \tag{7}$$

$$MUL = 3.12x_1^2 + 0.02x_2^2 - 0.07x_1x_2 - 8.33x_1 - 2.30x_2 + 75.96 \tag{8}$$

Analysis of variance and significance test of regression coefficient were carried out for the above quadratic regression model.

The F-value of the QFI regression model was 125.84, and the corresponding $P<0.0001$.

Results indicate that the regression model was extremely significant. The F-value of lack of fit was 2.24, and the corresponding $P >0.05$, indicating that the lack of fit was not significant. For QFI, there was interaction between depth and angle.

The F-value of the regression model of MIS was 144.93, and the corresponding $P <0.0001$, indicating that the regression model was extremely significant. The F-value of lack of fit was 6.30, and the corresponding $P >0.05$, indicating that the lack of fit was not significant. $P <0.0001$ for x_1, $P =0.2022>0.05$ for x_2, but $P =0.0079<0.01$ for x_2^2, indicating that the depth and angle have significant effects on the MIS. $P =0.0089<0.01$ for x_1x_2, indicating that there was interaction between depth and angle for the MIS.

The F-value of the MUL regression model was 90.66, and the corresponding $P<0.0001$, which indicates that the regression model was extremely significant. The F-value of lack of fit was 1.05, and the corresponding $P >0.05$, indicating that the lack of fit was not significant. $P <0.0001$ for x_1, $P >0.05$ for x_2, but $P =0.0006<0.01$ for x_2^2, so the depth and angle have significant effects on the MUL; $P =0.15912>0.05$ for x_1x_2, indicating that the interaction between depth and angle was not significant for the MUL.

The results of significance analysis showed that the equation fitted by the quadratic regression model was consistent with the actual situation, which can correctly reflect the relationship between seed metering performance index and depth and angle of agitator. The regression model can predict the test results well.

According to the change law of seed metering performance index (Fig. 6), with the increase of depth, the QFI first increases and then decreases, and the maximum value appears at about 3mm.

With the increase of angle, the QFI increased first and then decreased, and the maximum value was about 60°. For the MIS, it decreased significantly with the increase of depth. When the depth was 3.5mm, the MIS was close to zero. With the increase of the angle, the MIS gradually increased, but the increase range was small.

For the MUL, with the increase of depth, the rebroadcast rate increased significantly, when the depth was 2mm, the rebroadcast rate was close to zero; with the increase of the angle, the MIS changed slightly.
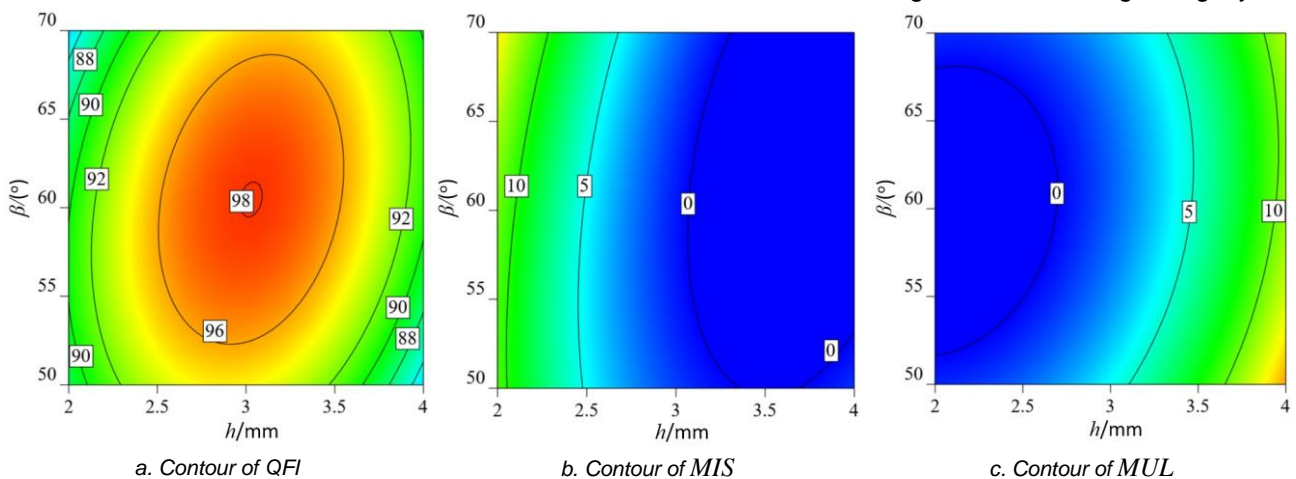

a. Contour of QFI   b. Contour of MIS   c. Contour of MUL

Fig. 6 - Effects of factors on the performance indexes

Taking the highest QFI and the minimum MIS as the optimization conditions, the optimal depth and inclination angle of agitator were 3.1 mm and 60.5° respectively.

Physical prototype test

Taking the optimal value of simulation test as the design parameters, the disk was made, and the physical test was carried out on the test bench (Fig. 7).

The tests were conducted at 16.7, 33.3, 50.0, 66.7 and 83.3 r/min, and the corresponding forward speed were 2, 4, 6, 8, 10 km/h respectively.
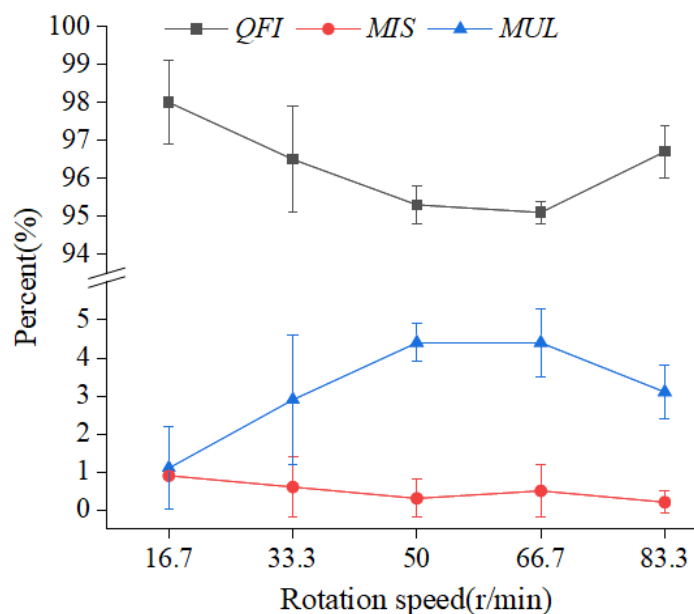

Fig. 7 - The results of physical prototype test

The QFI fluctuated with the increase of rotating speed. The highest QFI was 98.0% when the speed was 16.7r/min. The MIS and MUL were low, 0.9% and 1.1% respectively. With the increase of rotating speed, the QFI decreased. When the speed was 66.7 r/min, the QFI was the lowest (95.1%), and the MUL was the highest (4.4%), the MIS changed slightly, which was 0.5%. When the speed increased to 83.3 r/min, the QFI increased, which was 96.7%, the MUL was reduced to 3.1%. In the process of speed change, the MIS did not change significantly, and was always less than 1%.

Under the optimal parameters, the performance of the seed metering device with concave type agitator was excellent and met the requirements of precision seeding.

CONCLUSIONS

(1) In the speed range of 2-10 km/h, the MIS of concave type agitator was significantly lower than that of convex type and non-type.

(2) The depth and angle had significant influence on the QFI, and there was interaction effect. The depth and angle had significant influence on the MIS, and there was interaction effect. The depth and angle had significant influence on the MUL, but the interaction was not significant. The optimal depth and angle were 3.1 mm and 60.5° respectively.

(3) The results of physical prototype test showed that the QFI was more than 95.1% and the MIS was less than 1% in the speed range of 2-10 km/h, and the seed metering performance of the metering device was excellent.

REFERENCES

[1]   Ding, L., Yang, L., Liu, Sh., Yan, B., He, X., & Zhang, D. X. (2018), Design of air suction high speed precision maize seed metering device with assistant seed filling plate（辅助充种种盘玉米气吸式高速精量排种器设计）, *Transactions of the Chinese Society of Agricultural Engineering*, vol.34, issue 22, pp.1-11, Ed. Chinese Society of Agricultural Engineering, Beijing/P.R.C.; https://doi.org/10.11975/j.issn.1002-6819.2018.22.001;

[2]   Du, X., Liu, C., Jiang, M., Zhang F., Yuan H., & Yang, H. (2019), Design and experiment of self-disturbance inner-filling cell wheel maize precision seed-metering device（自扰动内充型孔轮式玉米精量排种器设计与试验）, *Transactions of the Chinese Society of Agricultural Engineering*, vol.3, issue.13, pp.23-34;

[3]   Karayel, D., Wiesehoff, M., Ozmerzi, A., & Muller, J. (2006), Laboratory measurement of seed drill seed spacing and velocity of fall of seeds using high-speed camera system, *Computers and Electronics in Agriculture*, vol.50, issue.2, pp. 89-96; https://doi.org/10.1016/j.compag.2005.05.005;

[4]   Khatchatourian, O., Binelo, M., & Lima, R. (2014), Simulation of soya bean flow in mixed-flow dryers using DEM, *Biosystems Engineering*, vol. 123, pp. 68-76; https://doi.org/10.1016/j.biosystemseng.2014.05.003;

[5]   Li, Z., Yu, J., Feng, Z., Fu, H., Zhang, L. & Fei, X. (2013), Simulation and performance analysis of a soybean seed metering device using discrete element method, *Sensor Letters*, vol.11, issue 6-7, pp.1217-1222; https://doi.org/10.1166/sl.2013.2897;

[6]   Liu, C., Du, X., Zhang, F., Ma, T., Zhang, H. & Li, Y. (2018), Design and test of cone diversion type horizontal plate wheat precision seed-metering device（锥面导流水平盘式小麦精量排种器设计与试验）, *Transactions of the Chinese Society for Agricultural Machinery*, vol.49, issue 12, pp.56-65; https://doi.org/10.6041/j.issn.1000-1298.2018.12.007;

[7]   Liu, H., Guo, L., Fu, L., & Tang, S. (2015), Study on multi-size seed-metering device for vertical plate soybean precision planter, *International Journal of Agricultural and Biological Engineering*, vol.8, issue 1, pp.1-8; https://doi.org/10.3965/j.ijabe.20150801.001;

[8]   Mao, X., Yi, S., Tao, G., Yang, L., Liu, H., & Ma, Y. (2015), Experimental study on seed-filling performance of maize bowl-tray precision seeder, *International Journal of Agricultural and Biological Engineering*, vol.8, issue 2, pp.31-3; https://doi.org/10.3965/j.ijabe.20150802.1809;

[9]   Shi, S., Zhou, J., Liu, H., H., Jian, S., & Zhang, R. (2019), Design and experiment of pneumatic precision seed-metering device with guided assistant seed-filling（驱导辅助充种气吸式精量排种器设计与试验）, *Transactions of the Chinese Society for Agricultural Machinery*, vol.50, issue 5, pp.61-70;

[10]   Singh, R., Singh, G., & Saraswat, D. (2007), Design and operational parameters of a pneumatic seed metering device for planting of groundnut (*Arachis hypogaea*) seeds, *Indian Journal of Agricultural Sciences*, vol.77, issue 1, pp.40-42;

[11]   Vianna, L., Reis, A., & Machado, A. (2014), Development of a horizontal plate meter with double seed outlets, *Revista Brasileira de Engenharia Agricola e Ambiental-Agriambi*, vol.18, issue 10, pp.1086-1091; https://doi.org/10.1590/1807-1929/agriambi.v18n10p1086-1091;

[12]   Wang, J., Tang, H., Wang, J., Li, X., & Huang, H. (2017), Optimization design and experiment on ripple surface type pickup finger of precision maize seed metering device, *International Journal of Agricultural and Biological Engineering*, vol.10, issue 1, pp. 61-71; https://doi.org/10.3965/j.ijabe.20171001.2050

[13]   Wang, J., Tang, H., Wang, Q., Zhou, W., Yang, W., & Shen, H. (2015), Numerical simulation and experiment on seeding performance of pickup finger precision seed-metering device based on EDEM（基于EDEM软件的指夹式精量排种器排种性能数值模拟与试验）, *Transactions of the Chinese Society of Agricultural Engineering*, 31(21), 43-50, https://doi.org/10.11975/j.issn.1002-6819.2015.21.006;

[14]   Yang, L., Yan, B., Yu, Y., He, X., Liu, Q., Liang, Zh., Yin, X., Cui, T., & Zhang, D. (2016), Global overview of research progress and development of precision maize planters, *International Journal of Agricultural and Biological Engineering*, vol.9, issue 1, pp. 9-26;

[15]   Yazgi, A., & Degirmencioglu, A. (2007), Optimisation of the seed spacing uniformity performance of a vacuum-type precision seeder using response surface methodology, *Biosystems Engineering*, vol.97, issue 3, pp. 347-356; https://doi.org/10.1016/j.biosystemseng.2007.03.013;

[16]   Yi, S., Liu, Y., Wang, C., Tao, G., Liu, H., & Wang, R. H. (2014), Experimental study on the performance of bowl-tray rice precision seeder, *International Journal of Agricultural and Biological Engineering*, vol.7, issue 1, pp. 17-25; https://doi.org/10.3965/j.ijabe.20140701.002;

[17]　Yu, J., Liao, Y., Cong, J., Yang, S., & Liao, Q. (2014), Simulation analysis and match experiment on negative and positive pressures of pneumatic precision metering device for rapeseed, *International Journal of Agricultural and Biological Engineering*, vol.7, issue 3, pp 1-12;

[18]　Zhang, G., Zang, Y., Luo, X., Wang, Z., & Li, Z. (2014), Line-churning tooth design and metering accuracy experiment of rice pneumatic precision hill-drop seed metering device on pregnant Japonica rice seed(粳稻穴播排种器直线型搅种装置设计及排种精度试验), *Transactions of the Chinese Society of Agricultural Engineering*, 30 (17), 1－9; https://doi.org/10.3969/j.issn.1002-6819.2014.17.001;

[19]　Zhang, G., Zang, Y., Luo, X., Wang, Z., Zhang, Q., & Zhang, S. (2015), Design and indoor simulated experiment of pneumatic rice seed metering device, *International Journal of Agricultural and Biological Engineering*, vol.8, issue 4, pp. 10-18; https://doi.org/10.3965/j.ijabe.20150804.1626;

[20]　Zhang, T., Liu, F., Zhao, M., Liu, Y., Li, F., Ma, Q., Zhang, Y., & Zhou, P. (2017), Measurement of physical parameters of contact between soybean seed and seed metering device and discrete element simulation calibration(大豆种子与排种器接触物理参数的测定与离散元仿真标定), *Journal of China Agricultural University*, vol.22, issue 9, pp. 86-92;

[21]　Zhao, Z., Li, Y., Chen, J., & Xu, L. (2010), Numerical analysis and laboratory testing of seed spacing uniformity performance for vacuum-cylinder precision seeder, *Biosystems Engineering*, vol.106, issue 4, pp. 344-351; https://doi.org/10.1016/j.biosystemseng.2010.02.012.