OPTIMISATION AND TESTING OF STRUCTURAL PARAMETERS OF INTERNAL TANGENT CIRCLE EXTERNAL GROOVED WHEELE FERTILISER DISCHARGER
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内切圆外槽轮式排肥器结构参数优化与试验

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ABSTRACT
Aiming at the problem of traditional external grooved wheel type fertilizer discharger, which discharges fertilizer unevenly, an internal tangent circle external grooved wheel type granular fertilizer discharger is designed. Firstly, the 19-19-19 NPK compound fertilizer produced by Stanley Company in China is selected, and the pulsatility of the straight groove wheel, external tangent circle groove wheel, and internal tangent circle groove wheel is compared and analyzed using the Hertz-Mindlin (no-slip) model in the EDM2020 simulation, then the structural parameters are optimized for the better type of groove wheel. Finally, the Field Oriented Control (FOC) algorithm is used to control the brushless motor to further optimize the coefficient of uniform volatility. The four factors and three levels response surface simulation test was conducted with the groove tooth inclination angle, number of grooves, diameter of the inner tangent circle and angular velocity of groove wheel as test factors. Simulation results showed that when the groove tooth inclination angle was 38.341°, the number of grooves was 9.999, the diameter of the inner tangent circle was 13.154 mm, and the angular velocity of groove wheel was 5.998 rad/s, the coefficient of uniformity of fluctuation of the discharged fertilizer was 4.11%. Based on practical considerations, the groove tooth inclination angle was set to 38°, the number of grooves to 10, the diameter of the inner tangent circle to 13 mm, and the groove wheel angular velocity to 6 rad/s for a bench validation test. The bench test results showed that the optimized internal tangent circle groove wheel fertilizer applicator achieved a uniform fluctuation coefficient of 6.32%, while incorporating FOC algorithm motor control further reduced the coefficient to 4.62%, meeting the design requirements for the fertilizer applicator.

摘要
针对传统外槽轮式排肥器排肥不均匀的问题，设计了一种内切圆外槽轮式颗粒肥料排肥器。首先，选用中国史丹利公司的复合肥（19-19-19），通过 EDM2020 仿真采用了 Hertz-Mindlin（无滑移）模型对比分析直槽轮、外切圆槽轮和内切圆槽轮的脉动性，然后针对较优型槽轮进行结构参数优化设计，最后利用 FOC 算法控制无刷电机进一步优化排肥均匀波动性系数。以槽轮槽齿倾角、槽轮槽数、内切圆直径和槽轮角速度为试验因素，进行四因素三水平响应面仿真试验。仿真试验结果表明：当内切圆槽轮槽齿倾角为 38.341°、槽轮数目为 9.999、内切圆直径为 13.154mm、槽轮角速度为 5.998rad/s 时，排肥均匀波动性系数较优值为 4.11%。根据实际情况取倾角为38°、槽轮槽数为10、内切圆直径为13mm、槽轮角速度为6rad/s 进行台架验证试验。台架验证试验结果表明:优化后的内切圆槽轮排肥器，排肥均匀波动性系数为 6.32%，而增加 FOC 算法电机控制后的排肥均匀波动性系数为 4.62%，符合排肥器设计要求。

INTRODUCTION
Precision agriculture technology is an agricultural production method based on information technology, which carries out real-time monitoring and data collection of the farmland environment through the use of modern sensors, communication networks, computers and other technological means, and applies these data to agricultural production decisions.

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Precision agriculture technology can help farmers realize refined management, improve production efficiency and quality, and reduce resource waste and environmental pollution. Fertilizer application is an important part in the application process of precision agriculture technology *(Liao et al., 2023)*. Precision fertilization not only reduces the use of chemical fertilizers and lowers production costs, but also avoids land pollution and ecological damage caused by over-fertilization. Therefore, how to realize precision fertilization has become an important direction of precision agriculture technology research.

At present, fertilizer dischargers are mainly classified into external chute wheel type, spiral type, disc type and collector-excluder type and so on. Among them, the external grooved wheel type fertilizer discharger is simple in structure, with simple and precise displacement adjustment, which is widely used in China's fertilizer application machinery. In order to improve the accuracy of the fertilizer discharger displacement, many scholars have explored the two aspects of structure and control, respectively. In terms of structure, *Wang Yubing* has designed the opposed double-spiral external grooved wheel fertilizer discharger for the problem of pulsation of traditional external grooved wheel fertilizer discharger *(Wang et al., 2022). Wang Jinfeng* used the discrete element method to qualitatively and quantitatively study the influence of the grooved wheel structural parameters on the fertilizer transport process *(Wang et al., 2023)*. *Wen Fujun* proposed a spiral grooved wheel fertilizer application device *(Wen et al., 2024)*. In fertilizer application control, *Zhou Liming* designed an online monitoring system for fertilizer application flow based on the principle of capacitive detection *(Zhou et al., 2022)*. *Dong Guoqiang* achieved precise control of fertilizer discharge by gradually extruding the fertilizer using a variable diameter and variable pitch structure *(Dun et al., 2023)*. *Mondal* proposed a novel sensorless field-oriented control (FOC) method for sensorless motor control *(Mondal et al., 2024).*

In summary, improvement of the groove wheel structure and addition of a fertilizer application control system can effectively improve the pulsation of the external groove wheel fertilizer discharger, thus improving the accuracy and continuity of the discharger. Therefore, this paper designs a new type of trough wheel and builds a FOC control system for it.

MATERIAL AND METHODS

External Grooved Wheel Fertilizer Discharger

The external grooved wheel type fertilizer discharger is a kind of agricultural machinery (as shown in Fig.1), which is used for spreading fertilizers evenly into the soil. The main structure of the outer grooved wheel type fertilizer discharger includes: fertilizer box, fertilizer discharging insert plate, arc base, grooved wheel.

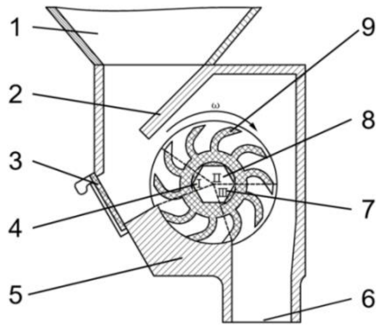


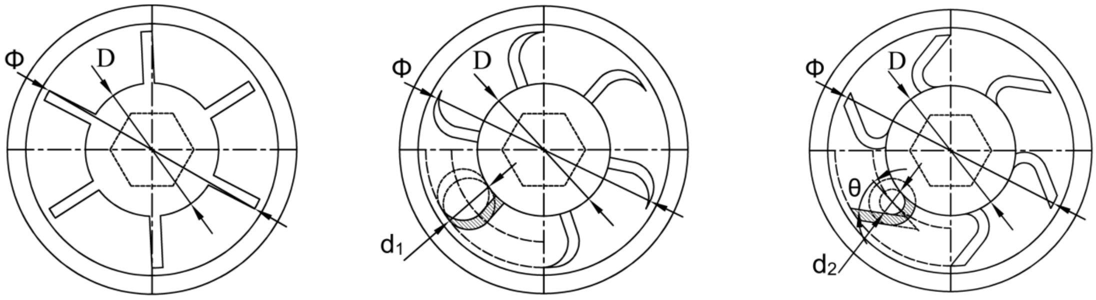
Fig. 1 - External Grooved Wheel Fertilizer Discharger
1. Fertilizer box; 2. Deflector plate; 3. Fertilizer unloading insert; 4. Fertilizer filling area; 5. Arc base; 6. Fertilizer discharge opening; 7. Fertilizer feeding area; 8. Fertilizer carrying area; 9. Trough wheel

The fertilizer discharger operates with side filling, directing granular fertilizer from the fertilizer box along the guide plate into the shell, where it enters the grooves of the groove wheel within the filling area. In the process of rotating the groove wheel, it passes through the fertilizer carrying area and fertilizer feeding area, and forcibly drives the granular fertilizer in the groove to be discharged from the fertilizer discharging port. Compared with the traditional groove wheel, this design can not only increase the range of particles into the groove, but also avoid the fertilizer sliding down automatically by gravity *(Zhang et al., 2015).*

Trough Wheel Designs

Trough wheels are the key component in an external trough wheel fertilizer discharger, and their primary function is to deliver fertilizer uniformly to the soil through rotation. The design of the chute wheel ensures uniform fertilizer delivery, and many external chute wheel fertilizer dischargers allow for adjustments in rotational speed and replacement of the chute wheel to accommodate different fertilizer types and application needs.

Among the factors of groove wheel structure that affect the operating effect of the groove wheel fertilizer discharger, the number of grooves, the effective working length, the radius of the groove wheel, and the cross-sectional shape of the individual grooves are the main factors *(Zhu et al., 2018)*. The appropriate cross-section shape and volume of the grooves can improve the filling effect of granular fertilizer, and when the filling rate of the grooves is maximized, the displacement per minute of the groove wheel no longer increases with the increase of rotational speed *(Wang et al., 2018).* In order to be able to improve the pulsation of the fertilizer discharger without changing the structure of the discharger housing and the effective length of the grooved wheel, and to make the discharging of fertilizer more uniform, this paper optimizes the design of the grooved wheel in terms of the shape of the groove tooth cross-section and the number of grooves, and designs the following different kinds of grooved wheels, which are shown in Fig. 2 as a comparison with the straight groove wheel. The length of the grooved wheel is 60 mm, the diameter of the outer circle Φ is 65 mm, and the diameter of the inner circle D is 35mm. d_1 is the diameter of the external tangent circle groove wheel (the outer tangent circle is tangent to the outer circle Φ); d_2 is the diameter of the inner tangent circle (the inner tangent circle is tangent to the inner circle D); and the groove tooth inclination angle θ is the angle between the grooved tooth and the diameter of the inner tangent circle (the said diameter is parallel to the tangent line between the inner tangent circle and the inner circle).



(a)Straight groove wheel （b）External tangent circle groove wheel （c） Internal tangent circle groove wheel

Fig. 2 - Different types of groove wheels

Discrete element simulation

Determination of simulation parameters and modelling

Pellet plant setup

In this experimental study, the 19-19-19 NPK compound fertilizer produced by Stanley Fertilizer Jilin Co., Ltd (measured average diameter of 100 grains 1.64 mm, standard deviation 0.18 mm, density 1.86 g·cm^{-3}) was selected as the test fertilizer, the particle modelling used pure spherical and non-agglomerated particles, and the material of fertilizer discharger was PLA plastic, and through the review of the relevant literature *(Li et al., 2023)*, the relevant parameters of simulation model were set as shown in Table 1.

Table 1

Global Variable Parameter Setting

Item	Property	Value
	Poisson ratio	0.25
Fertilizer particles	shear modulus/Pa	1.00×10^{7}
	densities/(kg·m^{-3})	1 861
	Poisson ratio	0.394
Groove wheel, Shell	shear modulus/Pa	3.18×10^{8}
	densities/(kg·m^{-3})	1 240
	coefficient of restitution	0.11
Pellet-Pellet	coefficient of static friction	0.30
	coefficient of rolling friction	0.10
	coefficient of restitution	0.41
Pellet-wheel, Shell	coefficient of static friction	0.32
	coefficient of rolling friction	0.18

Simulation analysis of pulsation of fertilizer discharger

Using SolidWorks 2022 to model the single screw fertilizer discharger and simplify the unnecessary structure, the model in SolidWorks 2022 is converted into STL file and imported into EDEM2020 software, and the model is built by filling in the parameters according to Table 1. A total of 50,000 fertilizer particles were generated in the fertilizer box, simulating a particle factory. All particles were released once the fertilizer applicator began to rotate. The relationships between the fertilizer particles and the fertilizer discharger casing, as well as between the fertilizer particles themselves were modeled using Hertz-Mindlin (no-slip) model, and the Auto Grid Resizing option in EDEM software was selected.

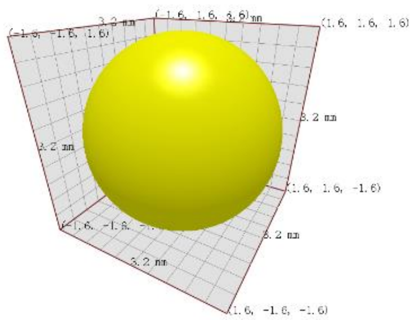
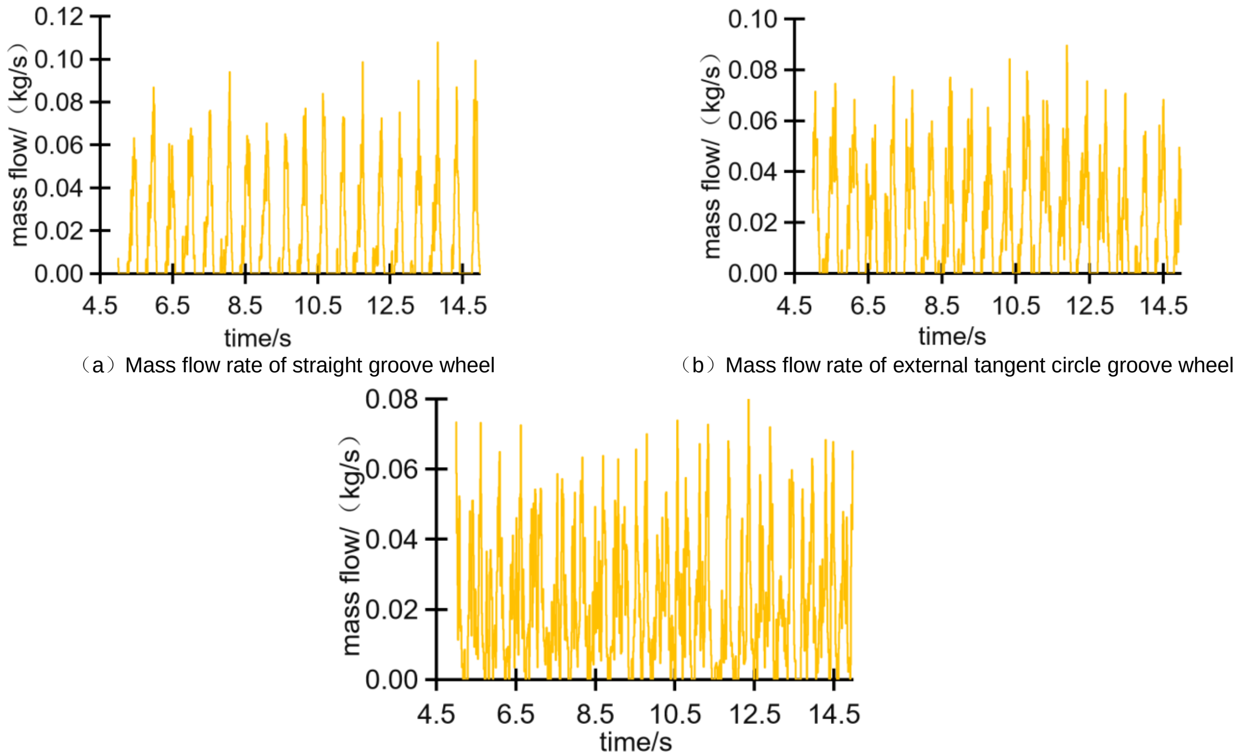


Fig. 3 - Fertilizer granules

Fig. 4 - Fertilizer discharge pulsatility simulation

Pulsatility analysis

In order to better observe the pulsation phenomenon of various grooved wheels when discharging fertilizers, three types of grooved wheels were set up for the simulation test: straight groove wheel, external tangent circle groove wheel and internal tangent circle groove wheel. The number of grooves was set to 6, and the angular velocity of groove wheel was set to 3.14 rad/s. In order to obtain a complete and accurate instantaneous discharge of the particle flow, a cylindrical virtual discharge sensor grid was set at the bottom of the grooved wheel at a position of 3 mm vertically downward, which was used for the detection of the instantaneous discharge of the particles. Fertilizer discharge pulsatility simulation is shown in Fig. 4, the cylindrical grid has a radius of 50 mm (detection range of 100 mm, larger than the fertilizer discharge port), a height of 30 mm, and a detection time interval of 0.01 s. The fertilizer discharger using three types of grooved wheels was simulated for 15 s respectively, and 4.5-14.5 s of them were taken to obtain Fig. 5.



（a）Mass flow rate of straight groove wheel

（b）Mass flow rate of external tangent circle groove wheel

（c）Mass flow of internal tangent circle groove wheel

Fig. 5 - Pulsation of different grooved wheels

This pulsation phenomenon is described in terms of the amplitude and time interval of the pulsation. The amplitude of the pulsation is the difference between the maximum value and the minimum value of the instantaneous displacement, the larger the amplitude of the pulsation, the more uneven the displacement. The time interval refers to the time difference between the maximum value and the minimum value of the instantaneous displacement of two adjacent times, the larger the time interval, the more obvious the pulsation, the more likely to cause the leakage of the application *(Song et al., 2021)*. From Fig. 5, it can be concluded that the internal tangent circle groove wheel discharging fertilizer pulsation amplitude is smaller, and the pulse time interval is smaller, so the internal tangent circle groove wheel discharging fertilizer is more uniform and has better fertilizer discharging effect in the case of a certain angular velocity of groove wheel and the number of grooves.

Response surface simulation test

Single factor test

Fertilizer discharger with different parameters of the grooved wheel was modeled, and the model was converted into STL file and imported into EDEM, and the parameters were set according to Table 1, and the particle factory was established in the fertilizer box, and a total of 50,000 fertilizer particles were generated, and the fertilizer discharger started to rotate after the generation of all the fertilizer particles. The angular velocity of groove wheel was set to 3.14 rad/s. The relationships between the fertilizer particles and the fertilizer discharger casing, as well as between the fertilizer particles themselves were modeled using Hertz-Mindlin (no-slip) model, and the Auto Grid Resizing option in EDEM software was selected. The grid method was used to count the data on the uniform volatility of fertilizer discharge *(Sugirbay et al., 2020)*, and the coefficient of uniform volatility was used as the evaluation index (the smaller the coefficient of uniform volatility represents the more uniform fertilizer discharge). A mass sensor was set on the conveyor belt and divided into 30 portions, each portion with a length of 350 mm and a width of 20 mm. the conveyor belt was moved at a speed of 0.2 m/s (this speed is only for the study of fertilizer dischargers) *(Dun et al.,2024)*, and the data were recorded at intervals of 0.01 s. The EDEM simulation model of the external grooved wheeled fertilizer discharger is shown in Fig. 6.

The coefficient of uniform volatility σ_u is as follows:

$$m_a = \frac{\sum_{i=1}^{30} m_i}{n} (i = 1, 2, \cdots, 30) \tag{1}$$

$$\sigma_u = \sqrt{\frac{\sum_{i=1}^{30} (m_i - m_a)^2}{m_a^2 (n-1)}} \times 100\% (i = 1, 2, \cdots, 30) \tag{2}$$

In the formula (1)~(2): m_i is the mass of fertilizer particles in the i-th grid, (g); n is the number of evenly divided grid cells in the monitoring area, n=10; m_a is the average mass of fertilizer particles in the grid cells, (g); σ_u is the coefficient of uniformity of volatility of fertilizer discharges, (%).

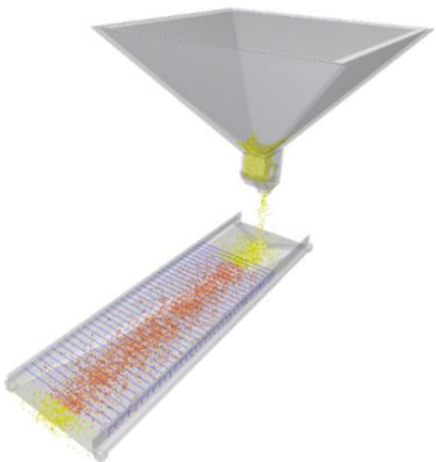


Fig. 6 – Single factor test process

In order to study the influence of each parameter of the trough wheel on the coefficient of uniform volatility, the degree of influence of the four factors affecting the coefficient of uniform volatility was taken and analyzed according to the actual use. The results are shown in Fig. 7.

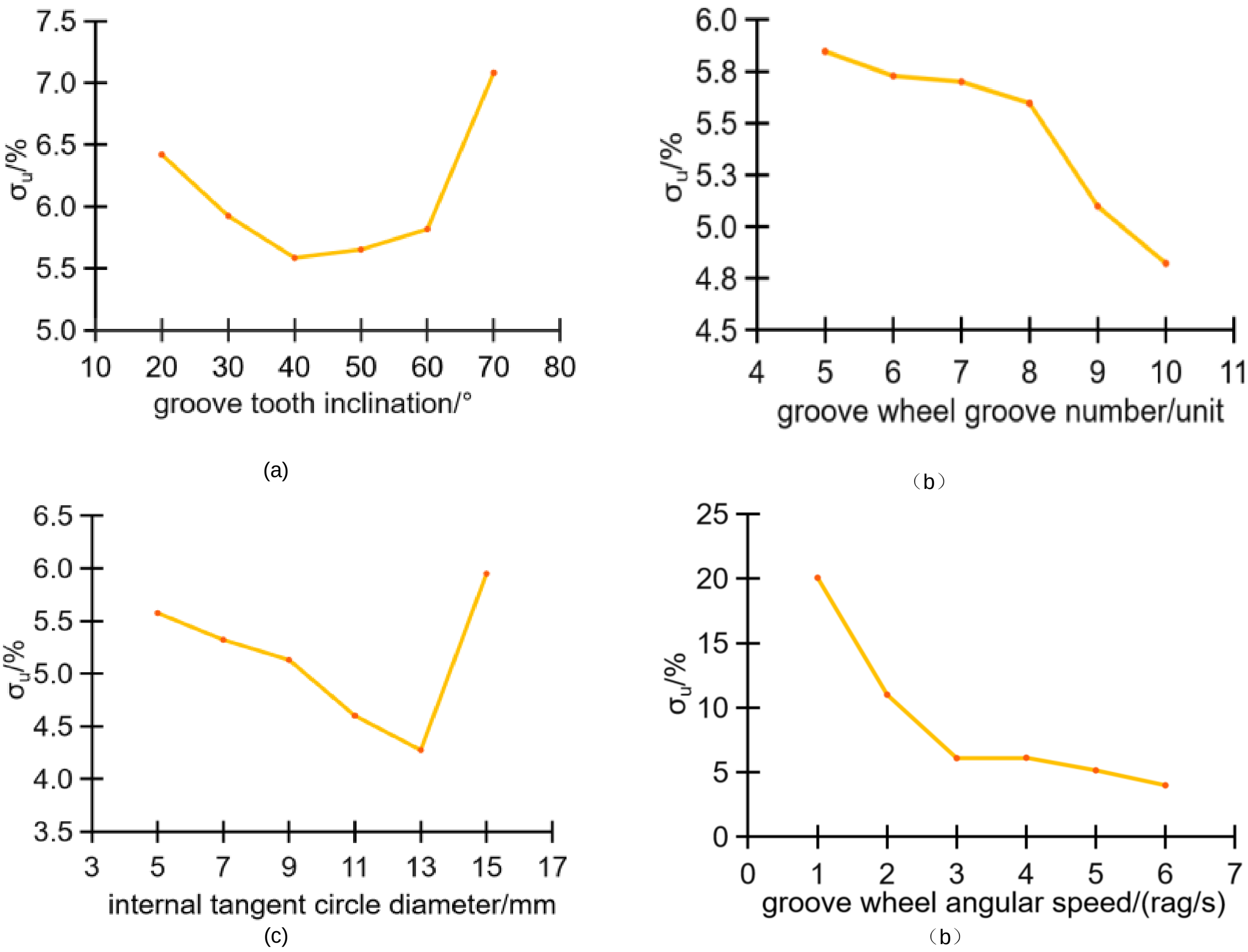


Fig. 7 – Results of Single factor test

It can be seen from Fig. 7(a) that with the increase of the inclination angle of the groove teeth, the uniform volatility coefficient of fertilizer discharge decreases and then increases; in Fig.7(b) it can be seen that with the increase of the number of grooves, the uniform volatility coefficient of fertilizer discharge decreases; Fig.7(c) shows that with the increase of the diameter of the inner tangent circle, the uniform volatility coefficient of fertilizer discharge decreases and then increases; Fig.7(d) shows that with the increase of the angular velocity of groove wheel, the uniform volatility coefficient of fertilizer discharge decreases.

Multifactor test

According to the preliminary pre-test and one-factor finding, the groove tooth inclination angle *A*, the number of grooves *B*, the diameter of the inner tangent circle *C* and the angular velocity of groove wheel *D* are the key factors affecting the coefficient of uniformity and volatility of the fertilizer discharger. In order to find the best working parameters of the fertilizer discharger, the four factors and three levels experimental design was used, and the factors and levels are shown in Table 2, and the experimental scheme and experimental results are shown in Table 3.

Table 2

Test factors and coding

Encodings	considerations			
	***A* / °**	***B* / unit**	***C* / mm**	***D* / (rad/s)**
-1	30	5	11	1
0	40	7	13	3.5
1	50	9	15	6

Table 3

Test Scheme and Results

Experiment Serial number	Experimental factors				
	A	***B***	***C***	***D***	**σ_u**
1	30	10	13	5	5.52678
2	40	8	15	5	5.53912
3	40	9	13	5	4.73283
4	40	9	11	6	5.08475
5	40	10	13	4	5.25807
6	50	8	13	5	6.59669
7	40	9	11	4	6.33458
8	40	9	13	5	4.89352
9	40	10	13	6	4.11044
10	50	9	11	5	7.0583
11	40	8	13	6	5.3971
12	40	9	13	5	4.98372
13	40	8	13	4	5.28156
14	30	9	13	4	6.60464
15	50	9	13	4	5.90993
16	30	8	13	5	4.97249
17	30	9	13	6	5.31614
18	40	9	15	6	4.50924
19	50	9	15	5	5.81091
20	30	9	11	5	5.76912
21	40	10	11	5	5.10965
22	40	9	15	4	5.96199
23	40	8	11	5	6.27953
24	50	9	13	6	6.83487
25	40	10	15	5	5.22641
26	30	9	15	5	5.33301
27	50	10	13	5	4.90294

The results of the test were analyzed by quadratic regression ANOVA and the results are shown in Table 4. According to the significance test, the F-value of the model was 5.98, $P < 0.01$, indicating that the quadratic regression model was highly significant. The coefficient of determination of the model, $R^2 = 0.8746$, proved that the model was well fitted. The significance of each factor was analyzed and the quadratic polynomial regression equation for the coefficient of uniform volatility was obtained as:

$$\begin{aligned}\sigma_u &= 4.87 + 0.2993 \times A - 0.3077 \times B - 0.2714 \times C - 0.3415 \times D \\ &- 0.562 \times AB - 0.2028 \times AC + 0.55334 \times AD - 0.2143 \times BC \\ &- 0.3158 \times BD - 0.057 \times CD + 0.7808 \times A^2 - 0.0236 B^2 \\ &+ 0.4534 \times C^2 + 0.2767 \times D^2\end{aligned} \tag{3}$$

Table 4 shows that the influence of each factor is *D* > *B* > *A* > *C*. It is shown that there is an interaction between the groove tooth inclination angle and the number of grooves, the groove tooth inclination angle and angular velocity of groove wheel.

Table 4

Analysis of variance of the coefficient of uniform volatility

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	12.08	14	0.8629	5.98	0.0018**
A	1.07	1	1.07	7.45	0.0183*
B	1.29	1	1.29	8.93	0.0113*
C	0.8831	1	0.8831	6.12	0.0293*
D	1.4	1	1.4	9.7	0.0089**
AB	1.26	1	1.26	8.76	0.0119*
AC	0.1645	1	0.1645	1.14	0.3066
AD	1.22	1	1.22	8.49	0.013*
BC	0.1837	1	0.1837	1.27	0.2813
BD	0.3989	1	0.3989	2.76	0.1223
CD	0.0103	1	0.0103	0.0713	0.7939
A^2	3.25	1	3.25	22.53	0.0005**
B^2	0.003	1	0.003	0.0206	0.8883
C^2	1.1	1	1.1	7.6	0.0174*
D^2	0.4084	1	0.4084	2.83	0.1183
Residual	1.73	12	0.1443		
Lack of Fit	1.7	10	0.1699	10.52	0.0899
Pure Error	0.0323	2	0.0162		
Cor Total	13.81	26			

Note: * denotes significant difference ,** denotes significant difference .

Analysis of the effect of interaction factors on the coefficient of uniform fluctuation of the fertilizer discharge

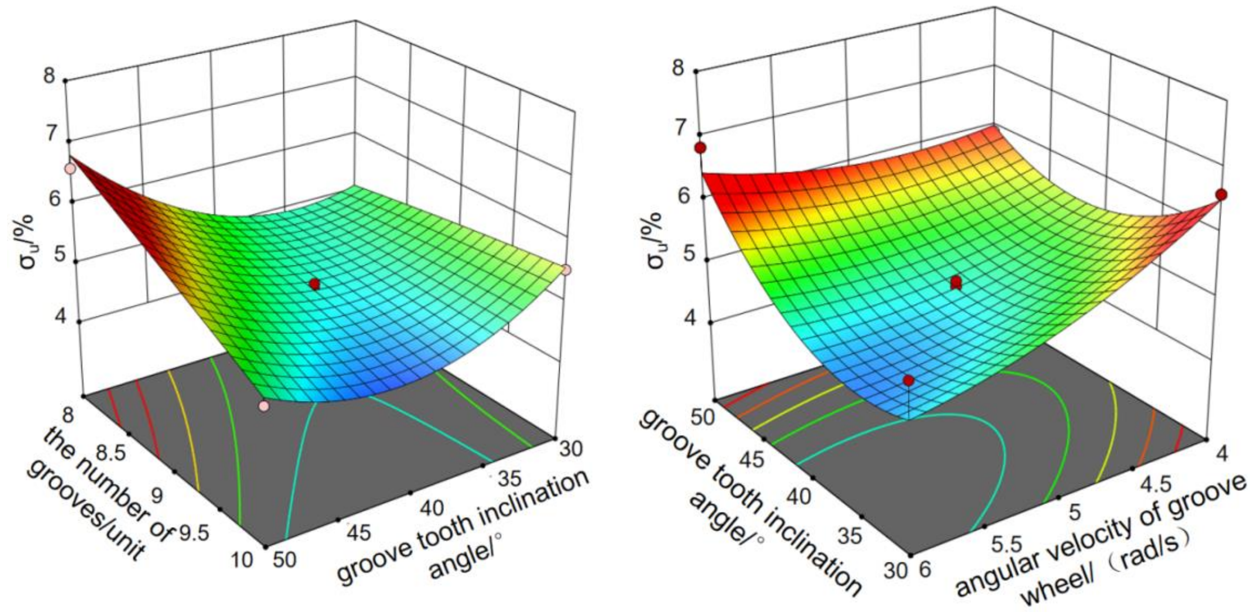
Interaction of groove tooth inclination angle and the number of grooves

Fig.8(a) shows the response surface diagram of the interaction between the inclination angle of the groove teeth and the number of grooves when the angular velocity of the groove wheel is 4 rad/s and the diameter of the inner tangent circle is 13 mm. When the groove tooth inclination angle is 30~40°, with the increase of the number of grooves, the coefficient of uniform volatility shows an increasing trend; when the groove tooth inclination angle is 40~50°, with the increase of the number of grooves, the coefficient of uniform volatility shows a decreasing trend. The reason is: when the groove tooth inclination angle is 30~40°, the bigger the number of grooves, the smaller the opening of the grooves, the more difficult to fill the fertilizer, the coefficient of uniform volatility shows an increasing trend. When the groove tooth inclination angle is 40~50°, the size of the groove opening meets the condition of filling fertilizer, so the coefficient of uniformity and volatility of fertilizer discharge shows a decreasing trend. Therefore, when the groove tooth inclination angle is 35~40° and the number of grooves is 9~10, the coefficient of uniform volatility is smaller.

Interaction of groove tooth inclination angle and angular velocity of groove wheel

Fig.8(b) shows the response surface of the interaction between the groove tooth inclination angle and angular velocity of groove wheel. When the number of grooves is 9 and the diameter of the inner tangent circle is 13 mm. When the groove tooth inclination angle is 30 ~ 40°, the angular velocity of groove wheel increases, the uniform volatility coefficient of fertilizer discharge presents a decreasing trend; when the groove tooth inclination angle is 40 ~ 50°, the angular velocity of groove wheel increases, the uniform volatility coefficient of fertilizer discharge presents an increasing trend.

The reason is as follows: fewer grooves lead to a shorter fertilizer filling time. Groove tooth inclination angle is 30 ~ 40°, the tangential force acting on the fertilizer is greater, which helps with fertilizer filling, so filling the fertilizer will not be affected by the filling time, showing a decreasing trend. Groove tooth inclination angle of 40 ~ 50°, the fertilizer tangential force is small, leading to insufficient filling. In this case, the filling process is more sensitive to time, showing an increasing trend. Therefore, the coefficient of uniform volatility is smaller when the groove tooth inclination angle is 35~40° and the angular velocity of groove wheel is 5 rad/s ~ 6 rad/s.



(a) (b).

Fig. 8 – Effect of interaction factors on the coefficient of uniform fluctuation of fertilizer discharge

Optimization of grooved wheel parameters

In order to ensure that the external grooved wheel type fertilizer discharger has a good performance of fertilizer discharge, the coefficient of uniform volatility is taken as an evaluation index, to optimize the structural parameters of the external grooved wheel. The objective function and constraints are:

$$\begin{cases} \min \sigma_u \\ s.t. \begin{cases} A \in [-1,1] \\ B \in [-1,1] \\ C \in [-1,1] \\ D \in [-1,1] \end{cases} \end{cases} \tag{4}$$

Optimization-Numerical module in Design-Expert 13 software was used to solve the optimization problem, and the results showed that the coefficient of uniformity of fertilizer discharge fluctuation was better when the groove tooth inclination angle was 38.341°, the number of grooves was 9.999, the diameter of the inner tangent circle was 13.154 mm, and the angular velocity of groove wheel was 5.998 rad/s. The coefficient of uniform volatility was better by 4.11%.

FOC algorithm

Brushless electric motor

The internal components of a brushless DC motor are the rotor and stator. The rotor, which can be considered as a permanent magnet (Fig.9), is located in the center of the motor and has magnets attached. The coil winding fixed at the inner edge of the motor serves as the stator. A three-phase, three-winding, two-pole internal rotor motor is modeled. When the direction of the current passed through the three-phase winding of the stator changes, the direction of the magnetic field generated by the stator also changes, and the rotor rotates under the influence of the magnetic force.

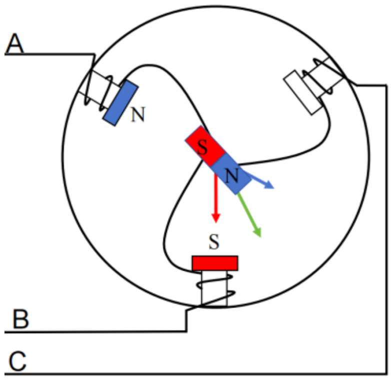


Fig. 9 – Brushless motor schematic

FOC Principle

The FOC (Field-Oriented Control) algorithm is an efficient motor control strategy, the core of which is to decompose the current of the motor into two components related to the orientation of the magnetic field, so as to realize the independent control of the motor speed and torque. The whole operation process of the FOC algorithm is a continuous feedback and adjustment process (Figure 10). It can adapt to load changes and changes in motor parameters to maintain efficient and stable operation of the motor.

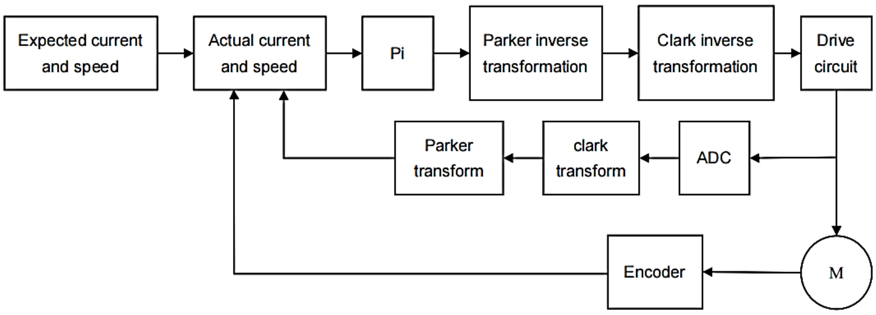


Fig. 10 – FOC Algorithm Schematic

FOC Realization

The AC power supply is converted from 220V AC to 24V DC by the power adapter to supply power to the FOC driver board, which has a built-in voltage regulator circuit to supply power to the ESP32 microcontroller and the encoder respectively, and the ESP32 microcontroller receives the real-time motor position data and the motor current data (of which the position data is provided by the encoder and the current data is provided by the FOC driver board). All the data are calculated by the ESP32 microcontroller and then PWM signals are sent to the FOC driver board, which outputs high-power PWM current to drive the motor according to the PWM signals. The specific electrical connection is shown in Figure 11.

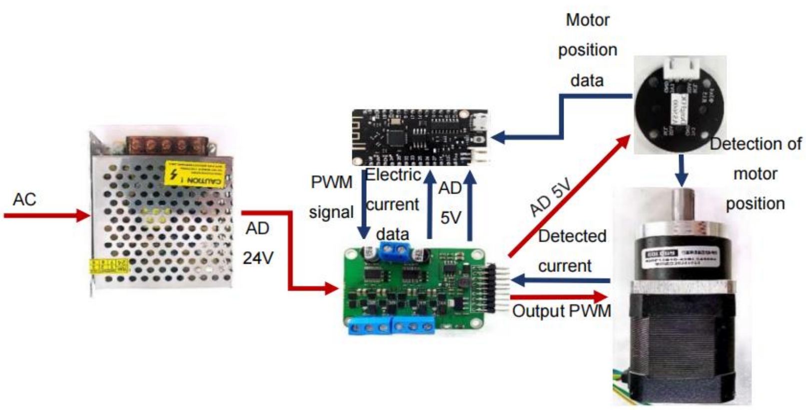


Fig. 11 – Electrical connection

This design takes Arduino SimpleFOClibrary to implement the FOC algorithm. The FOC driver board increases the current when the brushless motor is subjected to resistance, and its current versus speed relationship when the brushless motor receives a load is shown in Figure 12 below.

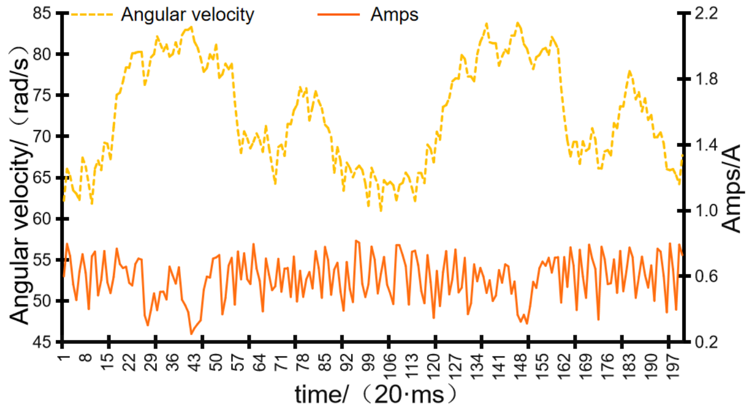


Fig. 12 – Current vs. speed under load

RESULTS

Bench Test

Based on the above parameter optimization results, for better machining and better control of rotational speed, the following parameters are taken: groove tooth inclination angle of 38°, number of grooved wheels of 10, diameter of the inner tangent circle of 13 mm, angular velocity of groove wheel of 6 rad/s. The grooved wheel parts and other related parts of the fertilizer discharger are processed by a 3D printer with the optimum parameter combination, and the conveyor belt is processed by using an aluminum profile. The bench-scale validation test of the external grooved wheel fertilizer discharger under the optimal combination of mechanism parameters was carried out indoors using conventional PWM motor control, as shown in Fig. 13.

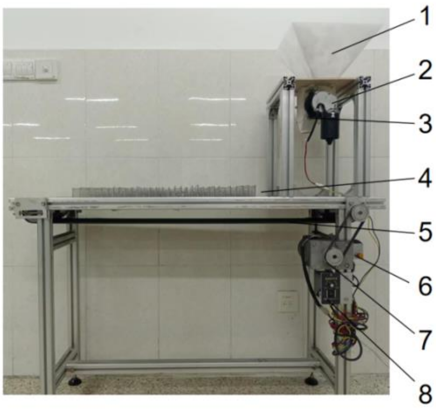


Fig. 13 - Bench Test

1 Fertilizer box 2 Discharger 3 Discharger motor 4 Fertilizer collection box 5 Conveyor belt 6 Fertilizer Discharger Motor Speed Controller 7 Belt Motor 8 Belt Speed Controller

The speed of the angular velocity of groove wheel was set to 6 rad/s and the speed of the conveyor belt was set to 0.2 m/s. When the fertilizer was discharged, the fertilizer collection box was put into the conveyor belt from the right side of the conveyor belt; and when it reached the left side of the conveyor belt, the fertilizer collection box was taken out. Repeat the process 5 times and calculate the coefficient of uniform volatility. Verify that the coefficient of uniform volatility is 6.32%, replace the motor and control system of the fertilizer discharger with the electronic control system shown in Fig. 11, and carry out this experiment for 5 more times. The coefficient of uniform volatility obtained from the validation test was 4.62%. The test results are more consistent with the prediction model within the error range, as shown in Table 5.

Table 5

Bench test results

	1	2	3	4	5	average value
PWM motor control	8	4.4	7.2	6.3	5.7	6.32
FOC algorithm	4.8	4.7	4.2	4.9	4.5	4.62

CONCLUSIONS

In this study, the internal tangent circle groove wheel granular fertilizer discharger is designed for the problem of uneven fertilizer discharge of the traditional outer grooved wheel type fertilizer discharger. The pulsatility of straight groove wheel, external tangent circle groove wheel and internal tangent circle groove wheel is analyzed using the Hertz-Mindlin (no-slip) model in the EDM2020 simulation. The structural parameters are optimized for the best type of grooved wheel. Finally, the FOC algorithm is used to control the brushless motor to further optimize the coefficient of uniform volatility. The following conclusions are drawn from the simulation and experimental studies:

(1) The discrete element simulation platform of the working process of the external grooved wheel fertilizer discharger was constructed by EDEM2020 software, and the pulsation of the external tangent circle groove wheel, internal tangent circle groove wheel and straight grooved wheel was compared. The simulation test shows that the internal tangent circle groove wheel discharges fertilizer more evenly.

(2) The four factors and three levels response surface simulation test was carried out using the groove tooth inclination angle, the number of groove wheels, the diameter of the inner tangent circle and the angular velocity of groove wheel as test factors. The simulation results show that when the groove tooth inclination angle is 38.341°, the number of grooves is 9.999, the diameter of the inner tangent circle is 13.154 mm, and the angular velocity of groove wheel is 5.998 rad/s, the improved value of the coefficient of uniform volatility is 4.11%.

(3) According to the optimal combination of structural parameters, the groove tooth inclination angle is 38°, the number of grooves is 10, the diameter of the inner tangent circle is 13 mm, and the angular velocity of groove wheel is 6 rad/s. The bench test and the whole machine test are carried out. The bench test and the whole machine test were carried out. The bench test showed that: the coefficient of uniform volatility by the traditional PWM motor was 6.32%; the coefficient of uniform volatility by the FOC motor was 4.62%.

The results of the discrete element method (DEM) simulation provide a theoretical basis for the design of the motor control strategy, enabling uniformity control of fertilizer discharge in practical applications.

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