Design and parameter optimization of flexible comb-type grass seed metering device

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Abstract: In order to optimize the structure schema of flexible comb-type grass seeder, the effects of combing teeth gap L, rotation speed of comb shaft N, seed metering device inclining angle α and groove strip inclining angle θ on the rate and uniformity of seeding were observed by test and analyzed, then the coefficient of seeding stability variation was explored in the simulating planting environment on the soil tank test bed based on the above four influencing factors, with Festuca arundinacea seeds as example. According to the results of regression analysis, the model fits well with the actual situation. L, N, α, and the interaction term of N and θ are significant, and the interaction term of θ and α is extremely significant. The analysis of interaction factor effect shows that the variation coefficient responds to the interaction of N and θ in the same manner as that responds to the interaction of θ and α, showing 'saddle' variation tendency. Suppose the acceptable maximum value of coefficient of seeding uniformity variation is 4%, then the inverse proportion relationship between factors is inferred according to the change trend of the above interaction factors and derivation of regression equation. Then the regression equation was simplified according to the inverse proportion equation, and four groups of parameters were obtained. Each parameter group was tested, and the test results agreed with the regression equation's predicting value, with the correlation coefficient 0.726. This research can provide reference for the development of seed metering devices and grass seeders.

Keywords: grass seeder, structural design, parameter optimization, agricultural machinery, flexible structures
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1 Introduction

The grassland degrades severely in northern China, while it just degrades slightly and allows high degree of utilization thanks to the advantageous climate and geographical environment in southern China, followed by broad prospects for development of grassland animal husbandry[1-3]. Most of grass seeders are pnuematic which allow large sowing width and quantity, coupled with high cost. Research papers about seeders also mainly focus on crop seeders[4,5]. Wang[6] designed an outer groove-wheel feeding device for air distributor in air seeder and conducted seeding test. VIsalakshi et al.[7] conducted three-year continuous experiment and confirmed that, with drum seeder, rice yield will be improved with seeding rate 30 kg/hm^2. Anantachara et al.[8] developed an artificial neural network (ANN) model for the prediction of the performance parameters of an inclined plate seed metering device. According to the above characteristics of pneumatic grass seeder, it is not preferred in Southern grassland consisting of small dispersive plots. The metering device of existing mechanical forage seeder is more applicable to sow small grass seeds with good fluidity, such as alfalfa, and it can hardly normally sow gramineous forage grass[9-11]. Zhao et al.[12] designed a small-scale alfalfa precision drill seeder using spiral outer groove-wheel. At present, no cheap mechanical forage seeder for small sowing quantity

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of gramineous forage grass has been developed.

In this study, flexible comb-type gramineous forage grass seed metering device was designed, more suitable for small grass seeder for small and dispersive grassland in Southern China. Metering device test bed has been designed, and seeding uniformity has been tested accordingly[13-15]. Many factors can influence the performance of metering device, including field operation environment and sowing machine's operation state, as well as the parameter setting of its components. In order to further enhance the practicality and structure of the metering device, the effects of parameters of its components on the seeding were determined in tests, and then the results of regression analysis were optimized.

2 Analysis of influencing factors

In essence, the seeding process "breaks up the whole into parts". According to the objective of design, the metering device should ensure metering uniformity and stability, so metering stability was selected as the index to be tested, the calculated metering variation coefficient was defined as the quantitative factor, and the four factors, combing teeth gap L, rotation speed of comb shaft N, seed metering device's inclining angle α and groove strip's inclining angle θ, were selected as factors for the tests.

2.1 Effects of combing teeth gap L and trajectory on seed discharging

The combing teeth were installed on the comb shaft, so N could be regarded as the combing teeth's circular motion speed. When N changes, the seed combing frequency will change correspondingly. When the width of combing tooth L_{tth} is reduced, its strength will decrease, its gap will increase, and its deformation will also increase accordingly, thus affecting the combing effects on seeds. The end of combing teeth's motion projection on the upper surface forms specific trajectory curve, when the combing teeth's structure and rotation speed change, the trajectory curve will also change accordingly, and the seed feeding process from seed metering box to groove via comb will be also affected.

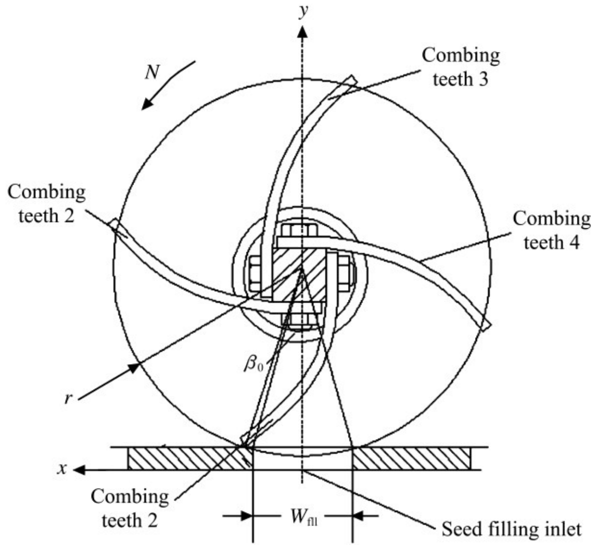
Suppose all teeth have the same deformation and the tooth rebound at seed filling inlet is neglected. At the moment $t = 0$, the combing teeth's end just locates at the edge of the seed filling inlet, then the angle between the combing tooth end's rotating radius and the vertical direction is the initial angle of combing tooth β_0, the distance between combing tooth rotation center and the seed filling inlet is 23 mm, then the initial angle will be

$$\beta_0 = \arctan(\frac{W_{\mathrm{fll}}}{2\times 23}) = \arctan(\frac{11}{2\times 23}) \approx 13.45° = 0.235 \text{ rad} .$$

At t moment, the rotation angle of combing teeth is $\beta = \beta_0 - \frac{\pi N}{30}t$, the curve projection equation of combing teeth will be

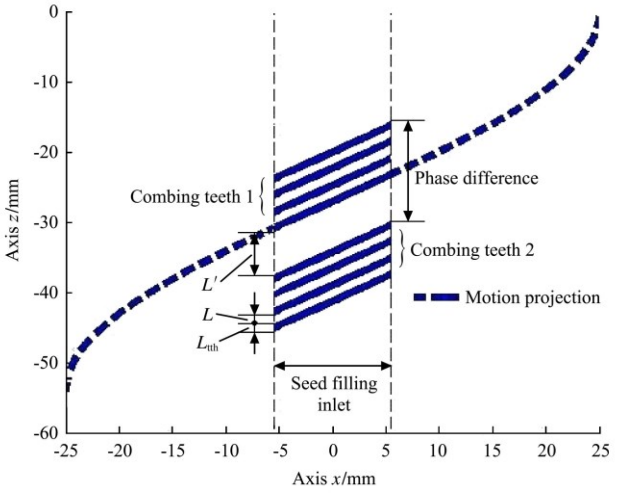
$$\begin{cases} S_x = r\sin(\beta_0 - \frac{\pi N}{30}t) \\ S_y = \frac{\pi N_{\mathrm{p}} D_{\mathrm{p}}}{60}t \end{cases}$$

where, (S_x, S_y) is coordinate of the combing tooth end, and the belt wheel's diameter and combing teeth's rotation radius are given, respectively D_{p} = 86 mm, and r = 25 mm, which are not shown in Figure 1. The seed filling inlet's width is W_{fll} = 11 mm which can be substituted into the above equation. A function is written by software MATLAB. Suppose the belt wheel's speed is N_{p} = 8 r/min, the seed combing shaft's speed is N = 8 r/min, and the comb teeth's width is 5 mm, then combing tooth end's motion projection near the seed filling inlet is shown in Figure 2.



Note: N is the rotation speed of comb shaft, r/min; β_0 is the initial angle of combing tooth, rad; W_{fll} is the seed filling inlet's width, mm; r is the combing teeth's rotation radius, mm.

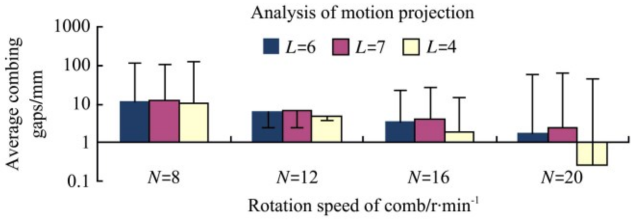
Figure 1 Schematic diagram of combing teeth



Note: L is combing teeth gap; L' is gap between two combing teeth; L_{tth} is combing tooth width

Figure 2 Schematic diagram of combing tooth end's motion projection

Seeding uniformity can be affected by combing teeth gap L and phase difference between two combing teeth. If we suppose the distance of combing teeth i and i+1(i = 1, 2, 3) is L', seeding uniformity in seed feeding process will depend on L and L' which generated by four combing teeth. The average value and variance of combing gaps in one cycle were analyzed by programming using MATLAB (Figure 3).



L-combing teeth gap; N=rotation speed of comb shaft

Figure 3 Average value and variance of combing gaps

Based on the above analysis, seeding uniformity will be better when N equals 12 and 16 r/min. The variance value is lowest with N = 12 r/min in three L levels.

2.2 Effects of *θ* on seed discharging

When θ changes, the seed dropping in seeding process also changes. Suppose N and N_p were both 16 r/min, several tests were conducted on the seed metering belts with different values of θ, and the Festuca arundinacea seed dropping in the metering device's working region was photographed regularly (Figure 4).

As is shown in Figure 4, when θ = 90°, groove strips' edges always remains at the same height, and the seeds have the same chance for falling in groove, so the seed discharging goes in only one groove at certain time. The seeds in next groove will not be discharged until the belt wheel rotates for certain angle, which causes 'ripple' trend of uneven seed discharging in unit time. When θ = 45°, the seeds are discharged between the groove's sidewall and septum strip. Before the seeds in previous groove completely drop, the next groove locates in the seed discharging area, and the seeds begin to drop, so the time for seed discharging of adjacent two grooves overlaps. When θ = 22.5°, the seed dropping process is similar to that when θ = 45°, but 3 grooves drop seeds simultaneously since θ reduces.


a. θ=90° b. θ=45° c. θ=22.5°

Figure 4 Effects of groove strip's inclining angle θ on seed discharging

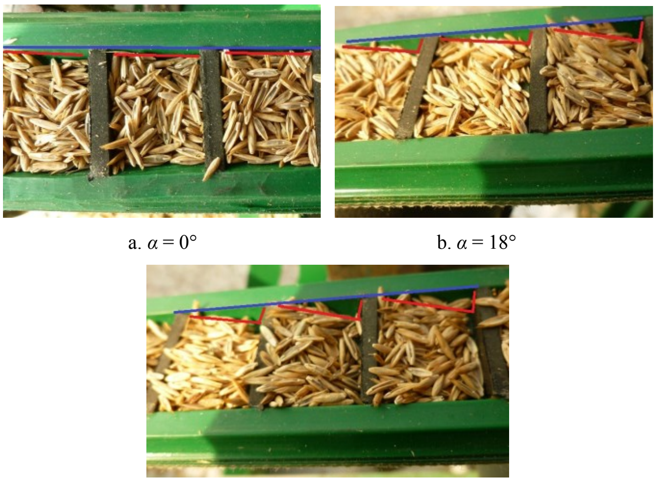
When grooves enter the seed discharging area, the simultaneous seed discharging in different grooves eliminate the ripple trend, and the time for seed discharging in individual groove will change with the change of θ.

2.3 Effects of α on seed discharging

Seed metering device inclining angle α refers to the inclining angle between seed metering belt or seed metering box and the motion plane. Seeds are granular with certain liquidity, so when the seeds fall to the groove, they may be distributed in different manners in the groove with constant volume and shape due to different inclining angles to the horizontal plane. Therefore, festuca arundinacea seed metering test was conducted, with N_p and N at 16 r/min. The power was cut off in the seed metering process, then the seed box was removed and the seed distribution in the groove was observed (Figure 5). In the figure, the blue lines refer to the edges of the seed metering belt's side walls; the red lines are those intersecting lines of seed plane in groove and seed metering belt.

According to the Figure 5, with the increase of α, the seeds in groove no longer fully fill the groove cavity.

Influenced by mobility, the top layer of seeds in each groove basically remains at the same horizontal level and forms certain included angle with the surface of seed metering belt, which demonstrates that the seed distribution is influenced by seed metering device's inclination angle. When this angle increases, the seed amount in groove decreases, so the amount of actual discharged seeds will decrease.



a. $\alpha = 0°$ b. $\alpha = 18°$

c. $\alpha = 27°$

Figure 5 Effects of seed metering device inclining angle α on seed discharging

3 Materials and methods

3.1 Test equipment and materials

The test is conducted on the soil bin tester (Figure 6). The related test indexes were designed according to the requirements of no-tillage forage planter defined in national standard literature GB/T 25421-2010. The height of seed metering device and soil surface can be adjusted by hydraulic lifting device on soil bin tester. The seed metering is connected with the trolley of soil bin tester, whose speed is then the planter's speed, via connecting plate.

Figure 6 Installation diagram of the seed metering

Tester's structure and planting area and trolley's buffer area are shown in Figure 7.

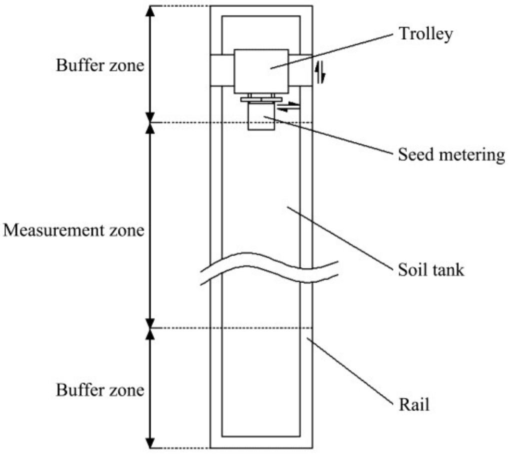


Figure 7 Structure diagram of soil bin tester

Soil bin tester mainly consists of soil tank, rail, trolley, speed control system and drive system. The soil tank, 40 m long, is divided into three zones, with buffers 10 m long located on both sides and the effective measurement area 20 m long located in the center. The trolley moves on soil tank. At the beginning, the trolley starts from the buffer and gradually accelerates to the desired speed 3 km/h which is the seeder's actual working speed. Seed metering test device connected to the front of trolley can move left and right.

3.2 Experimental method

According to the analysis and test, L, N, θ and α were determined as test factors. In the tests, the speed of wheel adjusting sowing quantity was fixed at 16 r/min. Since the relationship between the seed metering amount, the coefficient of seeding uniformity variation and test factors was unknown, so quadric rotational regression and orthogonal combination was integrated into the tests. Values of each factor, namely the level codes, are shown in Table 1.

Table 1 Coding of experimental factors and levels

Factor level	x_1 (L/mm)	x_2 (N/r·min^{-1})	x_3 (θ/(°))	x_4 (α/(°))
2	10	24	90	36
1	8	20	67.5	27
0	6	16	45	18
-1	4	12	22.5	9
-2	2	8	0	0

Note: L is combing teeth gap; N is rotation speed of comb shaft; θ is groove strip's inclining angle; α is seed metering device's inclining angle.

Preparation: Firstly, the soil in tank was watered, compacted by compactor roller and then leveled. Before the operation, the seeder was powered on, and then the wheel, *N* and the seeder's height were adjusted. The soil tank and trolley were moved to the buffer area. After starting, the trolley began to accelerate to the desired speed, then it moved forward 20-25 m and then returned. The seeds from the seeder were collected by seed collection bag and then weighed after the sowing. Each simulation sowing lasted for 1 min, and the test was repeated for 6 times under the same parameters, and after the same treatment, the average sowing quantity and the coefficient of seed metering variation were calculated.

4 Result and analysis

4.1 Test results

Seed metering test results are shown in Table 2, and the factor levels of combing teeth gap $L(x_1)$, rotation speed of comb shaft $N(x_2)$, groove strip inclining angle $\theta(x_3)$, seed metering device inclining angle $\alpha(x_4)$ were arranged.

Table 2 Test arrangement and test results

Serial number	Factor level					Sowing quantity	CV *y*/%
	x_0	x_1	x_2	x_3	x_4		
1	1	1	1	1	1	108.3185	4.457
2	1	1	1	1	-1	117.1415	2.311
3	1	1	1	-1	1	71.5875	3.981
4	1	1	1	-1	-1	103.2675	5.931
5	1	1	-1	1	1	103.8455	3.110
6	1	1	-1	1	-1	118.3730	3.464
7	1	1	-1	-1	1	78.8135	4.806
8	1	1	-1	-1	-1	86.6880	8.859
9	1	-1	1	1	1	124.9490	4.558
10	1	-1	1	1	-1	137.0460	1.924
11	1	-1	1	-1	1	80.9760	1.775
12	1	-1	1	-1	-1	87.0780	2.034
13	1	-1	-1	1	1	117.3825	5.022
14	1	-1	-1	1	-1	133.2075	1.882
15	1	-1	-1	-1	1	80.2175	4.742
16	1	-1	-1	-1	-1	105.4525	8.972
17	1	-2	0	0	0	104.6355	1.671
18	1	2	0	0	0	73.4035	6.373
19	1	0	-2	0	0	105.2120	1.875
20	1	0	2	0	0	107.8580	1.631
21	1	0	0	-2	0	104.9390	3.695
22	1	0	0	2	0	111.6275	3.106
23	1	0	0	0	-2	110.7865	4.390
24	1	0	0	0	2	76.6175	2.644
25	1	0	0	0	0	104.3590	2.013
26	1	0	0	0	0	101.3410	2.039
27	1	0	0	0	0	102.4600	3.737
28	1	0	0	0	0	99.7700	3.200
29	1	0	0	0	0	99.3710	3.402
30	1	0	0	0	0	99.6810	2.763
31	1	0	0	0	0	107.0330	8.397
32	1	0	0	0	0	106.6020	3.943
33	1	0	0	0	0	101.1010	2.555
34	1	0	0	0	0	102.4510	3.122
35	1	0	0	0	0	102.7610	2.589
36	1	0	0	0	0	102.2240	3.664

4.2 Regression model and analysis

1) Model analysis:

Sum of square of error SS_e, error's degrees of freedom f_e, error's mean square value V_e, m_0 means the times of test repetition at zero level center point, and m_0=12 in this test:

$$SS_e = \sum_{i=1}^{m_0}(y_i - \bar{y})^2\,,\quad f_e = m_0 - 1\,,\quad V_e = SS_e / f_e$$

Sum of square of lack of fit SS_l, lack of fit's degrees of freedom f_l, lack of fit's mean square value V_l:

$$SS_l = SS_r - SS_e\,,\quad f_l = f_r - f_e\,,\quad V_l = SS_l / f_l$$

According to Table 3, the value of the model's lack of fit $F_1 < F_{0.05}(10,11) = 2.85$, and that of equation's significance is $F_2 > F_{0.05}(14,21) = 2.20$, which demonstrates the reasonability of model and the good fit of regression equation and actual circumstance of seeding.

Table 3 Model test and the regression equation inspection

	Sum of square	Degrees of freedom	Sum of mean square value	*F* value	Test value
Regression	SS_{reg}=80.4058	f_{reg}=14	V_{reg}=5.7433	$F_2=V_{reg}/V_r$ =2.3065	$F_{0.05}(14,21)$= 2.20
Remnant	SS_r=52.2892	f_r=21	V_r=2.4900		
Lack of fit	SS_l=21.2045	F_l=10	V_l=2.1205	$F_1=V_l/V_e$ =0.7504	$F_{0.05}(10,11)$= 2.85
Error	SS_e=31.0847	f_e=11	V_e=2.8259		
Total	SS_t=132.6950	F_t=35			

F inspection of the regression equation's coefficient was conducted (V_r=2.4900, f_r=21), and the significance levels were respectively defined as 0.01 and 0.1. According to the *F* test table, x_1, x_3, x_3 and x_2x_3 are obviously significant, and x_3x_4 is extremely significant. According to the results of significance test, the simplified regression equation can be obtained excluding insignificant items.

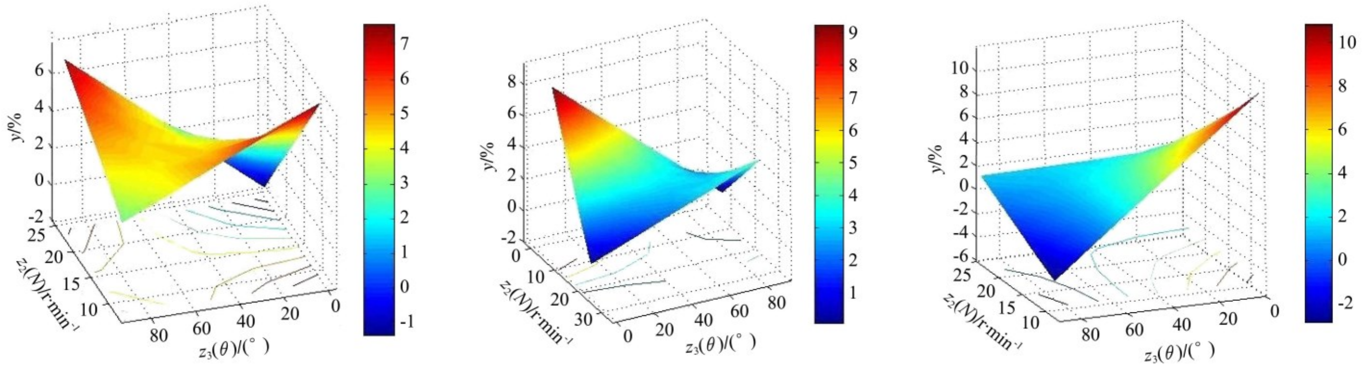
$$\begin{aligned}\hat{y} = 3.4522 + 0.6422x_1 - 0.599x_2 - 0.6479x_3 + \\ 0.8394x_2x_3 + 1.1288x_3x_4\end{aligned} \tag{1}$$

The regression coefficient of all variables x_i in regression equation are in dimensionless coding space, which eliminates the influence of original variable value and unit; therefore, the contribution of various factors to the regression equation can be displayed by comparing the absolute value of regression coefficient[16,17]. For further analysis on the above factors, the regression equation is treated with dimensionality reduction to explore the effects of two factors on the coefficient of seed discharging stability variation, and x_i will be changed into z_i, which has its unit.

2) Analysis of effects of two interactive factors

In the formula, the effects of two interactive factors, θ and α, N and θ, on seed discharging stability variation y, were explored with given values of the other two factors, and the results were shown in Figure 8.

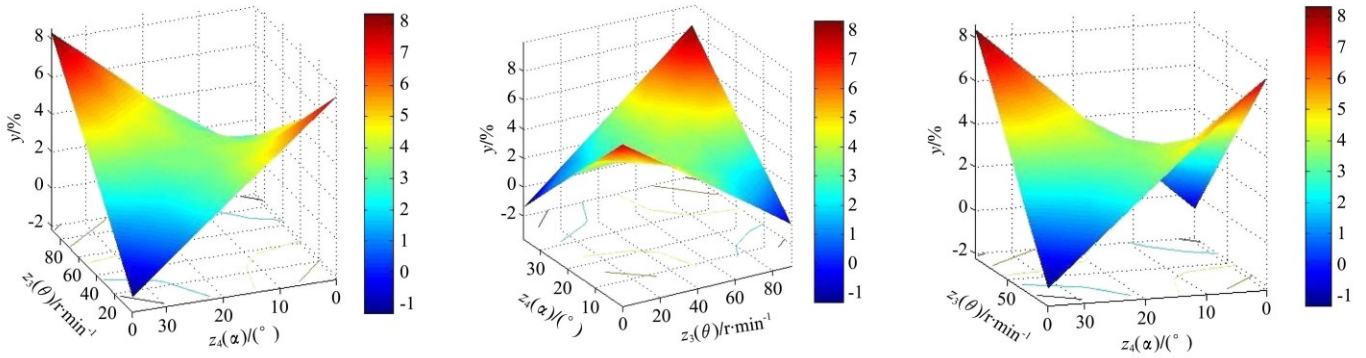
As indicated in Figure 8 and Figure 9, the effects of interactive factors, θ and α, N and θ, on seed discharging stability variation both show "saddle" trend[12,13], which proves that the simultaneous increase or decrease of the two factors can enhance the coefficient of seed discharging stability variation, while their opposite change will be followed by decrease of the coefficient of seed discharging stability variation.



a. z_1 and z_4 are the values at level 1 b. z_1 and z_4 are the values at level 0 c. z_1 and z_4 are the values at level -1

Note: z_2-rotation speed of comb shaft N; z_3-groove strip's inclining angle θ; y-variable coefficient values of combing teeth gap L (z_1) and seed metering device's inclining angle α (z_4) are specified.

Figure 8 Effects of two interactive factors z_2 and z_3 on y



a. z_1 and z_2 are the values at level 1 b. z_1 and z_2 are the values at level 0 c. z_1 and z_2 are the values at level -1

Note: z_3-groove strip's inclining angle θ; z_4-seed metering device's inclining angle α; y-variable coefficient values of combing teeth gap L (z_1) and rotation speed of comb shaft N (z_2) are specified.

Figure 9 Effects of two interactive factors z_4 and z_3 on y

When θ and α increase, fewer and fewer grooves enter the seed discharging area simultaneously, and the seed quantity reduces in individual groove because α increases, which enhances the "ripple" trend and variation coefficient. When both decreases, the amount of seed discharged increases, and the grooves discharging seeds superimpose, weakening the "ripple" trend and variation coefficient. When only α changes, "ripple" trend exists still since all the grooves contain the same amount of seeds. However, since θ and the amount of grooves discharging seeds simultaneously remain constant, so the "ripple amplitude and frequency" does not change, and they draw little influence on the seed discharging stability. Thus it is concluded that α is not the only one significant factor influencing the variation coefficient.

The interaction term of N and θ is significant factor, which shows the change of N can cause the change of combing tooth trajectory. Since the trajectory lies above the seed feeding mouth, closest to seed feeding mouth and grooved strip, the combing tooth ends' motion trajectory and θ jointly affect the seed discharging, and thereby affect the seed discharge stability.

4.3 Parameter optimization and test verification

The national standard[14,15] defines the performance index of coefficient of total seed discharging stability variation. The coefficient of gramineous forage grass seed discharging stability variation should be no more than 6%. According to this standard value, the acceptable range of coefficient of regression variation is 0-4%. All possible combinations in Table 1 are programmed via MATLAB, and 286 parameter combinations can meet the requirements of coefficient of seeding variation. In order to reduce the range of parameter values, several special ones are selected as actual parameters for the design and manufacturing of seed metering device. In fact, according to the change trend of interactive factors and regression equation (1), when the variable beyond the two interactive factors is constant, the relationship between the two interactive factors can be realized by function 2, with z_2 and z_3 as example.

$$z_3 = \frac{a_1 + a_2 z_2}{a_3 + a_4 z_2} \tag{2}$$

In order to determine a few variable combinations corresponding to performance index defined in national standards, it is only necessary to find some special ones. Then the formula (2) can experience coordinate transformation, with z_2 replaced by $z_2 - a_3/a_4$ to simplify the parameters, and it is found that z_2 and z_3 satisfy the inverse proportion of the following formula:

$$z_3 = \frac{a}{z_2} + b \tag{3}$$

When z_2 is given with the maximum and minimum values (24 r/min and 8 r/min), according to the inverse proportion relationship, the final results are $a = 1080$ and $b = -45$ when $z_3=0°$ and $z_3=90°$ respectively as minimum value and a maximum value. Similarly, the relation equation of interaction term of groove strip inclining angle z_3 and seed metering device inclining angle z_4 can be obtained. When they are substituted into formula 1, the variables z_2 and z_4 can be eliminated. To further narrow the scope, the regression value of variation coefficient was calculated with MATLAB ($z_1 \in [2,4]$, $z_3 \in [0,45°]$). When the results were acceptable, the values of $z_1 \sim z_4$ were recorded, and finally four groups of qualified parameter combinations were achieved. The regression values of variation coefficients were verified in tests according to the optimized value of each parameter, in the same manner as the above one. The variable values, the predicted value of regression equation of variation coefficient and the test results are shown in Table 4.

Table 4 Optimization results of variable coefficient *y*

	z_1 (L/mm)	z_2 (N/r·min^{-1})	z_3 (θ/(°))	z_4 (α/(°))	y/%	
					Regression value	Test value
1	2	16	22.5	25.66	1.8546	1.8185
2	4	16	22.5	25.66	2.4968	2.4171
3	2	12	45	18	2.7669	2.6977
4	4	12	45	18	3.4091	2.9080

As shown in Table 4, each of the four main factors retains 2 values. Based on any optimization result, the test value of variation coefficient will be no more than 4% of defined optimization value[18,19], the correlation coefficient of test value of four parameter combinations' variation coefficients and predicted values of regression equations is $\rho=0.726$, showing significant correlation and indicating good fits of the original regression model.

5 Conclusions

The results of test of regression coefficient display that L, N and θ are all significant factors, and the interaction terms of N and θ as well as θ and α are extremely significant factors. The variation coefficient responds to the interaction term of N and θ in the same manner as that does to the interaction term of θ and α, showing "saddle" tendency. This shows that in the two interaction effects, when the two factors change in opposite directions, namely one decreases and the other increases, the variation coefficient decreases, whereas, when the two interactive factors increase or decrease simultaneously, the variation coefficient increases.

In order to meet the national standards, it was assumed that the two interactive terms, (z_2 and z_3, z_3 and z_4) satisfied certain inverse proportion function based on regression equation, and its relation was calculated. The calculation results of variation coefficient show that the four groups of optimized parameter combinations can enable the coefficient of seed discharging stability variation to be no more than 4% in line with the design requirement, and the test values well agree with the predicted values of regression equation. Seed flow is regarded as complex granular particle motion. The coupling effect of seed packing and flexible teeth deformation will be investigated in further research.

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