Design and experimental research on disc-type seeding device for single-bud sugarcane seeds

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Abstract: Mechanized sugarcane seeding is one of the effective technical measures for improving seeding uniformity and operation efficiency. However, the imperfection of supporting equipment limits the promotion and application of this technology. As there are some problems in domestic sugarcane planting machines currently, such as large auxiliary labor, high labor intensity, low seeding uniformity, and large amount of seeds, a disc-type single-bud sugarcane seed metering device was innovatively designed on the basis of the analysis of physical properties of single-bud sugarcane seeds and the combination with agronomic requirements for field planting in this paper. Solidworks was used to simulate and analyze the mechanism, check the theoretical parameters, and process the test prototype. Through single-factor experiments, the effective factors affecting seeding uniformity were determined. A multi-factor orthogonal rotation test was designed, data were collected and then SPSS was used to get the optimal parameters for the seeding uniformity: the advancement speed of machine is 0.22 m/s, the number of disc seeding grooves is 10, the rotating disc speed is 0.18 r/s, and the seeding uniformity is 86.2%; the seeding uniformity was verified by field trial, and the results showed that the average seeding uniformity of the field verification was 83%, with the error 3.2% relative to the optimization result. The relative error is within 10%, indicating that the optimization result is reliable and meets the requirements of seeding uniformity, thus providing theoretical basis for the research and development of the disc-type single-bud seeding device.

Keywords: sugarcane, single-bud sugarcane seed, disc-type seeding device, seeding uniformity

DOI: 10.25165/j.ijabe.20231602.6973

Citation: Liu X P, Niu Z J, Li M, Hou M X, Wei L J, Zhang Y, et al. Design and experimental research on disc-type seeding device for single-bud sugarcane seeds. Int J Agric & Biol Eng, 2023; 16(2): 115–124.

1 Introduction

Sugarcane is one of the main economic crops in the southern region of China, of which the planting area ranks third in the world, after Brazil and India, and it accounts for more than 85% of sugar planting area in China. Its sugar yield accounts for more than 90% of total sugar[1]. At present, the main sugarcane growing countries in the world such as Australia, India, Brazil, Cuba, etc. have basically realized mechanized planting. The planting machines are mainly classified into whole-rod type, real-time cutting type and pre-cutting type[2]. In our country, there are usually some problems in mechanized planting, such as large auxiliary labor, high labor intensity, low seeding uniformity, and large amount of seeds, which directly limit the development and promotion of sugarcane mechanized planting technology. The seed metering device is the key unit of the sugarcane planter[3,4], which directly determines the working performance of the sugarcane planter. In order to solve the problems in the existing sugarcane planter such as stuck seeds and uneven seeding, the disc-type single-bud sugarcane metering device was innovatively designed in this paper and the single-bud sugarcane seeds with the advantages of less pests and diseases and high tillering rate were selected as the research objects[5,6].

The development of sugarcane planter abroad is in the stage of market application. Massey Ferguson of Australia has designed a two-stage conveyor belt planter[7], which has large capacity, high operation efficiency and is suitable for field operation. Moslem Namjoo, a researcher from Iran[8], used seed tray and chain to realize seed feeding and sowing, and developed chain plate seed metering device. Syngenta of Switzerland and Deere jointly developed a fully automatic mechanized planter of bucket spoon type for single-bud sugarcane seeds in 2012. Such planters have complex structure and large size, which are suitable for field operation. Most sugarcane fields in China are small and medium-sized plots, and the agronomic requirements such as planting row spacing and plant spacing are quite different from those abroad, so the planters cannot be directly introduced and applied; domestic general economic 2CZ-2 semi-automatic full-cut sugarcane planter is characterized by heavy demand for auxiliary labor, uneven sowing, unstable operation quality and low operation efficiency; Cao et al.[9] improved the 2CZQ-2 full-cut sugarcane planter by changing vertical feeding to horizontal feeding in 2016, thus reducing auxiliary labor; Xu et al.[10] developed the finger-clip double bud pre-cutting sugarcane planter in 2016, innovatively proposing the orderly arrangement of sugarcane seeds in the seed box in terms of

Received date: 2021-08-05 **Accepted date:** 2023-02-20

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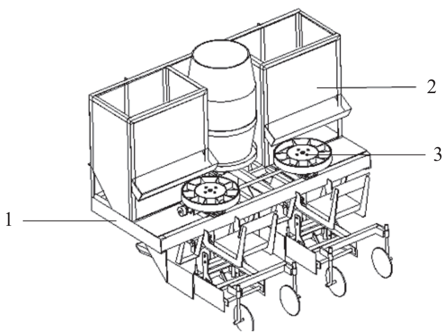
sugarcane mechanized planting technology. Z906 lifting pre-cutting automatic sugarcane planter developed by Guangxi Liugong Machinery Co., Ltd. in recent years has large seed storage and high operation efficiency, but it needs to be improved in terms of production cost, seed leakage rate and seed metering uniformity. In conclusion, due to these disadvantages, sugarcane farmers have low willingness to use planting machinery. Therefore, according to the planting requirements of main sugarcane producing areas in China, the sowing device of disc single-bud sugarcane planter was designed in this study.

2 Integral structure of disc-type single-bud sugarcane metering device

The disc-type single-bud sugarcane metering device[11] is composed of seeding box, rotating disc, hydraulic motor, frame, etc., as shown in Figure 1. The sugarcane seeds in the seed box are conveyed through the filling groove on the rotating disc to the seeding port evenly, thus completing orderly work, avoiding uneven seeding.



1.Main frame 2. Sugarcane seed box 3. Rotating disc

Figure 1 Integral structure diagram of disc-type single-bud sugarcane metering device

2.1 Introduction of working principle

When the disc-type single-bud sugarcane metering device is working, the tractor outputs the pressure oil of the hydraulic pump and drives the hydraulic motor to rotate through the throttle valve, which in turn drives the rotating disc to transport the cane seeds in the sugarcane seed box, and then the seeds are transported to metering port to conduct seed-metering operations; in actual operations, according to the softness and flatness of the soil, the speed control lever of the tractor, the hydraulic output control lever and the hydraulic throttle valve of the planter should be adjusted in real time, so as to make the moving speed of tractor and hydraulic oil flow rate meet the requirements of the land planting environment, as shown in Figure 2; when seeds are stuck in the seed box or uneven seed filling occurs in rotating disc filling tank, the sugarcane seeds can be manually placed once more, to achieve uniform seeding.

Figure 2 Speed regulating and hydraulic regulating

2.2 Physical properties of single-bud sugarcane seeds

Due to different growth environment of sugarcane and uneven nutrient absorption, the diameter and geometric shape of individual sugarcane buds in the single-bud segment vary to great extent, which easily affects the parameter design of the single-bud sugarcane seed metering device, resulting in poor adaptability of the seed device, so the seeding requirements cannot be met. Thus it is necessary to analyze the geometric characteristics of single-bud sugarcane seeds. The physical characteristics of sugarcane seeds should be considered in particular for the design of seed metering device.

In this paper, the single-bud sugarcane seeds Yue Tang 93-159 was selected, and the length and diameter were measured and analyzed. Before the test, the sugarcane seeds were selected manually to ensure that the single-bud segment of the sugarcane seeds was healthy and free of damage, and 200 segments were randomly selected. Then, the length and diameter of the randomly selected 200 segments of single-bud segment of sugarcane seeds were measured by electronic digital vernier calipers, and the measured data were analyzed. When the variation coefficient was greater than 4, it was necessary to randomly select 200 segments of sugarcane seeds for repeated measurement, and the standard deviation calculation and analysis of the 400 segments of sugarcane seeds were carried out; the measurement and analysis were repeated until the variation coefficient was less than 4, and the accurate characteristic parameters of the single-bud segment of sugarcane seeds were obtained, so the average length was 57.70 mm and the average diameter was 28.85 mm; the results are listed in Table 1.

Table 1 Feature size analysis results of Yue Tang 93-159 single-bud segment sugarcane

Items	Length/mm	Diameter/mm
Max	83.23	41.13
Min	48.83	15.63
Average value	57.70	28.85
Standard deviation	0.75	0.46
Coefficient of variation	1.31	0.82

The 100-grain weight refers to the weight obtained by weighing 100 single-bud segment cane seeds in grams. It is an important indicator to show the size and fullness of sugarcane seeds in a single-bud segment, and an important reference for the structural design of the seed-metering device. The sugarcane seeds Yue Tang 93-159 were selected as the test varieties, and 100 intact single-bud segment sugarcane seeds with diameters of 35-45 mm and lengths of 50-60 mm were randomly selected as a group, and then 10 groups were continuously selected. The 100-grain weight of single-bud segment of sugarcane seeds was measured by a De Ante balance with a range of 5000 g and the accuracy of 0.01 g. The average value $\bar{X}$ of the 100-grain weight of sugarcane seeds was calculated by collecting data, and the standard deviation and the coefficient of variation were calculated by Equations (1) and (2). After analysis, when the variation coefficient is less than 4, accurate measurement results can be obtained; when the variation coefficient is greater than 4, it does not meet the requirements and needs second measurement and analysis. The final results are listed in Table 2, and the average 100-grain weight is 2881.46 g.

Table 2 Calculation results of 100-grain weight of single-bud sugarcane seed

Group	100-grain weight X/g	Average value $\bar{X}$/g	Standard deviation S/g	Variation coefficient C
1	2945.33	2881.46	163.92	0.06
2	2623.32			
3	2819.41			
4	2639.74			
5	2947.35			
6	3161.17			
7	2826.18			
8	3161.52			
9	2863.13			
10	2827.45			

$$S = \sqrt{\frac{n\left(\sum X^2\right) - \left(\sum X\right)^2}{n(n-1)}} \tag{1}$$

$$C = S/\bar{X} \tag{2}$$

where, S denotes standard deviation, g; X denotes the 100-grain weight of each group, g; N denotes the measuring times; C denotes the variation coefficient; $\bar{X}$ denotes the average value of the 100-grain weight, g.

2.3 Rationality inspection of design and assembly of key components

2.3.1 Rotating disc seeding device

The rotating seeding disc is mainly composed of a rotating disc, a mounting plate for worm gear reducer, a worm gear reducer, a turntable circle plate, a turntable ring, a seeding groove, a turntable flange, a coupling, etc., as shown in Figure 3. The rotating seeding disc and the worm gear reducer are connected together and fixed obliquely below the sugarcane seed box.

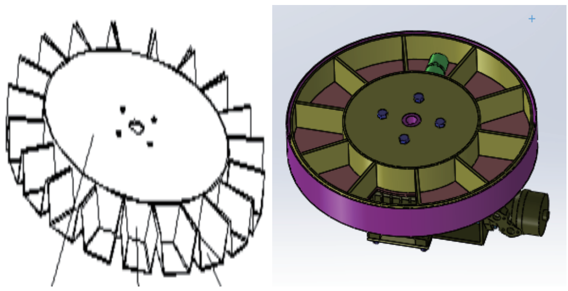


Figure 3 Structural diagram of key components of rotary disc metering device

As the maximum length of the sugarcane seed in a single-bud segment is 83.23 mm, the radius of the inner circle of the seed-metering disc drive is supposed to be 100 mm. Combined with the geometric characteristics such as the average length of the sugarcane seed of 55.70 mm and the average diameter of 28.85 mm, the relationship between the single-bud sugarcane seed and the row is determined. The relationship between the diameters of the discs:

$$N = \frac{360^\circ}{\theta} \tag{3}$$

$$R = \frac{L}{\sin\frac{180^\circ}{N}} \tag{4}$$

$$\theta = \frac{\pi R}{180^\circ} \tag{5}$$

$$l_{\text{inner}} = 2\pi r \tag{6}$$

$$N_1 = \frac{l_{\text{inner}}}{L} \tag{7}$$

where, N denotes the number of segments; θ denotes the angle between the upper and lower arc edges of the disc filling groove and the line connecting the center of the circle, (°); R denotes the diameter of outer circle of disc, mm; L denotes the length of sugarcane seed, mm; l_{inner} denotes the length of inner circle, mm; N_1 denotes the number of the filling groove.

By calculating, the outer diameter of the disc was determined as 366.46 mm; the number of the filling grooves was 7.5 to 12.8, finally the outer diameter was 400 mm, and the number of filling grooves was from 7 to 13. The loading weight of the container was set from 500 to 600 kg, the planting width of the machine was 2.2 m, the working time was 3 h (considering the factors such as tractor start and stop, turning, mechanical lift, and proficiency of handlers and workers); besides the geometric characteristics of the single-bud sugarcane seeds, the agronomic requirements for sugarcane were also considered, so as to obtain the line spacing, 1.2-1.4 m; 5 to 8 seeds were planted per meter, and the space between seeds was 75 mm to 225 mm. The operating area of the seeding device was calculated, and the steps are shown as follows.

$$x = \frac{I}{J} \tag{8}$$

$$q = \frac{M}{\bar{X}} \tag{9}$$

$$K = q \times X \tag{10}$$

$$s = k \times l \tag{11}$$

$$M = \frac{s}{10\,000} \tag{12}$$

where, $\bar{X}$ denotes the average value of 100-grain weight, kg; M denotes the loading weight of the container, kg; J denotes the number of sugarcane seed per meter; I denotes the number of segments, 100; X denotes the planting space of 100 segments of sugarcane seeds, m; l denotes the line spacing of sugarcane seeds, m; q denotes the cumulative number of 100-grain weight when the container is in full load; K denotes the straight line distance when the container is in full load, m; M denotes the operating area when the container is in full load, hm^2.

By calculating, the operating area was determined between 0.5-1.0 hm^2, and the movement speed was between 0.1-0.42 m/s.

On the basis of the calculation of the number of filling grooves of the disc and the moving speed of the machine, the rotating speed calculation formula was applied and then the speed was obtained as between 0.1-0.3 r/s.

$$\omega = \frac{2\pi n}{60} \tag{13}$$

$$v = \omega r_1 \tag{14}$$

where, r_1 denotes the inner circle radius of the disc, mm; ω is the angular velocity, rad/s; v is the angular velocity, m/s; n is the angular velocity, r/s;

2.3.2 Analysis of seed guide groove design

Driven by the impeller in the filling groove of the rotating disc, the sugarcane seeds made a circular motion with their own motion and relative motion, transporting the sugarcane seeds to the seeding port of the disc, and falling to the seed guide groove under the action of the movement inertia and its own gravity, which evenly rolled down into the planting ditch. In order to avoid the influence of generated amplitude on the seeding uniformity when the machine moves forward, combined with the basic agronomic requirements of sugarcane seed, the movement state of the sugarcane seeds on the seed guide groove was analyzed by a cylindrical coordinate system and a mechanical model was established, as shown in Figure 4, with reference to the design and mechanism analysis of the sugarcane trough wheel seed metering device by Li et al.[12] and the research on the seeding method of horizontal disc seed planter[13,14].

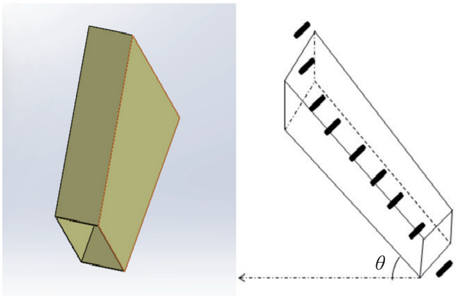


Figure 4 Seed guide groove

The structural parameters of the seed guide groove are of great significance to the quality of sugarcane seeding. And it is mainly composed of the seed guide plate at bottom and the left and right guard plates welded together, which is fixed according to a certain proportion of inclination angle and installed under the seeding opening, relying on the frame of the planting machine and the two pieces of scraper plates of the ditching plow. In order to avoid the direct contact between the sugarcane seeds and the seed guide groove as well as the consequent injury to seeds, the rubber block is installed on the seed guide plate at bottom, and the rubber surface friction coefficient μ is 0.8. The force analysis of the single-bud sugarcane seed in the seed guide groove was conducted, as shown in Figure 5, and then the following relationship between the sliding motion speed of a single-bud sugarcane seed and the inclination angle of the seed guide groove can be obtained as:

$$F_x = \left(m\alpha - F_f\right) + F_\alpha \cos(90^\circ - \theta) \tag{15}$$

$$F_y = mg + \left(m\alpha - F_f\right)\sin\theta - F_\alpha \sin(90^\circ - \theta) \tag{16}$$

$$F_f = mg\sin\theta = \mu mg\cos\theta \tag{17}$$

where, α is the sliding downward acceleration of single-bud segment sugarcane seed, m/s^2; F is the bearing reaction of single-bud sugarcane seed, n/m; F_f is the friction of single-bud sugarcane seed, n/m; θ is the inclination angle of seed guide groove, (°).

From Equations (15)-(17), it can be seen that the minimum inclination angle of the inclined surface of the seed guide $\theta = \arctan\mu = \arctan 0.8 = 38.65^\circ$. In the design, the seed guide groove is put inclined to the seed guide plate at bottom, with the angle $\theta = 40^\circ$. The greater the inclination angle of the seed guide groove, the greater the acceleration component of the single-bud sugarcane seed in the x-axis direction, and the smaller the acceleration component in the y-axis direction, which makes the sum of the friction force of the sugarcane seed in the y-axis direction and the support reaction force is less than that of the gravity and acceleration components of the sugarcane seeds. The greater the downward force of the single-bud sugarcane seeds along the seed guide groove, the greater the acceleration, the higher the movement speed; when the inclination angle is smaller, the force on the sugarcane seeds is just right contrary to the larger inclination angle, so the movement speed of the sugarcane seeds is relatively reduced, resulting in the inconsistency of the seeding speed and the machine advancement speed, reducing the uniformity of the single-bud sugarcane seeding and failing to meet the seeding requirements.

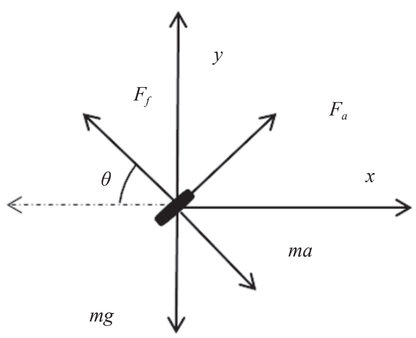


Figure 5 Stress analysis of sugarcane seed in seed guide groove

2.3.3 Motion interference detection of seeding mechanism

The motion simulation function in SolidWorks software was used to simulate the motion state of the device during operation, and motion constraint conditions were added to detect the interference of each component, to see whether there are interference problems between the components of the seeding device, and check the rationality of the design between the components. During the process of interference detection, it was found that there was a fit deviation between the keyway of the worm gear reducer connected with the flat key and the keyway of the rotating disc, which made the disc seeding device unable to perform three-dimensional simulation movement, as shown in Figure 6. The data of the flat-head flat key, output shaft keyway, and disc keyway in the disc seeding device were optimized and adjusted, to conduct second motion simulation till the problem was solved and the verification was completed.

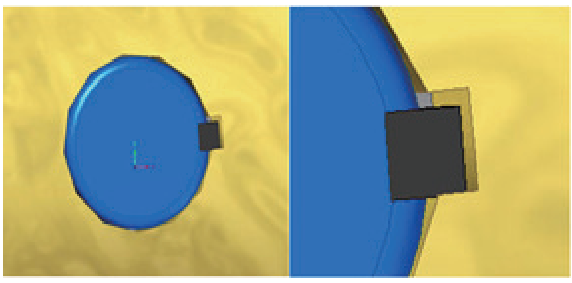


Figure 6 Partial drawing of fit deviation

2.3.4 Mechanical analysis of power output shaft of turbine reducer

The power output shaft of turbine reducer is the key component of the disc-seeding device, of which the power transmission is realized mainly by the connection of the flat-head flat key with the rotating disc of the seeding device, so as to drive the rotating disc to rotate. Then the sugarcane seeds are transported to the disc seeding port, fall into the inclined seed guide groove, and roll down into the planting trench under the interaction of inertial force and gravity. According to the structural size, quality, input power, and rotation speed of the rotating disc, the strength check and static analysis on the contact between the worm gear keyway output shaft and the keyway of the rotating disc connected with the flat-head flat key are carried out. As shown in Figure 7, the worm gear shaft and the rotating disc squeeze the flat-head flat key. In order to prevent crushing and shearing, the flat-head flat key is verified for strength.

$$\sigma_\rho = \frac{2000T}{Kld} = \frac{4000T}{hld} \leq [\sigma_\rho] \tag{18}$$

$$T = Fy \approx F\frac{d}{2} \tag{19}$$

$$K = 0.5h \tag{20}$$

$$l = L \tag{21}$$

where, T is the transmitted torque, N·m; K is the contact height of the tooth surface between the flat key and the keyway of the worm gear shaft, mm; h is the height of the flat key with flat head, mm; l is the working length of the flat key, mm; d is the diameter of the worm gear shaft, mm; L is the nominal length of flat key, mm; b is the width of flat key with flat head, mm; $[\sigma_\rho]$ is the weakest allowable extrusion stress of the rotating disc profile, flat key, and worm gear shaft material, MPa.

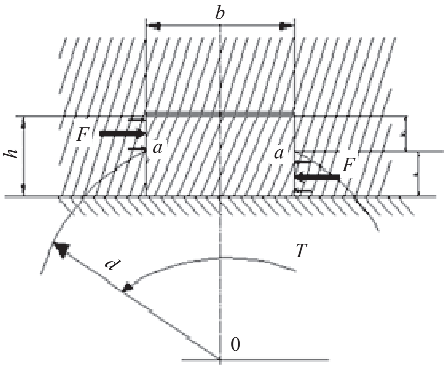


Figure 7 Stress analysis of flat key connection

The strength of the flat-head flat key can be obtained as 34.01 MPa, which is less than the allowable extrusion stress $[\sigma_\rho]$(120-150 MPa), and then the equivalent cloud diagram of stress and strain is obtained. As shown in Figure 8, the stress is mainly concentrated on the side and the maximum stress is 21.22 MPa, less than the allowable stress 120 MPa. The maximum deformation position is at the bottom end of the flat key, the maximum deformation displacement is 0.0032 mm, the amount of deformation is small, and its strength is within the allowable range of working conditions, thus meeting the requirements of the operation.

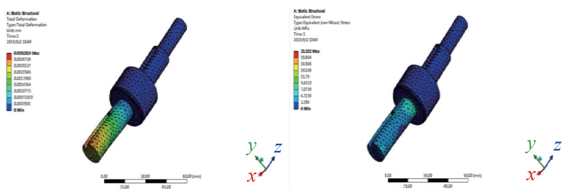


Figure 8 Equivalent cloud chart of flat-head flat key under torsion condition

Since the contact between the keyway of the worm gear output shaft and the flat key is the key mechanism component under force, the strength of the 45# keyway needs to be verified:

$$\tau_T = \frac{T}{W_T} \approx \frac{9\,550\,000\dfrac{P}{n}}{0.2d^3} \leq [\tau_T] \tag{22}$$

where, τ_T is the torsion shear stress of worm gear shaft, MPa; T is the torque of the worm gear shaft, N·mm; W_T is the torsion section coefficient of worm gear shaft, mm^3; n is the rotational speed, r/min; P is the transfer power, kW; d is the calculated diameter at the end of the keyway of the worm gear shaft, mm; $[\tau_T]$ is the allowable torsion shear stress, MPa;

The strength of the worm gear shaft is 34.8 MPa, within the range of the allowable torsional shear stress (25-45 MPa). In order to prevent crushing and fracture, 40Gr is selected again. After strength calculation, the torsional strength of the worm gear shaft is 20.32 MPa, less than the allowable torsion shear stress (35-55 MPa), and then the equivalent cloud diagram of stress and strain is obtained, as shown in Figure 9. It can be seen from the diagram that the stress is mainly concentrated on the side of the flat key, and the maximum stress is 21.22 MPa, less than the allowable stress 25 MPa. The maximum deformation position is at the bottom end of the flat key, the maximum deformation displacement is 0.0032 mm, the amount of deformation is small, and its strength is within the allowable range of working conditions, thus meeting the requirements of working performance.

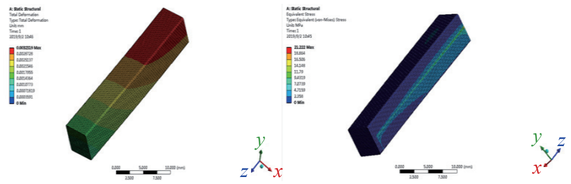


Figure 9 Equivalent cloud chart of turbine output shaft under torsional condition

3 Optimization of working parameters Introduction

3.1 Test Condition

The Key Laboratory of Tropical Agricultural Equipment of Chinese Academy of Tropical Agricultural Sciences can provide the conditions for the single-factor soil bin test. A sugarcane field with the size of 330 m×190 m is selected as multifactor test site, located in the sugarcane base of the South Asian Institute of the Chinese Academy of Thermal Sciences, Zhanjiang City, Guangdong. The tested variety is Yuetang 93-159. The sugarcane field has been well prepared before the test.

The ditching depth in the test is 230-3000 mm, and a 100 m round trip operation is conducted in each test.

3.2 Performance Indicators

According to the research on the basis of related seeding, it is confirmed that the seeding uniformity is an important reference indicator for testing the performance of the seeding device[15,16]. Therefore, the seeding uniformity of single-bud cane seeds is selected[17,18] as the test indicator in the test. Based on the relevant planting and agronomic requirements of single-bud sugarcane seeds, it is ensured that the single-bud sugarcane seeds are arranged 5-8/m, and the distance between the seeds of the sugarcane seeds is 120-160 mm, which is the best seeding range. According to the related regulations in GB/T6973-2005 "Single Seed (Precision) Planter Test Method", when the half of the theoretical seed spacing is greater than the actual one, it is specified as reseeding; when the 1.5 times of theoretical seed spacing is less than the actual one, it is specified as missed seeding, namely, the seed spacing of single-bud sugarcane seeds within the range of 75-225 mm is the qualified seed spacing, and then the qualified indicator of the corresponding single-bud sugarcane seed spacing is:

$$y = \frac{n}{N}100\% \tag{23}$$

where, y is the seeding uniformity; n is the qualified sample size; N is the theoretical sample size.

According to the relevant regulations of JB/T 10293-2013 "Technical Conditions of Single Seed (Precision) Planter", the performance indicator of single seeding operation is obtained, as listed in Table 3.

Table 3 Performance indicators of single seed sowing operation

Items	Seed spacing x/cm		
	≤10	>10-20	>20-30
Qualified indicator for seed spacing	≥60	≥75	≥80
Variation coefficient of qualified seed spacing	≤40	≤35	≤30

3.3 Single-factor test

The single-bud segment disc type sugarcane seed metering device is taken as the research object; according to the previous design and analysis, the rotating disc rotation speed X_1, the number of disc seed filling grooves X_2, and the moving speed of the machine X_3 are the influencing factors of the test; the seeding uniformity Y is the test indicator. The test bench is processed, which is driven by the soil tanker. As shown in Figure 10, the speed range is 0-12 m/s, and the adjustment accuracy is 0.1 m/s. During the test, other factors remained unchanged, so as to guarantee the control of the single-factor change.

Figure 10 Soil tank test vehicle

Before the test, the test bench of the single-bud segment rotating disc seed metering device was fixed on the soil tank test vehicle, the single-bud segment sugarcane seeds were filled into the cane seed box, whether the hydraulic system has oil leakage or blockage problems should be checked, and the output hydraulic oil flow was adjusted in combination with the forward speed. In order to avoid uneven seeding pitch and large vibration fluctuations of the seeding device due to too large speed fluctuations during the acceleration and deceleration phases when the machine was moving forward and stopping, the test samples should be collected from the moving period excluding the starting 20 m and stopping 20 m, as shown in Figure 11. In order to reduce the test error and the impact on the seeding performance, each group of tests were repeated 3 times. When collecting samples, a tape measure was used to measure the grain distance between two adjacent segments of sugarcane seeds. If the distance between two segments of sugarcane seeds is less than 75 mm, the test sample is regarded as a reseeding sample; if the grain distance is between 75 mm and 225 mm, the test sample is regarded as a qualified sample; if the distance between two sugarcane seeds is greater than 225 mm, the test sample is regarded as a missed seeding sample, and the data of qualified test samples were recorded.

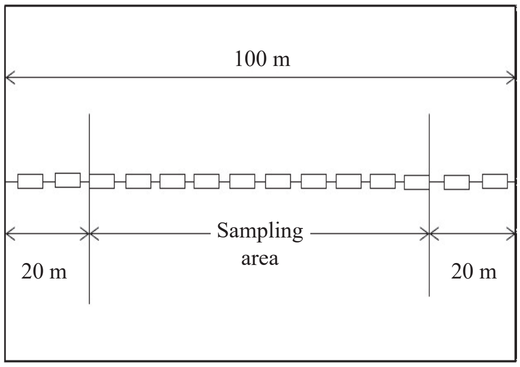


Figure 11 Sampling diagram

3.3.1 Rotating speed of disc

The forward speed of the machine was adjusted to 0.36 km/h, and the number of seeding grooves of the disc was 10/device. The test was carried out to obtain the relationship curve between the rotating disc speed and the seeding uniformity[20], as shown in Figure 12.

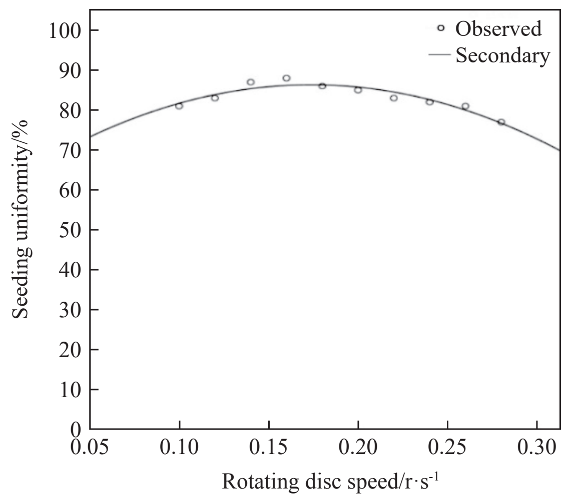


Figure 12 Relation of rotating disc speed and seeding uniformity

SPSS software was adopted to perform regression statistical analysis on the test results; the mathematical model of the rotating disc speed and the seeding uniformity was obtained as follows:

$$Y = -852.273X_1^2 + 296.288X_1 + 60.585 \tag{24}$$

The significance test of the regression mathematical model of the rotating disc speed and the seeding uniformity shows that F_1=0.001<0.05, R_1^2=0.881, which means that the rotating disc speed has a very significant effect on seeding uniformity, and the fitting of regression mathematical model is favorable.

3.3.2 The number of disc seeding grooves

The forward speed of the machine was adjusted to 0.36 km/h, and the disc rotating speed was 0.1 r/s. The test was carried out to obtain the relationship curve between the number of disc seeding grooves and the seeding uniformity[21], as shown in Figure 13.

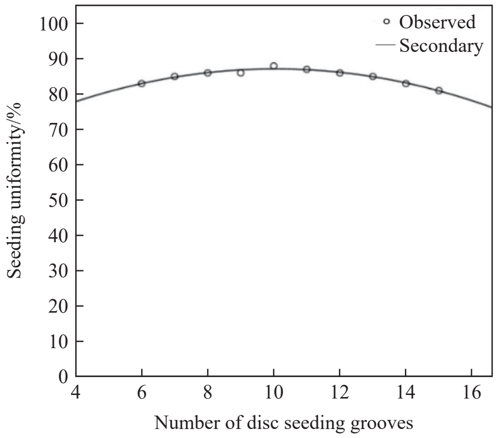


Figure 13 Relation curve of the number of disc seeding grooves and seeding uniformity

SPSS software was adopted to perform regression statistical analysis on the test results; the mathematical model of the number of disc seeding grooves and the seeding uniformity was obtained as follows:

$$Y = -2.54X_2^2+5.099X_2+61.532 \quad (25)$$

The significance test of the regression mathematical model of the number of disc seeding grooves and the seeding uniformity showed that the number of disc seeding grooves has a very significant effect on seeding uniformity, and the fitting of regression mathematical model is favorable (F_2=0.00<0.05, R_2^2=0.96).

3.3.3 Forward speed of the device

The disc rotating speed was adjusted to 0.1 r/s, and the number of seeding grooves of the disc was 10/device. The test was carried out to obtain the relationship curve between the number of disc seeding grooves and seeding uniformity[22], as shown in Figure 14.

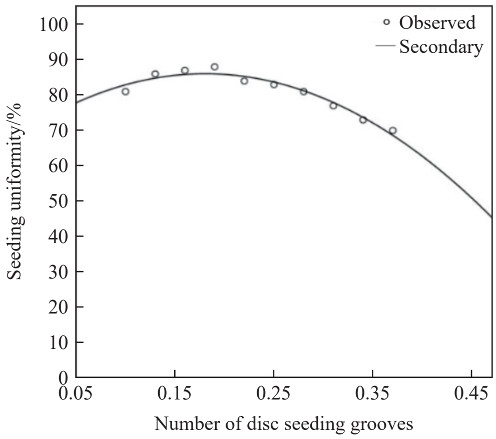


Figure 14 Relation of forward speed and seeding uniformity

SPSS software was adopted to perform regression statistical analysis on the test results, and the mathematical model of forward speed and the seeding uniformity was established as follows:

$$Y = -484.007X_3^2+174.554X_3+70.303 \quad (26)$$

The significance test of the regression mathematical model of the forward speed and the seeding uniformity shows that F_3= 0.000<0.05, R_3^2=0.951, which means that the forward speed has a very significant effect on seeding uniformity, and the fitting of regression mathematical model is favorable.

3.3.4 Results analysis of single-factor test

According to the analysis of single-factor test above, the regression mathematical model of each influencing factor was established in the seeding process of the single-bud sugarcane seed disc type seeding device, and three influencing factors were determined as effective ones. For specific values[23,24]: the speed of the rotating disc was 0.14-0.22 r/s, the number of disc seeding grooves was 8-12/device, and the forward speed of the device was 0.16-0.28 km/h. A test factor level coding table was established, as listed in Table 4.

Table 4 Test factor level coding table

Level	X_1/m·s^{-1}	X_2 (pieces per device)	X_3/r·s^{-1}
Upper asterisk arm (1.682)	0.28	12	0.22
Upper level (1)	0.26(0.255)	11(11.184)	0.2(0.203)
Zero level (0)	0.22	10	0.18
Lower level (–1)	0.19(0.18)	9(8.811)	0.16(0.156)
Lower star arm (–1.682)	0.16	8	0.14
Change interval Δ	0.035	1.189	0.023

3.4 Multi-facto quadratic regression orthogonal rotation test

Prototypes were processed and multi-factor experiment in field was designed. Compared with other experiments, the regression orthogonal rotation test has the advantages of less test times, easy calculation, and reduced coefficient correlation. According to the analysis results of the single-factor test, a total of 23 groups were needed after looking up the table for 3 factors and 5 levels. Test data were collected, the influence of various factors on the target value was analyzed, to establish the functional relationship between the factors and the target value, and solve the optimal structural parameters of the seed metering device [25].

3.4.1 Test results and analysis

Based on the designed quadratic regression orthogonal rotation test scheme, the code value of each influencing test factor is used as the independent variable, and the experimental results with the seeding uniformity as the test indicator are listed in Table 5.

Table 5 Test results

No.	Test factors			Test indicator
	X_1/m·s^{-1}	X_2 (pieces per device)	X_3/r·s^{-1}	y/%
1	0.26	11	0.20	81.3
2	0.26	11	0.16	84.3
3	0.26	9	0.20	83.5
4	0.26	9	0.16	85.3
5	0.19	11	0.20	83.3
6	0.19	11	0.16	86.2
7	0.19	9	0.20	85.3
8	0.19	9	0.16	87.6
9	0.28	10	0.18	86.6
10	0.16	10	0.18	88.1
11	0.22	12	0.18	86.3
12	0.22	8	0.18	86.2
13	0.22	10	0.22	83.2
14	0.22	10	0.14	83.6
15	0.22	10	0.18	87.3
16	0.22	10	0.18	86.1
17	0.22	10	0.18	86.6
18	0.22	10	0.18	86.3
19	0.22	10	0.18	85.3
20	0.22	10	0.18	86.2
21	0.22	10	0.18	86.6
22	0.22	10	0.18	85.5
23	0.22	10	0.18	86.1

SPSS software is used to perform secondary regression statistical analysis for the test results in Table 5, to obtain test factors such as forward speed, the number of disc seeding grooves, rotating disc speed and other test factors as well as test indicators—the mathematical regression model of seeding uniformity is:

$$y = 85.5-0.825Z_1-0.48Z_2-0.837Z_3+0.025Z_1Z_2+0.04Z_1Z_3-0.225Z_2Z_3+0.192Z_1^2-0.413Z_2^2-1.21Z_3^2 \quad (27)$$

Through the F and t tests of the regression equation, the significance test of the regression mathematical model and regression coefficient is obtained. The significance test results of the regression equation based on the analysis of variance are listed in Table 6.

Table 6 Results of variance analysis

Variance source	Degree of freedom	Sum of squares	Mean square	F value	Significance
Regression	9	47.72	5.302	F_1=6.43	**
Lack of	13	10.73	0.825		
fit	5	7.87	1.574	F_2=4.40	*
Error	8	2.86	0.3575		
Total	22	58.45			

Note: $F_{0.05}(9, 13)$, $F_{0.01}(1, 13)$, $F_{0.01}(9, 13)$, "**" "*" indicate extremely significant and significant levels, respectively.

As shown in Table 6, F_1=6.43>$F_{0.01}$(9, 13)=4.19, indicating that the regression equation of the seeding uniformity is extremely significant when a=0.01. F_2=4.4>$F_{0.05}$(5,8)=6.63 suggests the regression equation is out of fit, but the equation fits well at the center of test.

In order to test the regression coefficients in the regression equation, the impact of the first and the second interactive terms of each factor on the significance of seeding uniformity was tested. By using SPSS software, the significance of each coefficient in regression is measured through the F and t test, when a=0.01, as listed in Table 7.

Table 7 Significance test results

Regression coefficient	Degree of freedom	Sum of squares	Mean square	F value	Significance
Z_1	1	8.680	8.680	10.521	**
Z_2	1	2.940	2.940	3.563	*
Z_3	1	8.940	8.940	10.836	**
Z_1Z_2	1	0.005	0.005	0.006	
Z_1Z_3	1	0.013	0.013	0.016	
Z_2Z_3	1	0.405	0.405	0.491	
Z_1^2	1	0.583	0.583	0.706	
Z_2^2	1	2.709	2.709	3.283	*
Z_3^2	1	23.444	23.444	28.416	**

Note: $F_{0.05}(9, 13)$, $F_{0.01}(1, 13)$, $F_{0.01}(9, 13)$, "*" indicates significant and "**" indicates extremely significant.

From the test results of the significant factors in Table 7, it can be seen that within the selection range of each influencing factor, the primary and secondary order of each factor affecting the seeding uniformity is: forward speed, disc speed, and number of disc seeding grooves. In the primary term of the regression model, the number of Z_2 disc seeding grooves has a significant effect on the seeding uniformity, and the forward speed Z_1 and the disc speed Z_3 have a significant impact on the seeding uniformity; in the quadratic term, Z_2^2 disc seeding grooves has a significant effect on the uniformity of seeding and metering. The forward speed Z_1^2 and the disc speed Z_3^2 have a significant impact on the seeding uniformity; during the interaction, both Z_1Z_2 and Z_2Z_3 have a significant effect on seeding uniformity, and the influence by Z_1Z_3 on seeding uniformity is not significant. Eliminating the insignificant items, the simplified regression equation is

$$y= 85.5-0.825_1-0.48_2-0.837_3-0.413_2^2-1.21_3^2 \quad (28)$$

The coding equations Z_1=(X_1–0.22)/0.04, Z_2=(X_2–10)/2 and Z_3=(X_3–0.18)/0.04 are substituted into the regression equation of (28), and the final regression is obtained by further simplifying the regression equation:

$$y= 61.3765-20.625X_1+1.825X_2+251.325_3-0.10325_2^2-756.25_3^2 \quad (29)$$

3.4.2 Solving for the optimal value

In order to further improve the seeding uniformity of the single-bud segment disc seeding device, combining the single-bud segment sugarcane planting agronomic requirements, with the seeding uniformity as the optimization goal, the SPSS data analysis software was used to optimize the mathematical model parameters of regression Equation (29), and the objective function was obtained as:

$$y= 61.3765-20.625X_1+1.825X_2+251.325_3-0.10325_2^2-756.25_3^2 \quad (30)$$

The planning constraints are:

$$\text{s.t}\begin{cases} 0.16 \le X_1 \le 0.28 \\ 6 \le X_2 \le 12 \\ 0.16 \le X_3 \le 0.28 \end{cases} \quad (31)$$

The final result of the optimization solution: the forward speed is 0.22 m/s, the number of disc seeding grooves is 10/device, the disc rotating speed is 0.18 r/s, and the seeding uniformity is 86.2%.

3.5 Verification of the test

The prototype of seed metering device of the was adjusted to meet the optimal parameters, and multiple sets of field experiments were conducted, as shown in Figure 15, to check the fit with the optimization analysis results above[26-28]. The Nokia mobile phone with GPS speed measurement software installed was used, to take real-time measurement and collection of the traveling speed of the tractor during the test. The test is carried out according to the designed test plan in the test site with a length of 100 m. The mobile phone speed measurement software collects data from the real-time forward speed and adjusts the speed control lever, direction control lever and accelerator pedal in the tractor cab to make the travel speed of the tractor meet the predetermined requirements. In order to reduce the influence of the tractor on the seeding performance of the seed metering device during the acceleration and deceleration phases, data collection was carried out after the test tractor had advanced 20 m from the test point, and the data collection was stopped 20 m to the end.

Figure 15 Seed-metering effect of field trials

The seeding uniformity and the injury rate were selected as the test indicators, and the test was conducted under the optimal combination of seeding uniformity parameters, and the results are listed in Table 8.

Table 8 Field verification test scheme and results

No.	Test factors			Test indicators			
	X_1/ m·s^{-1}	X_2 (pieces per device)	X_3/ r·s^{-1}	Seeding uniformity	Mean value/%	Injury rate/%	Mean value /%
1				83.0		0	
2				83.5		0	
3	0.22	10	0.18	82.0	83	0	0
4				83.0		0	
5				83.5		0	

According to the relevant regulations in JB/T 10293-2013 “Technical Conditions of Single Seed (Precision) Planter”, the average seeding uniformity is 83%. Compared with the theoretical optimization result, the relative error is 3.2%, within the range of 10%, which indicates the optimization result is reliable. The average value of the injury rate is 0, indicating the seed metering device does not damage the seed during the seeding process, and meets the operational requirements of single-bud sugarcane seed metering performance.

4 Conclusions

According to the demonstration of the three-dimensional prototype model of the single-bud segment disc seeding device, the processing of the prototype is completed in the processing center. The following conclusions are derived through tests and analysis:

(1) By single-factor test, the effective factors influencing seeding uniformity are determined, and the factor level diagram can be made.

(2) On the basis of the single-factor test, a multi-factor quadratic regression orthogonal rotation test is conducted, SPSS software is used to analyze the test results, and the order of each influencing factor on seed metering uniformity is determined as: the forward speed, the rotating disc speed, and the number of disc seeding grooves; by establishing a mathematical model for the relation between main parameters and quality evaluation indicators, optimization and analysis are conducted, so as to get the optimal values.

(3) The verification test is undertaken for optimization results, to ensure the best parameter combination of seeding uniformity: the forward speed is 0.22 m/s, the number of disc seeding grooves is 10, the rotating disc speed is 0.18 r/s, and the seeding uniformity is 83% under this condition.

(4) By test analysis, it is found that the main reasons for the decrease in seeding uniformity are as follows. The forward speed of the tractor is mainly controlled by the operator. There are inconsistencies in the speed gear shift and the accelerator pedal control, so it is difficult to control stably, which results in low forward speed stability and affects the accuracy of seeding uniformity. The speed while assisting the artificial filling of single-bud sugarcane seeds into the disc seeding grooves and the rotation speed of the disc may not achieve real-time uniformity. It is a three-point suspension connection between the test device and the tractor. Due to the unevenness of the seeding ground, the entire seeding machine vibrates greatly, and the seeding accuracy and the seeding speed are reduced to some extent.

Acknowledgements

This work was financially supported by National Key Research and Development Project (Grant No. 2017YFD0700805); Special Fund for Basic Scientific Research Business Expenses of Chinese Academy of Tropical Agricultural Sciences (Grant No. 16301320 22001); Hainan Natural Science Foundation Project (Grant No. 520QN331); Zhanjiang Science and Technology Plan Project (Grant No. 2021A05011 and 2021A05189); Special Topic on the Construction of Key Laboratory of Zhanjiang Science and Technology Planning Project (Grant No. 2020A05004).

[References]

[1] Murilo dos S V, Daniel S P N, Kássio dos S C, Fábio R M. Modelling the trash blanket effect on sugar-cane growth and water use. Computers and Electronics in Agriculture, 2020; 172(5): 105361.

[2] Elsheery N, Sunoja V S J, Wen Y, Zhu J J, Cao K F. Foliar application of nanoparticles mitigates the chilling effect on photosynthesis and photo protection in sugarcane. Plant Physiology and Biochemistry, 2020; 149(4): 50–60.

[3] Yang R, Li J, Liu Q, Huang W S, Yin K, Qiao X, et al. Gradient-based method for the identification of multi-nodes in sugarcane. Information Processing in Agriculture, 2020; 1: 1–9.

[4] Liu Q T, Mo J L, Li T H. Technical status and key technical problems of sugarcane planter in China. Sugarcane Industry, 2011; 5: 52–58. (in Chinese)

[5] Liang Y L, Yu S F, Zhen Z, Zhao Y J, Deng J M, Jiang W G. Climatic change impacts on Chinese sugarcane planting: Benefits and risks. Physics and Chemistry of the Earth, 2020; 116: 1–8.

[6] Adalberto P J. Perspectives on bioenergy and biotechnology in Brazil. Applied Biochemistry and Biotechnology, 2015; 121(1): 59–70.

[7] Naik R, Annmalai S J K, Nair N V, Prasad N R. Studies on mechanization of planting of sugarcane bud chip settings raked in protrays. Sugar Tech, 2013; 15(1): 27–35.

[8] Namjoo M, Razavi J. Development and evaluation of a new double-row sugarcane billet planter with overlap planting pattern. Agricultural Mechanization in Asia, Africa and Latin America:AMA, 2014; 45(2): 57–64.

[9] Cao Y L. Improvement and test of 2CZQ-2 seed cutting sugarcane planter. Guangzhou: South China Agricultural University, 2016. (in Chinese)

[10] Xu C, Liu P, Meng W G. Design analysis of finger clip seeding device based on precutting sugarcane seeder. Agricultural Development and Equipment, 2016; 5: 55–56. (in Chinese)

[11] He F G, Deng G R, Li M, Niu Z J, You X. Design of electromagnetic vibration-type single-bud sugarcane seed metering device. Sugar Tech, 2019; (6). doi:10.1007/s12355-019-00715-y.

[12] Dong X H, Niu Z J, Li M. Design and test of trough wheel sugarcane healthy seedling planter. Mechanical Design and Manufacture, 2017; (12): 265–268.

[13] Anantachar M, Prasanna K G V, Guruswamy T. Neural network prediction of performance parameters of an inclined plate seed metering device and its reverse mapping for the determination of optimum design and operational parameters. Computers and Electronics in Agriculture, 2010; 72(2): 87–98.

[14] Yan B X, Zhang D X, Cui T, H X T, Ding Y Q, Yang L. Design of synchronous rotary air suction corn precision metering device with metering plate and negative pressure chamber. Transactions of the CSAE, 2017; 33(23): 15–23. (in Chinese)

[15] Chen K K, Yuan Y W, Zhao B, Jin X, Lin Y, Zheng Y J. Finite element modal analysis and experiment of rice transplanter chassis. Int J Agric & Biol Eng, 2022; 15(5): 91–100.

[16] Liu H X, Liu J X, Tang S F, Xu X M. Design and seed filling mechanism analysis of opposed swash plate high speed precision soybean metering device. Journal of agricultural engineering, 2016; 32(20): 24–31. (in Chinese)

[17] Yang S, Zhai C Y, Gao Y Y, Dou H J, Zhao X G, He Y K, et al. Planting uniformity performance of motor-driven maize precision seeding systems. Int J Agric & Biol Eng, 2022; 15(5): 101–108.

[18] Chen Y L, Jia H L, Wang J X, Wang Q, Zhao J L, Hu B. Design and experiment of convex spoon metering device of soybean high speed precision seeder. Journal of Agricultural Machinery, 2017; 48(8): 95–104.

(in Chinese)
[19] Yang R B, Chai H H, Shang S Q. Design and performance test of tilt disc metering device for peanut planter. Transactions of the CSAM, 2014; 45(6): 79–84. (in Chinese)
[20] Wu D L, Ding D, Cui B W, Jiang S, Zhao E L, Liu Y Y, et al. Design and experiment of vibration plate type camellia fruit picking machine. Int J Agric & Biol Eng, 2022; 15(4): 130–138.
[21] Wang Y C, Qiu L C, Zhang W J, Li Q C. Design and experiment of friction type vertical disc precision seed metering device. Journal of Agricultural Engineering, 2012; 28(1): 22–26. (in Chinese)
[22] Zhao X S, Ran W J, Hao J J, Bai W J, Yang X L. Design and experiment of the double-seed hole seeding precision seed metering device for peanuts. Int J Agric & Biol Eng, 2022; 15(3): 107–114.
[23] Li C H, Gao Y Z, Zhang B H. Experiment on seed metering performance of air blown inclined disc seed metering device. Transactions of the CSAM, 2008; 39(10): 90–94. (in Chinese)
[24] Bao W Y, Liu A T, Lin J, Yang W G, Wu S H, Lv C Y, Li B F. Experimental study on 2bg-2 ridge rolling disc cultivator. Agricultural Mechanization Research, 2009; 31(8): 126–129. (in Chinese)
[25] Ahmad F, Adeel M, Qiu B J, Ma J, Shoaib M, Aamir S, et al. Sowing uniformity of bed-type pneumatic maize planter at various seedbed preparation levels and machine travel speeds. Int J Agric & Biol Eng, 2021; 14(1): 165–171.
[26] Zhou F J, Li X L, Yin B X. Design and experiment of rice metering device with spoon type seed collection and piston hole binding. Journal of Northeast Agricultural University, 2018; 49(8): 73–82. (in Chinese)
[27] Hwang S-J, Nam J-S. Optimization of roller shape for roller-type onion pot-seeding machine. Int J Agric & Biol Eng, 2020; 13(1): 111–119.
[28] Jia H L, Chen Y L, Zhao J L, Wang J X, Guo M Z, Zhuang J. Design and experiment of air suction mechanical compound soybean precision metering device. Journal of Agricultural Machinery, 2018; 49(4): 75–86,139. (in Chinese)