



# Design of Electromagnetic Vibration-Type Single-Bud Sugarcane Seed Metering Device

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**Abstract** The objectives of this research were to solve the problem that the existing sugarcane seed metering device had high per cent of damaged seeds and omission rate. An electromagnetic vibration-type single-bud sugarcane seed metering device was designed. It made use of the characteristic of vibrating automatic metering to avoid damaging buds. And it could be adjusted to different sowing speeds by setting the controller. The migratory mechanism was analysed. The helix angle and working parameters of the metering device were obtained by the experiment. The results of the experiment showed that the order of factors affecting the qualification rate was amplitude > frequency > helix angle. The best qualification rate of the metering device was achieved when the helix angle was 6°, the amplitude was 0.4 mm and the frequency was 53.2 Hz, and the results of verification experiments showed that the qualification rate of metering was over 80% and the per cent of damaged buds was 0 with the best parameter combination. This metering device met the standard requirements of sugarcane seeds metering.

**Keywords** Agricultural machinery · Seed metering device · Single-bud sugarcane seed · Electromagnetic vibration · Design · Experiment

## Introduction

The perennial planting area of sugarcane in China is 1.5 million ha, accounting for over 90% of Chinese sugar crop. At present, single-bud sugarcane planting is the least seeding rate planting technology, when the seeding rate is about 2000 kg/ha and the germination rate is up to 70%. Compared with multiple buds sugarcane planting, the seeding amount is reduced by 83.3%, which is convenient for the seed selection, disinfection and mechanization (Liang et al. 2014). However, sugarcane planting mainly depends on artificial cultivation and the mechanization level is low in China (Wang and Jianlin 2012). Thus, the planter suitable for single-bud sugarcane planting is urgently needed.

The seed metering device is the core part of sugarcane planter, whose working performance directly influences sugarcane planting quality. The study of other countries for sugarcane metering devices focuses on the pre-cut type metering device, in which the belt or chain is adopted for sugarcane sowing. The sugarcane metering devices are highly automatic and efficient, but reseeding, leakage and injury are very serious (Pessoa Jr 2005; Kumar and Singh 2012; Taghinezhad et al. 2013; Naik et al. 2013; Namjoo and Razavi 2014; Singh and Singh 2016; Thienyaem et al. 2014, 2016). A Chinese study for sugarcane metering devices mainly focuses on the cutting-type metering devices, in which the roller clamping and cutting method is adopted to achieve planting. However, there is serious injury to the buds and the method relies on manual assistance feeding and sowing, which leads to high leakage rate and low qualification rate and evenness (Yang et al. 2007; Wang et al. 2013; Huang et al. 2014, 2015a, b; Zeng et al. 2015; Liu et al. 2018). The existing single-bud sugarcane seed metering devices are composed of sorting mechanism

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and planting mechanism, which can sow single-bud sugarcane orderly and reduce the leakage rate, but the buds are damaged seriously by planting mechanism (Liu et al. 2013a, b; Huang et al. 2015a, b).

Therefore, in order to reduce the injury rate and leakage rate and improve the qualification rate and evenness of the sugarcane metering device, a single-bud sugarcane seed metering device was designed on the basis of the electromagnetic vibration without any damage characteristic (Zhang et al. 1992, 1996; Li and Zhao 2000; He et al. 2003; Wang et al. 2015). The influence factors of planting quality were determined by analysing the migratory mechanism of single-bud sugarcane. The influence factors on the rate of planting quality were analysed through experiments. This study aims to provide theoretical reference basis for optimizing the single-bud sugarcane seed metering device.

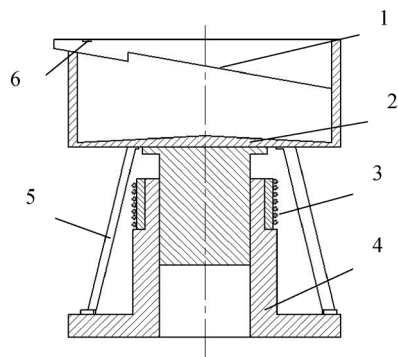
## Materials and Methods

### Main Frame

Electromagnetic vibration is a new seed sowing technology, which has the advantages of simple transmission, accurate control, no damage to seeds, high precision and good evenness (Yang et al. 2012). The electromagnetic vibration-type single-bud sugarcane seed metering device (Fig. 1) is mainly composed of spiral groove, disc, seed-cleaning plate, substructure, spring, controller (Fig. 2) and coil.

### Metering Mechanism

When the metering device works, alternating current is loaded on the coils after half-wave rectification of alternating current of certain frequency. The disc is the



**Fig. 1** Schematic view of the electromagnetic vibration-type single-bud sugarcane seed metering device. 1 Spiral groove, 2 disc, 3 coil, 4 substructure, 5 spring, 6 seed-cleaning plate

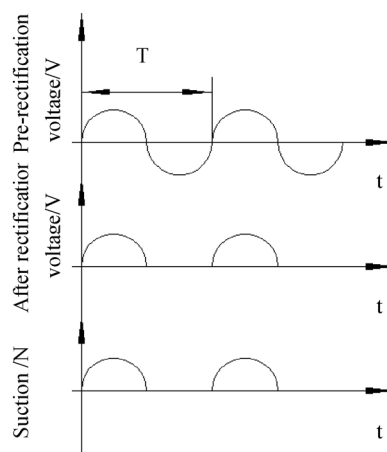


**Fig. 2** Controller of the amplitude and frequency

downward movement and rotary motion under the influence of suction, which is generated when the coils are energized, and spring. The disc returns to the original position under the reaction force of spring when the suction is zero. The spiral groove and disc occur in harmonic vibration during a period of the suction (Fig. 3). The single-bud sugarcane, which acceleration meets certain conditions, is motion and adjustment under the influence of the gravity, friction and inertial force. The vertical single-bud sugarcane is in the lying state when it passes the ladder of the spiral groove. The redundant single-bud sugarcane returns to the disc automatically by the seed-cleaning plate so that only one sugarcane seed is planted. The sowing speeds are adjusted for tractor speed by setting the controller.

### Analysis of Migratory Mechanism

Only the forward motion and throwing motion meet the requirements of metering for the device. So it is necessary to study the critical condition of the throwing motion of sugarcane seeds by analysing its state. The mechanical model of sugarcane seed (Fig. 4) is built by making the spiral groove become to straight groove.



**Fig. 3** Transformation of the suction

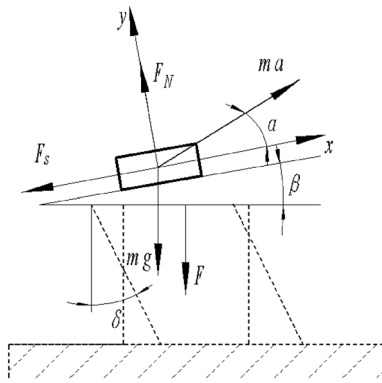


Fig. 4 Mechanical model of sugarcane seed

When the disc and the spiral groove are downward and rotate, the sugarcane seed is in the upward movement if the inertial force is higher than the friction force; if not the sugarcane seed is stationary. When the disc and the spiral groove are upward and rotate, the sugarcane seed is in the downward movement if the inertial force is higher than the friction force; if not the sugarcane seed is stationary. The sugarcane seed is in the skidding state when the inertial force is less than the gravity (Fig. 5); otherwise, the sugarcane seed is in the throwing state. The displacement of sugarcane seed under throwing state depends on the time. The displacement is maximum when the time of throwing is equal to the downward movement time of spiral groove (Fig. 6). The displacement is smaller when the sugarcane seed returns to the spiral groove in advance or delay (Fig. 7).

The displacement of sugarcane seed at the direction of inertial force is given by the formula as follows:

$$S = A \sin \omega t \tag{1}$$

where  $S$  is the displacement of sugarcane seed, mm,  $A$  is the amplitude of disc, mm, and  $\omega$  is the angular frequency of suction, Hz.

The conditions of sugarcane seed under skidding state (Liu 2007; Yang et al. 2007) are given by the formula as follows:

$$A\omega^2 \cos \omega t \geq \frac{g(\mu \cos \beta - \sin \beta)}{\cos \alpha - \mu \sin \alpha} \tag{2}$$

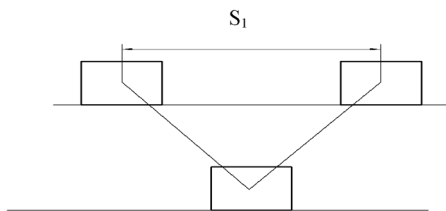


Fig. 5 Displacement of sugarcane seed under skidding state

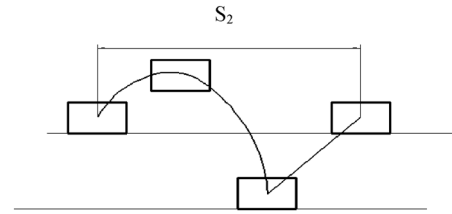


Fig. 6 Maximum displacement of sugarcane seed under throwing state

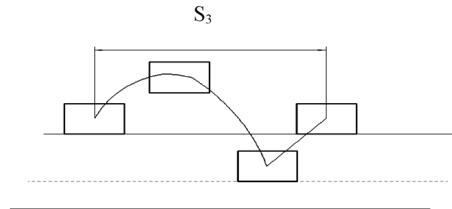


Fig. 7 Smaller displacement of sugarcane seed under throwing state

where  $\alpha$  is the angle between the direction of the vibration and the spiral groove,  $\beta$  is the helix angle of spiral groove,  $\mu$  is the friction coefficient between sugarcane seed and spiral groove.

The conditions of sugarcane seed under throwing state (Liu 2007; Yang et al. 2007) are given by the formula as follows:

$$A\omega^2 \cos \omega t \geq \frac{g \cos \beta}{\sin \alpha} \tag{3}$$

The skidding state of sugarcane seed is selected when the metering device is designed since the skidding state is more stable than the throwing state. So the conditions of sugarcane seed under skidding state are given by the formula as follows:

$$\frac{g(\mu \cos \beta - \sin \beta)}{\cos \alpha - \mu \sin \alpha} \leq A\omega^2 \cos \omega t \leq \frac{g \cos \beta}{\sin \alpha} \tag{4}$$

The skidding speed of sugarcane seed is given by the formula as follows:

$$x' = \frac{A\omega \cos(\mu - \alpha)}{\cos \mu} [\cos \varphi_k - \cos \varphi - \sin(\varphi - \varphi'_k)] \tag{5}$$

where  $\varphi_k$  is the hypothetical slipping angle of forward direction,  $\varphi'_k$  is the true slipping angle of forward direction, and  $\varphi$  is the phase angle.

The hypothetical slipping angle of forward direction is given by the formula as follows:

$$\sin \varphi_k = \frac{\sin(\mu - \beta)}{K \cos(\mu - \alpha)} \tag{6}$$

where  $K$  is the stiffness of all springs, N/m.

The true slipping angle of forward direction is given by the formula as follows:

$$tg\varphi'_k = \frac{\sin\varphi'_k - \cos\theta_k \sin\varphi'_k}{\theta_k \sin\varphi_k - \sin\theta_k \sin\varphi'_k} \tag{7}$$

where  $\theta_k$  is the slide angle of forward direction, °.

So the average skidding speed of sugarcane seed is given by the formula as follows:

$$v = \frac{A\omega(\sin\varphi'_m - \sin\varphi_k) \cos(\mu - \alpha)(\sin\varphi'_m + \sin\varphi'_k)}{4\pi \cos\mu \sin\varphi_k} \tag{8}$$

where  $\varphi'_m$  is the true stopping angle of forward direction, °.

$$\varphi'_m = \varphi'_k + \theta_k. \tag{9}$$

According to the above results, the skidding speed of sugarcane seed is mainly determined by amplitude of disc, angular frequency of suction, angle between the direction of the vibration and the spiral groove, helix angle of spiral groove, the friction coefficient between sugarcane seed and spiral groove and the stiffness of all spring.

### Design of Planter Plate

The disc is designed as ladder-type spiral in order to avoid discontinuous metering and improve the quality and efficiency of planting. Diameter, which is determined by the length and number of sugarcane seed, is an important structural parameter for disc (Fig. 8).

The diameter of disc is given by the formula as follows:

$$D = \frac{L}{2 \sin(\frac{180^\circ}{N})} \tag{10}$$

where  $L$  is the length of sugarcane seed, mm, and  $N$  is the number of sugarcane seed.

The length of single-bud sugarcane seed is about 50 mm. So the diameter of the disc is determined by the number of sugarcane seed. The number of sugarcane seed should be as large as possible in order to reduce the motion resistance of sugarcane seed. According to the frame size of sugarcane planter, the diameter of the disc is designed to be 600 mm (Fig. 9).

Fig. 8 Sugarcane seeds in the disc

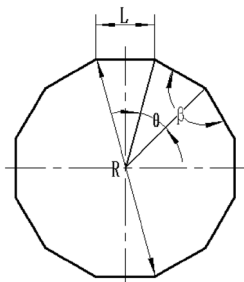


Fig. 9 Disc

### Design of Spiral Groove

The spiral groove is composed of the welding between the plate and disc. The width of spiral groove is determined by the diameter of sugarcane seed. The diameter of sugarcane seed is about 30 mm. So the width of spiral groove is designed to be 50 mm. In order to avoid congestion and seed clearing, a ladder, which is a height of 10 mm, is designed on the spiral groove. The number of the spiral is designed to be 2.5. The helix angle of spiral groove is designed to 4°–10° (Zhang et al. 1996; Liu 2007). The final helix angle depends on the experiment results.

### Design of Vibration System

The vibration system, which is composed by spring and vibrator (Fig. 10), is the power source of the metering device.

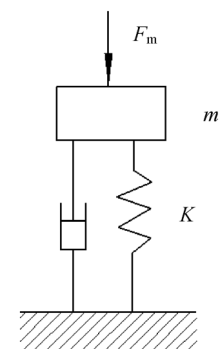
The stiffness of all springs is given by the formula as follows (Dong et al. 2005, Dong and Yang 2006; Liu and Zhao 2008; Yang et al. 2009).

$$K = \frac{16iEbh^3}{\alpha l^3} \tag{11}$$

where  $i$  is the number of all springs,  $E$  is the elasticity modulus, MPa,  $b$  is the width of spring, mm,  $h$  is the thickness of spring, mm,  $\alpha$  is the compression coefficient and  $l$  is the length of spring, mm.

The field parameters of spring are presented in Table 1.

Fig. 10 Vibration system model



**Table 1** Parameters of spring

Particular	Detail
Material	60Si2MnA
Number	8
Elasticity modulus (MPa)	$2.06 \times 10^5$
Width (mm)	20
Thickness (mm)	3
Compression coefficient	1.3
Length (mm)	250

The stiffness of all springs is designed to be 700,983.14 N/m. The angle between the direction of the vibration and the spiral groove is equal to the installation angle of spring. The installation angle of spring is designed to be 25°, so the angle between the direction of the vibration and the spiral groove is 23° (Liu et al. 2005). The voltage of vibrator is designed to use alternating current which voltage is 220 V.

**Materials and Equipment**

The experiments are carried out in order to obtain the helix angle and working parameters of the electromagnetic vibration-type single-bud sugarcane seed metering device (Fig. 11). The experiment is conducted at the Research Institute of Agricultural Machinery, Chinese Academy of Tropical Agricultural, Zhanjiang City, Chinese Guangdong Province (Fig. 12). The materials and equipment are presented in Table 2.

Single factor experiments and orthogonal experimental design of regression method are used to study the relationship between the factors (helix angle, amplitude of disc, angular frequency of suction) and the qualification rate of metering. The travelling speed of s test bench is set to 2 km/h. The sample data are collected at 20 m in the interior of the test bench displacement. To reduce experiment error, each group of the experiment is repeated three times.



**Fig. 11** Electromagnetic vibration-type single-bud sugarcane seed metering device



**Fig. 12** Experiment field

In accordance with agronomic of single-bud sugarcane planting, 5–7 segments of sugarcane seeds should be guaranteed every meter, so the theoretical spacing of single-bud sugarcane seed is about 200 mm. When the seed spacing is less than half of the theoretical spacing, this refers to repetition. When the seed spacing is greater than 1.5 times of the theoretical spacing, this refers to omission (Yang et al. 2005). Thus, the qualified seed spacing of single-bud sugarcane is 100–300 mm. The evaluation index of metering performance is presented in Table 3 (Liu et al. 2013a, b). The qualification rate of metering is given by the formula as follows:

$$y = \frac{n}{N} \times 100\% \tag{12}$$

where *n* is the qualification sample size and *N* is the total sample size.

**Table 2** Parameters of the materials and equipment

Particular	Values
<b>Crop parameters</b>	
Variety	Xintaitang RCO22
Mean length (mm)	56.7
Mean diameter (mm)	29.8
Laboratory size (m)	30 × 3
<b>Metering device parameters</b>	
Maximum height (mm)	450
Maximum diameter (mm)	600
Frequency range (Hz)	0–90
Frequency precision (Hz)	0.1
Amplitude range (mm)	0–10
Amplitude precision (mm)	0.1
<b>Tape parameters</b>	
Range (m)	0–7.5
Precision (mm)	1
<b>Goniometer parameters</b>	
Range (°)	0–360
Precision (°)	1



**Table 3** Evaluation index of different seed spacing

Particular	Seed spacing < 100 mm	Seed spacing = 100–200 mm	Seed spacing > 200 mm
Qualification rate (%)	≥ 60	≥ 75	≥ 80
Coefficient of variation (%)	≤ 40	≤ 35	≤ 30

**Table 4** Programme and results of single factor experiments

E. no.	Helix angle (X <sub>1</sub> ), °	Amplitude (X <sub>2</sub> ), mm	Frequency (X <sub>3</sub> ), Hz	Qualification rate (y), %
1.	4	0.6	55	84.2
2.	5	0.6	55	80.8
3.	6	0.6	55	76.2
4.	7	0.6	55	63.7
5.	8	0.6	55	58.9
6.	9	0.6	55	53.4
7.	10	0.6	55	51.5
8.	7	0.3	55	75.9
9.	7	0.4	55	78.4
10.	7	0.5	55	83.2
11.	7	0.6	55	83.8
12.	7	0.7	55	82.6
13.	7	0.8	55	81.3
14.	7	0.9	55	80.8
15.	7	0.6	40	78.5
16.	7	0.6	45	81.2
17.	7	0.6	50	84.9
18.	7	0.6	55	85.7
19.	7	0.6	60	84.6
20.	7	0.6	65	81.3
21.	7	0.6	70	80.1

**Results and Discussion**

**Single Factor Experiments**

The programme and results of single factor experiments are presented in Table 4.

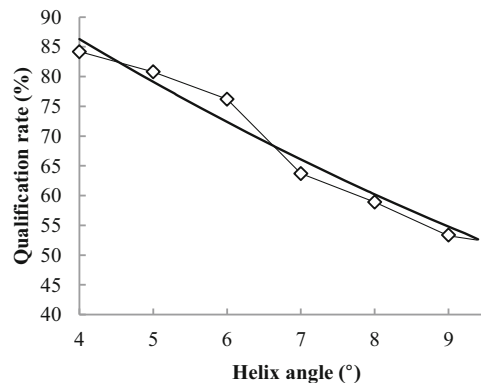
The relation between factors and qualification rate of metering is given by the formulas as follows:

$$y_1 = 0.22X_1^2 - 7.83X_1 + 93.9 \tag{13}$$

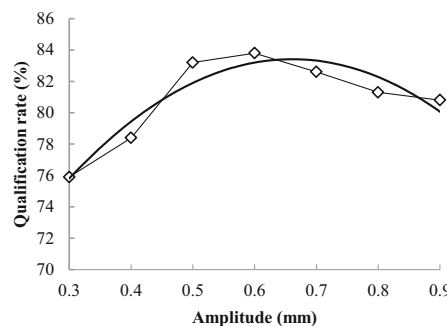
$$y_2 = -0.58X_2^2 + 5.39X_2 + 71 \tag{14}$$

$$y_3 = -0.69X_3^2 + 5.72X_3 + 73.33 \tag{15}$$

The results of the significant test of each formula and coefficient show that the *P* value of the helix angle and qualification rate of metering is 0.01103, the *P* value of the amplitude and qualification rate of metering is 0.00101, and the *P* value of the frequency and qualification rate of

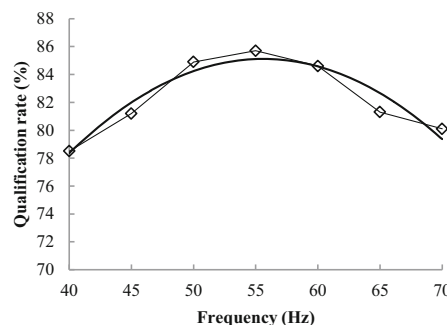


**Fig. 13** Regression curve of helix angle and qualification rate



**Fig. 14** Regression curve of amplitude and qualification rate

metering is 0.00115. So helix angle, amplitude and frequency have a strong impact on the qualification rate of metering. The fitting degrees of each formula, which is well fitted, are more than 0.9. The regression curve of each factor and qualification rate is built (Figs. 13, 14, 15).



**Fig. 15** Regression curve of frequency and qualification rate

It is seen from the regression curve of helix angle and qualification rate that the qualification rate gets lower with the increase in helix angle. The speed of sugarcane seed becomes lower with the increase in helix angle. Thus, the omission is so serious that the qualification rate gets lower.

It is seen from the regression curve of amplitude and qualification rate that the qualification rate first increases and then decreases with the increase in amplitude. The speed of sugarcane seed is higher with the increase in amplitude, thus leading to higher qualification rate. When the speed of sugarcane seed is too high, the over-sowing is so serious that the qualification rate gets lower.

It is seen from the regression curve of frequency and qualification rate that the qualification rate first increases and then decreases with the increase in frequency. The speed of sugarcane seed is faster and faster with the increase in frequency, thus leading to higher qualification rate. When the speed of sugarcane seed is too high, the over-sowing is so serious that the qualification rate gets lower.

**Orthogonal Experimental Design of Regression Method**

The level range of each influencing factor is determined according to the results of single factor experiments. The levels of factors are presented in Table 5. The results of orthogonal experimental design of regression method are presented in Table 6.

The relation between factors and qualification rate of metering is given by the formula as follows according to the results of the experiments.

$$y = 79.115 - 1.507z_1 - 7.523z_2 - 4.387z_3 + 2.55z_1z_2 + 2z_1z_3 - 1.425z_2z_3 - 0.823z_1^2 - 3.334z_2^2 - 3.052z_3^2. \tag{16}$$

The results of the significant test of the formula and coefficients are presented in Table 7.

It is seen from the table that the formula shows a significant lack of fit, but the formula is fitted well to most of the experiment results. The significance of formula is very obvious. The influence of helix angle on qualification rate is significant. The influence of amplitude on qualification rate is very significant. The influence of frequency on qualification rate is very significant. The influence of the product of helix angle and amplitude on qualification rate is not significant. The influence of the product of helix angle and frequency on qualification rate is significant. The influence of the product of amplitude and frequency on qualification rate is significant. The influence of the square of helix angle on qualification rate is not significant. The influence of the square of amplitude on qualification rate is

**Table 5** Levels of factors for experiments

Level	Helix angle (°)	Amplitude (mm)	Frequency (Hz)
Upper asterisk arm	10	0.7	60
Upper level	9	0.6	57.5
Zero level	8	0.5	55
Lower level	7	0.4	52.5
Lower asterisk arm	6	0.3	50
interval	1	0.1	2.5

**Table 6** Results of experiments

E. no.	Helix angle (°)	Amplitude (mm)	Frequency (Hz)	Qualification rate (%)
1.	9	0.6	57.5	65.6
2.	9	0.6	52.5	68.6
3.	9	0.4	57.5	64.2
4.	9	0.4	52.5	69.5
5.	7	0.6	57.5	69.4
6.	7	0.6	52.5	88.4
7.	7	0.4	57.5	86.2
8.	7	0.4	52.5	91.5
9.	10	0.5	55	64.6
10.	6	0.5	55	85.5
11.	8	0.7	55	81.8
12.	8	0.3	55	82.5
13.	8	0.5	60	67.8
14.	8	0.5	50	84.5
15.	8	0.5	55	83.9
16.	8	0.5	55	83.8
17.	8	0.5	55	82.6
18.	8	0.5	55	81.6
19.	8	0.5	55	83.6
20.	8	0.5	55	83.2
21.	8	0.5	55	83.4
22.	8	0.5	55	83.5
23.	8	0.5	55	84.6

very significant. The influence of the square of frequency on qualification rate is very significant. The order of factors affecting the qualification rate is amplitude > frequency > helix angle. The formula is given by gradual analysis as follows:

$$y = 79.115 - 1.507z_1 - 7.523z_2 - 4.387z_3 + 2.55z_1z_2 + 2z_1z_3 - 3.334z_2^2 - 3.052z_3^2. \tag{17}$$

The level codes are substituted in the formula, and thus,

**Table 7** Results of the significant test of formula

Particular	Freedom	Sum	Average	<i>F</i> value	<i>P</i> value
Regression	9	1502.85	166.983	25.833	0.000
Residual	13	84.035	6.464		
Lack of fit	5	78.233	15.647	21.582	0.000
Error	8	5.802	0.725		
$z_1$	1	31.019	31.019	4.799	0.047
$z_2$	1	772.996	772.996	119.585	0.000
$z_3$	1	262.863	262.863	40.666	0.000
$z_1z_2$	1	52.020	52.020	8.048	0.014
$z_1z_3$	1	32.000	32.000	4.950	0.044
$z_2z_3$	1	16.425	16.425	2.541	0.137
$z_1^2$	1	10.767	10.767	1.666	0.220
$z_2^2$	1	176.693	176.693	27.335	0.000
$z_3^2$	1	148.067	148.067	22.906	0.000

the final relation between factors and qualification rate of metering is given by the formula as follows:

$$y = -997.773 - 58.257X_1 + 105.17X_2 + 47.16X_3 + 25.5X_1X_2 + 0.8X_1X_3 - 333.4X_2^2 - 0.48X_3^2 \quad (18)$$

The best qualification rate and parameter combination are obtained by optimizing the formula. The best qualification rate of theory is 85.6%, and the best parameter combination is 6°, 0.4 mm and 53.2 Hz. The best qualification rate of theory with 95% confidence intervals is 84.2–87.4%.

### Verification Experiment

The verification experiments were conducted under the condition of the best parameter combination. The verification experiment includes the laboratory experiment and field experiment (Fig. 16). While the tractor is moving in the forward direction, the furrow opener opens up the seed channel, and then, the sugarcane seeds planted (Fig. 17). The results of the laboratory experiments are presented in Table 8, and the results of the field experiments are presented in Table 9.

It is seen from the table that the average of qualification rate of the laboratory experiment is 85.5%. The average of qualification rate of the field experiment is 80.4%. All qualification rates are more than 80%, so this metering device meets the standard requirements. There is a certain difference between the qualification rate of the laboratory experiment and that of field experiment. The reasons for the decline in the qualification rate of the field experiment are the forward velocity of tractor instability and the unevenness of the ground. There is no damage to the buds as compared to conventional sugarcane metering devices.



**Fig. 16** Sugarcane planter with electromagnetic vibration-type single-bud sugarcane seed metering device



**Fig. 17** View of field after metering using tractor drawn mechanical planter for sugarcane seed raised in portray

### Conclusions

An electromagnetic vibration-type single-bud sugarcane seed metering device was designed. The metering device has the characteristics of automatic sowing and without any



**Table 8** Results of laboratory experiment

E. no.	Helix angle (°)	Amplitude (mm)	Frequency (Hz)	Qualification rate (%)
1.	6	0.4	53.2	84.9
2.	6	0.4	53.2	86.3
3.	6	0.4	53.2	85.4

**Table 9** Results of field experiment

E. no.	Helix angle (°)	Amplitude (mm)	Frequency (Hz)	Qualification rate (%)
1.	6	0.4	53.2	81.2
2.	6	0.4	53.2	80.1
3.	6	0.4	53.2	79.6
4.	6	0.4	53.2	80.4
5.	6	0.4	53.2	80.8

damage. The factors influencing the skidding speed of sugarcane seed were determined by migratory mechanism analysis. The order of factors affecting the qualification rate was amplitude > frequency > helix angle. The laboratory experiments proved that the best qualification rate was achieved when the helix angle was 6°, the amplitude was 0.4 mm and the frequency was 53.2 Hz. The verification experiments proved that the qualification rate of metering was more than 80% and the per cent of damaged buds was 0 under the condition of the best parameter combination, and this metering device met the standard requirements.

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#### Compliance with Ethical Standards

**Conflict of interest** Fengguang He, Ganran Deng and Zhaojun Niu have received research Grants from Tropical Agricultural Machinery Research Institute, Chinese Academy of Tropical Agricultural Sciences. Xiao You, from Hainan Provincial Institute of Agricultural Machinery, participated in manuscript modification. Ming Li is a member of Tropical Agricultural Machinery Research Institute, Chinese Academy of Tropical Agricultural Sciences. The authors declare that they have no conflict of interest.

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