# EXPERIMENTAL STUDY ON THE SEEDING PERFORMANCE OF THE SPOON-WHEEL MAIZE SEED-METERING DEVICE UNDER VIBRATION CONDITIONS
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# 勺轮式排种器在振动条件下的排种性能试验研究

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## ABSTRACT

*The seeder was tested and evaluated for field operations vibration characteristics in light of the issue that the spoon-wheel maize precision seeder vibrates due to the field operating conditions, which impairs the performance of the seed-metering device. During field testing, it was discovered that the seed-metering device vibrated greater as the forward speed increased, resulting in a higher peak vibration acceleration. However, fluctuations in forward speed did not affect the frequency distribution of the peak vibration acceleration. Time-domain and spectrogram investigations revealed that the vibration frequency of the seed-metering device was predominantly within 0~10 Hz for seeder operating speeds ranging from 2~6 km/h, with acceleration values spanning from 0.85~1.86 m/s$^2$. An electromagnetic seeding test stand was established in response to the discoveries. The essential variables governing the seeding performance of the spoon-wheel seed-metering device were then investigated using orthogonal tests, such as forward speed, vibration frequency, and vibration acceleration. The empirical results elucidated a hierarchical relationship between these factors and seeding quality. Specifically, vibration frequency emerged to be the predominant factor, followed by vibration acceleration, and forward speed. The seeding quality of the seed-metering device was negatively correlated with increases in forward speed and vibration acceleration, which led to a lower qualified rate, higher leakage rate, and variation coefficient. Overall, the qualified rate, leakage rate, and variation coefficient were all significantly influenced by the three factors.*

## 摘要

*针对勺轮式玉米精量播种机受田间作业工况的影响而产生振动，从而影响排种器排种性能的问题，对播种机进行田间作业振动特性测试与分析。田间试验结果表明，随着前进速度的增加，排种器受到的振动越剧烈，振动加速度峰值越大。但是振动加速度峰值的频率分布不受前进速度影响。当播种机的田间作业速度为 2~6 km/h 时，通过时域和频谱图分析，发现排种器的振动主频集中在 0~10 Hz，加速度范围为 0.85~1.86 m/s$^2$。搭建振动排种试验台，通过正交试验对影响勺轮式排种器排种性能的前进速度、振动频率、振动加速度三个因素进行试验研究。结果表明：影响合格指数的因素主次关系为振动频率、振动加速度、前进速度；随着前进速度和振动加速度的增加，会导致排种器的合格指数降低、漏播指数及变异系数上升；三个因素对合格指数、漏播指数和变异系数均有显著性影响。*

## INTRODUCTION

Crop productivity is largely dependent on the efficiency with which seeding gear operates, making it a crucial component of agricultural production *(Yang et al., 2016)*. One of China's four major grain-producing regions, the hilly and mountainous areas of Southwest China are distinguished by the complex terrain, heavy soil, and uneven soil surface in their agricultural production land *(Han et al., 2023)*. The capability of the seeder to effectively seed will be adversely affected by its high vibration when operating in the field *(Zheng et al., 2020; Zhai et al., 2019)*. To strengthen seeding performance, vibration technology is currently mostly deployed in seeding machinery through the design and testing of vibration parts and vibration reduction devices, such as vibration seeding plates *(Wang et al., 2013; Chen et al., 2012; Liu et al., 2014)*.

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The seed metering device is the core component of the seeder *(Han et al., 2018; Su et al., 2022)*, whose capability is directly impacted by the working environment of the seeder *(Zhang et al., 2023)*. Based on how it operates, the seed-metering device can be classified into two categories: mechanical and pneumatic *(Gao et al., 2021; Han et al., 2023)*. The spoon-wheel seed-metering device is mechanical, mainly relying on gravity to facilitate seed cleaning and distribution, with the advantages of not easily injured seeds, good seeding quality, and adaptability to the shapes of the seeds, and is widely utilized in the production practices of the hilly and mountainous areas in southwest China *(Zhang et al., 2016; Zhang et al., 2023; Huang et al., 2021)*.

Scholars both at home and abroad have been focusing more on how vibration affects the performance of the seed-metering device in recent years. Liao et al. donned the 2BFQ-6 rape precision combined direct seeding machine as the research object, the vibration tester was utilized to assess the vibration of the direct seeding machine. They also constructed a vibration simulation seeding test bench to conduct the bench test and investigate the impact of mechanical vibration on the seeding performance *(Liao et al., 2022; Zheng et al., 2023)*. The target seeding rate of a rapeseed centralized seed-metering device at various vibration frequencies was elevated by Wu et al. by adjusting the longitudinal distance *(Wu et al., 2022)*. Boydas et al. explored the repercussions of four distinct vibration levels on the homogeneity of flow uniformity of grains like wheat and barley, the findings indicated that the vibration intensity had an enormous impact on the barley flow consistency while not affecting all of the wheat flow *(Boydas et al., 2007)*. Vishnyakov et al. studied the main factors influencing the quality of seeding by vibration device and, according to research results, a graph of their influence on estimates of seeding was constructed *(Vishnyakov et al., 2015).* Emrah's research indicates that planter vibration greatly interferes with the seed discharging process of the planter and reduces the uniformity of seed discharging, thus affecting the quality of the planter *(Emrah, 2021).* The study by Min et al. aimed to investigate the optimum vibration condition of the seed hopper on the vacuum suction nozzle seeder for improving seeding performance *(Min et al., 2008).* Based on a theoretical analysis of the working process of sowing winter-wheat seeds using a vibrating sowing apparatus, analytical dependences of the actual and calculated specific weight costs on the acceleration of vertical and horizontal oscillations of the apparatus trough were obtained, which graphically illustrated the uniformity of the distribution of winter wheat seeds by Alexander et al *(Alexander et al., 2021).* To address the issue of the existing sugarcane seed-metering device having a high percentage of damaged seeds and an omission rate, an electromagnetic vibration-type single-bud sugarcane seed-metering device availed itself of the automatic vibrating metering feature to avoid ruining the buds *(He et al., 2019; Wu et al., 2023)*.

To inspect whether the seed-metering device would resonate with the working process, an approach that consisted of modal analysis and vibration testing was employed by Liu et al. to examine the vibration properties of the air-suction seed-metering device, and its vibration response under the excitation of the tillage surface during the seeding operation *(Liu et al., 2019; Liu et al., 2021)*. To survey the influence of the vibration of the air-suction no-tillage planter on the seeding performance, the spectrum map was obtained through MATLAB processing and analysis, the greatest vibration point was identified, and the major parameter model influencing the vibration of the no-tillage planter was established by Zhao et al *(Zhao et al., 2012; Zhang et al., 2015; Dong et al., 2015;)*. To cope with the matter of the low level of intelligence of the air-suction vibrating disc seed meter, Cheng et al. proposed an online monitoring system scheme for the air-suction vibrating disc seed meter based on the Internet of Things and configuration software *(Cheng et al., 2022)*.

To attempt to perform the seeding performance of the mechanical seed-metering device in vibration conditions, a vibration seed-metering simulation test bench was erected by Huang et al. The seeding test was carried out for the pick-up finger seed-metering device based on the two distinct factors of vibration frequency and amplitude, and the results showed that the qualified rate gradually decreased with the increase of the two factors. *(Huang et al., 2019; Wang et al., 2019)*. Wang et al. conducted an experimental study to investigate the implication of vibration on the sowing quality of a shovel-type precision seeder and explored the vibration characteristics of the seeder. The results advocated that the vibration frequency of the seeder was concentrated in the low-frequency region, the vibration intensity increased with speed, and an increase in vibration intensity would lead to a reduction in seeding performance *(Wang et al., 2008; Zhang et al., 2014)*.

The spoon-wheel type maize precision seeder, which is prevalently employed in hilly and mountainous areas of Southwest China, is the subject of this study. The field vibration signals of the seeder in the time and frequency domains under various speed settings were systematically analyzed.

A vibration seeding test intermediary was constructed for controlled testing to facilitate extensive wisdom. The primary objective was to discern the impact of the field vibration characteristics of the seeder on the seeding performance of the seed-metering device. The findings derived from this study are intended to provide insightful recommendations for the refinement and enhancement of the spoon-wheel seed-metering device, ultimately elevating the operational quality of the seeder amidst field vibration scenarios.

## MATERIALS AND METHODS

### *Theoretical analysis of vibration characteristics of the spoon-wheel maize precision seeder*

### *Structure and working principle of the seeder*

The field vibration characteristics of the spoon-wheel seed-metering device were tested and analyzed in this study employing the maize spoon-wheel seeder produced cooperatively with Sichuan Agricultural University and Hebei Nonghaha Machinery Group Co. The tractor and seeder were joined via a three-point hitch. The essential technical aspects of the seeder are listed in Table 1.

**Table 1**

**Main parameters of the maize spoon-wheel seeder**

| Parameters | Unit | Values |
|---|---|---|
| Overall size | [mm] | 1595×1590×1200 |
| Furrowing depth | [mm] | ≤280 |
| Maximum fertilization | [kg/hm$^2$] | 1050 |
| Rows | / | 3 |
| Row spacing | [mm] | 500-700 |
| Plant spacing | [mm] | 120-310 |

The planting unit, ground wheel, three-point hitch, fertilizer tank, and fertilizer applicator are some of the essential parts that collectively make up the seeder assembly. Wherein, the planting unit is mainly composed of a spoon-wheel seed-metering device, a parallel four-link mechanism, a packer wheel, a seeds case, and a seed-furrow opener. The parallel four-link mechanism is tightly fastened to the three-point hitch by a tension spring. Additionally, the two ground wheels of the seeder are symmetrically affixed on the three-point hitch. The operating power of the spoon-wheel seed-metering device is mainly transmitted by the ground wheels through the chain drive. The general structure of the seeder is depicted in Fig. 1.

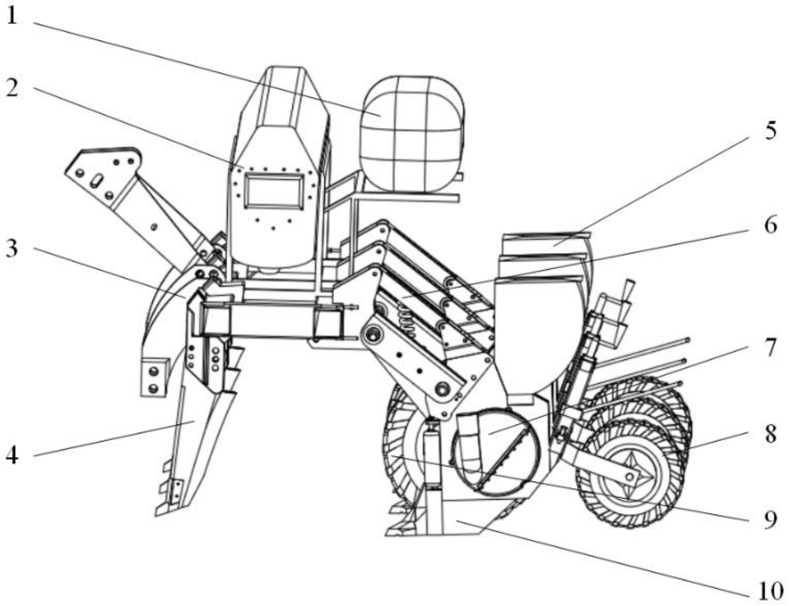


**Fig. 1 - The structural diagram of the spoon-wheel maize seeder**

*1. Reservoir; 2. Fertilizer tank; 3. Three-point hitch; 4. Fertilizer applicator; 5. Seeds case; 6. Parallel four-link mechanism; 7. Spoon-wheel seed-metering device; 8. Packer wheel; 9. Ground wheel; 10. Seed-furrow opener*

The seed-metering device is the core component of the seeder, and its structural parameters directly determine the sowing quality. The spoon-wheel type seed-metering device, which is more commonly adopted on seeders in southwest China, consists of a rear shell, seed-guiding wheel, spacer plate, spoon-wheel disc, front shell, and other components. The concrete structure of the seed-metering device is displayed in Fig. 2. The rear shell mainly serves as a fixation and support for the seed-metering device. The scoop-wheel disc utilizes the scoop to ladle up the seeds and deliver them to the seed-guiding wheel. The spacer plate separates the spoon-wheel disc from the seed-guiding wheel, and its opening location dictates the initial position of the seed delivery from the spoon to the seed-guiding wheel. The seed-guiding wheel receives the seed delivered by the spoon-wheel disc and releases it smoothly from the seed-metering device. The movement of the seeds in the seed-metering device will be easily observed through the transparent front shell.

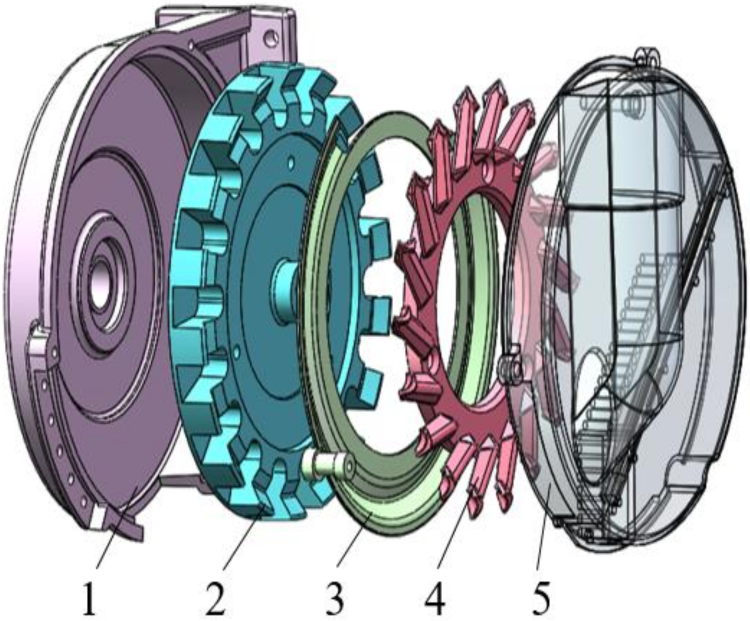


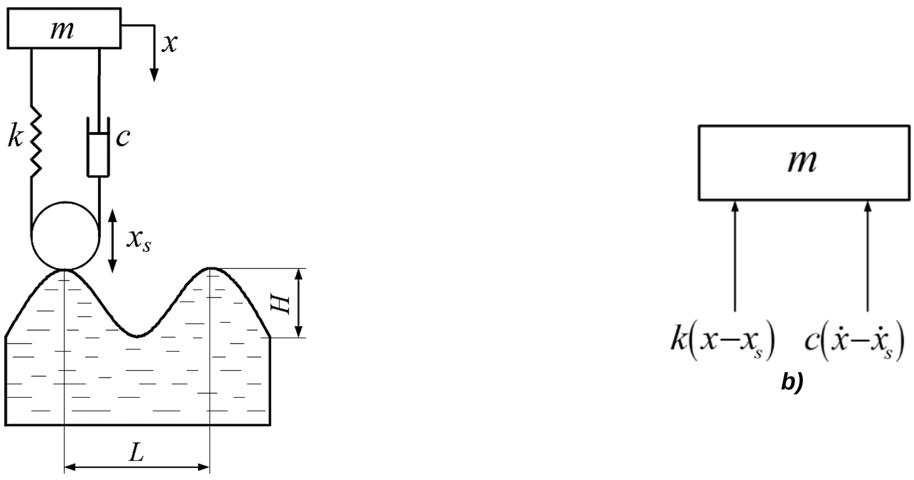
**Fig. 2 - Schematic diagram of the spoon-wheel seed-metering device**

*1. Rear shell; 2. Seed-guiding wheel; 3. Spacer plate; 4. Spoon-wheel disc; 5. Front shell*

The fertilizer pipe uniformly distributes the fertilizer into the ditch to finalize the fertilization after the seeder goes on the field. Meanwhile, the trench is initially created by the seed-furrow opener, the ground wheels rotate with the advance of the tractor and transmit the power to the spindle of the seed-metering device through the chain drive to actuate its operation. The single seed in the spoon falls into the trench regularly from the seed-metering device. The packer wheel, which can be contoured following the undulation of the field terrain, is followed by a parallel four-bar mechanism with a tension spring. To guarantee optimal soil-seed contact, the packer wheel could cover and annihilate the seeds in the trench. Moreover, contingent upon demand, the seeder can also irrigate the seeds to offset the soil drought triggered by an absence of irrigation in southwest China during the sowing season.

### *Theoretical model of the seeder vibration characteristics*

Regardless of the adjustable connection between the seeder and the three-point hitch, the undulation of the field surface will cause varying degrees of vibration to be enacted to the seeder, which will ultimately result in a vertical displacement modification of the seed-metering device. To legitimately simplify the vibration system model of the seeder, the secondary factors affecting the vibration characteristics of the seeder field operation and lateral vibration are disregarded. Each component of the seeder is assumed to be a rigid body. The stiffness of the fertilizer applicator, seed-furrow opener, and depth-limiting wheel, which are in direct contact with the soil, is a linear function of displacement, while the damping force generated by the interaction with the soil is a linear function of velocity *(Zhang et al., 2014; Liu et al., 2016; Gao et al., 2022)*. The field soil profile can be converted to a sine function while the seeder is running. The mass of the seeder is set to $M$, the amplitude to $H$, and the length in the forward direction to $L$. The simplified vibration system model of the seeder is portrayed in Fig. 3.



**a)** **b)**

**Fig. 3 - The vibration system model of the spoon-wheel maize planter**

*a) Vibration system model; b) Mass block*

The seeder exhibits simple harmonic motion at the supporting point with the following equation of motion:

$$x_s = H\sin\omega t \tag{1}$$

In which:

$$\omega = 2\pi\frac{v}{L} \tag{2}$$

The displacement of the seeder mass block (*m*) was considered to be the generalized coordinates, and the direction of descent was specified to be positive. When the distance between the mass block (*m*) and the static equilibrium position is *x*, the spring deformation should be $x$-$x_s$, and the relative velocity between the mass block and the supporting point is $\dot{x}-\dot{x}_s$. Consequently, the mass block was susceptible to the elastic resilience $k(x$-$x_s)$, and the damping force $c\left(\dot{x}-\dot{x}_s\right)$, as illustrated in Fig.2 (b). The differential equation of motion for the seeder vibration can be expressed as follows using Newton's law of motion:

$$m\ddot{x} = -k\left(x-x_s\right)-c\left(\dot{x}-\dot{x}_s\right) \tag{3}$$

Combining Eq. (1) with Eq. (3) produces the following results:

$$m\ddot{x}+c\dot{x}+kx = H\sqrt{k^2+\left(c\omega\right)^2}\sin\left(\omega t+\arctan\frac{c\omega}{k}\right) \tag{4}$$

Where in Eq. (4),

$$\begin{cases} F_d = H\sqrt{k^2+\left(c\omega\right)^2} \\ \psi = \arctan\dfrac{c\omega}{k} \end{cases} \tag{5}$$

Consolidating the above equations and introducing Eq. (6):

$$\begin{cases} \omega_n = \sqrt{\dfrac{k}{m}} \\ \zeta = \dfrac{c}{2\sqrt{mk}} \\ \Delta_{st,d} = \dfrac{F_d}{m\omega_n^2} \end{cases} \tag{6}$$

Eventually, the vibration equation for the field operation of the seeder was estimated to be:

$$\ddot{x}+2\omega_n\zeta\dot{x}+\omega_n^2x = \Delta_{st,d}\,\omega_n^2\sin\left(\omega t+\psi\right) \tag{7}$$

where: $F_d$ is the amplitude of the excitation force in N, $\psi$ is the phase difference of the excitation in rad, $\omega_n$ is the natural frequency of the seeder in Hz, $\zeta$ is the damping coefficient of the seeder, and $\Delta_{st,d}$ is the net displacement in m.

As demonstrated in Eq. (7), the majority of vibration-causing factors during field operation are the structure, forward speed of the seeder, and soil flatness.

### *Test and analysis of the field operation vibration characteristics*

An empirical study was carried out on the vibration characteristics of the spoon-wheel seed-metering device used in the seeder. Conforming to the vibration frequency and acceleration of the seeder during field operation as estimated by the preparatory test, the UT6819A vibration tester and CA-YD-103 piezoelectric transducer were identified to construct a vibration seeding test stand.

### *Experimental conditions and schematic design*

A three-row spoon-wheel maize precision seeder was adopted for the vibration characteristic test trials. The supporting power was provided by a Kubota M704 tractor, and the previous crop at the test was oilseed rape. The plots were rototilled in preparation for the execution of the study. The parameters of the traits of the field blocks and tractors employed in the test are listed in Table 2.

**Table 2**

**Field vibration test equipment and parameters relevant to field characteristics**

| Categories | Parameters | Values |
|---|---|---|
| Tractor | Calibrated engine rotational speed [r/min] | 2500 |
| | Overall size ($L$×$W$×$H$) [mm] | 4110×1950×2560 |
| Field characteristic parameters | Average soil moisture content [%] | 32.28 |
| | Average soil firmness [kPa] | 718.89 |
| | Capacity [g·cm$^3$] | 1.26 |

The forward speed has an immense impact on the vibration characteristics of the seeder, as can be recognized by the preceding analysis of the theoretical model of those characteristics. To conduct the single-factor test of the effect of the forward speed on the vibration characteristics of the seeder, the various forward speeds were first identified as test factors in this study. Since restrictions on the field plot area and soil viscosity in the hilly and mountainous areas of southwest China, the seeder can't run at a speedy pace to guarantee the quality of seeding. To perform the vibration characteristic test of the seed-metering device at various operating speeds, the forward speed will be adjusted to ranged working conditions, such as 2~6 km/h.

The seeder was suspended over the tractor at three points, as indicated in Fig. 4(a). The vibration sensor was mounted horizontally on the anti-tangle roller bracket, as noted in Fig. 4(b). Real-time monitoring of the tractor's forward speed was attempted with GPS. Since the seeder vibration during field operation was primarily in the vertical direction, the vibration data of the seed-metering device in the vertical direction within 10 seconds after the seeder operates smoothly are predominantly captured. Three replicate tests were performed for each forward speed, and the average value was taken as the ultimate measurement of what would occur.

*a)* *b)*

**Fig. 4 - Field Experiment**

*a) Experimental seeder; b) Sensor mounting position*

### *Seeding performance test of the spoon-wheel seed-metering device under vibration condition*

### *Construction of the vibratory seeding test stand*

A test table for the vibration characteristics of the spoon-wheel seed-metering device test was erected based on the field vibration characteristic of the seeder, as shown in Fig. 5. The main components of the test bench include a JPS-12 type seed-metering device performance test bench, a computer, an acceleration sensor, a vibration tester, a shaker, a spoon-wheel seed-metering device, and other pieces. By altering the speed of the conveyor belt motor on the JPS-12 seed metering test stand, the forward speed of the seeder in the field was simulated. The spoon-wheel seed-metering device was positioned in the center of the metal plate, and the top rod of the exciter acted on the metal plate to secure the entire exciter to the top of the bench. The metal plate was fastened to the bench by four springs, and the vibration load was applied to the metal plate via an exciter. To validate that the seed-metering device runs at a specific vibration frequency and vibration acceleration, the vibration characteristics of the seed-metering device were continuously monitored using the vibration test equipment. When the seed-metering device was in application, the seeds fell from the seed-voting port onto the seedbed belt, which was sprayed with a layer of oil to simulate soil to minimize seed bounce. Lastly, the seeding data was monitored and collected in real-time by the image processing unit of the seed-metering device performance test bench.

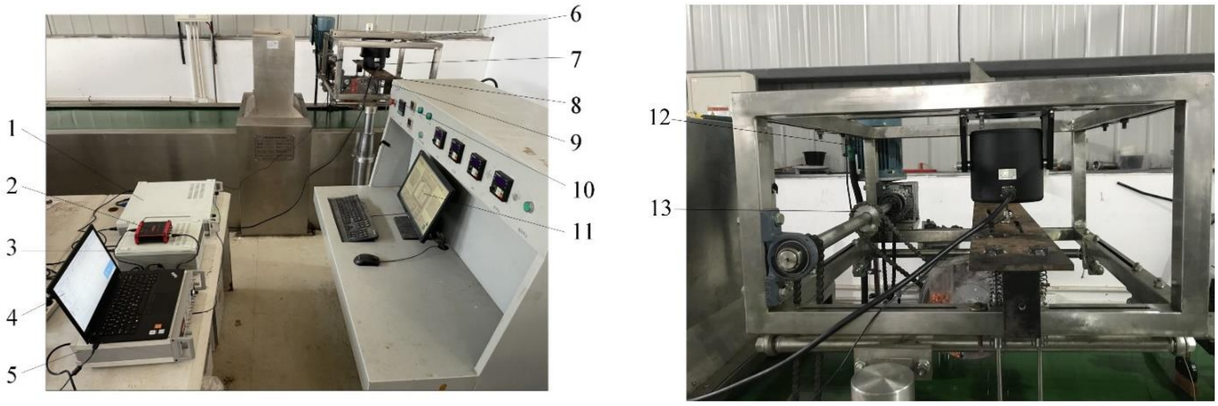


**Fig. 5 - Vibration testing stand for the seed-metering device**

*1. Power amplifier; 2. Data collector; 3. Sweep signal generator; 4. Computer; 5. Vibration tester; 6. Metal bench; 7. Exciter; 8. The metal plate; 9. Vibration acceleration sensor; 10. Spoon-wheel seed-metering device; 11. Operation monitor; 12. Motor; 13. Gearing*

### *Orthogonal Experimental Design*

According to the theoretical analysis model and vibration test results, the working performance of the seed-metering device under vibration conditions is associated with the forward speed, vibration frequency, and vibration acceleration. To comprehend the effect of vibration on the seeding performance of the spoon-wheel seed-metering device, measurements were conducted on the impacts of various forward speeds, vibration frequencies, and vibration accelerations. The qualified rate, multiple rate, leakage rate, and variation coefficient served as evaluation indicators, paired with the three-factor and five-level orthogonal test design approach. Under the agronomic requirements for planting maize net crops in the hilly and mountainous areas of southwest China, the theoretical plant spacing was fixed at 20 cm. The orthogonal test design is listed in Table 3.

**Table 3**

**Three factors five levels orthogonal test factor level table**

| Levels | Factors | | |
|---|---|---|---|
| | A Forward speed [km/h] | B Vibration frequency [Hz] | C Vibration acceleration [m/s$^2$] |
| 1 | 2 | 2 | 0.8 |
| 2 | 3 | 4 | 1.1 |
| 3 | 4 | 6 | 1.4 |
| 4 | 5 | 8 | 1.7 |
| 5 | 6 | 10 | 2 |

## RESULTS

### *Experiment results and analysis of field operation*

The root-mean-square (RMS) of vibration acceleration was used as an evaluation indicator of the seeder vibration amplitude in field operations. The vibration time domain analysis of the seeder in the vertical direction at various forward speeds is depicted in Fig. 6. The time-domain graphic demonstrated that the seeder's vertical vibration acceleration rises with the forward speed, intensifying the vibration effect.

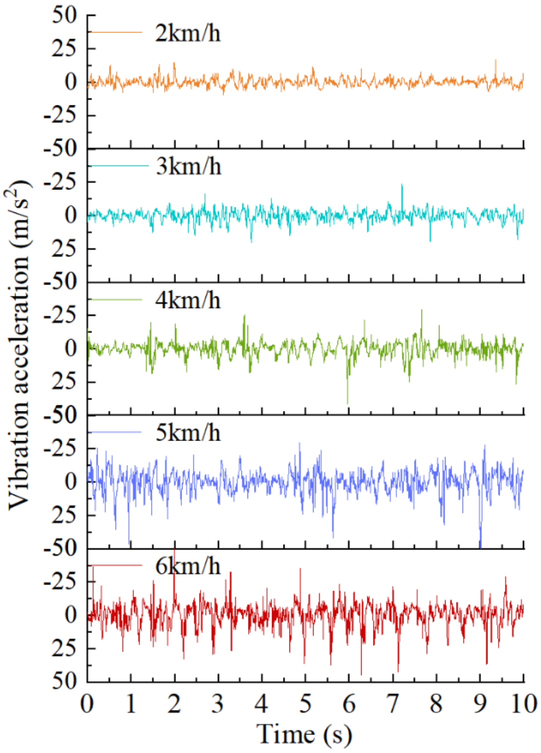


**Fig. 6 - Time domain diagram**

The spectrum analysis of the seeder's vertical direction at various forward speeds is exhibited in Fig. 7. The spectrogram analysis revealed that the seeder was mostly vibrated at low frequencies around forward speeds of 2~6 km/h. The foremost vibration acceleration was generated in this frequency range, where the stronger vibration was predominantly focused at 0~10 Hz. The maximum value of vibration acceleration evolves in lockstep with the forward speed.

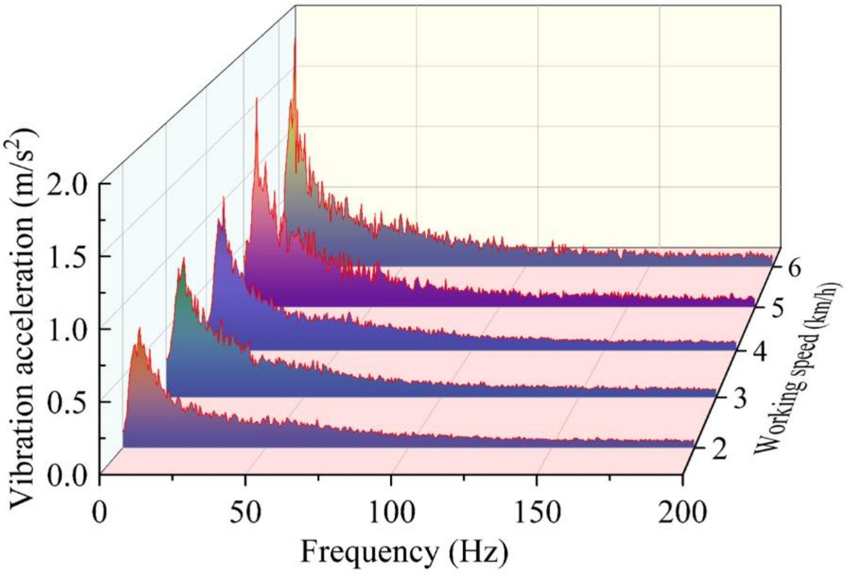


**Fig. 7 - Spectrogram**

The vibration characteristic parameters corresponding to various forward speeds were identified leveraging spectrum analysis, as stated in Table 4. The peak vibration acceleration ascends along with rising forward speed as well as the seeder vibration intensity. Nevertheless, the frequency distribution of the peak vibration acceleration is independent of the forward speed.

**Table 4**

**Vibration characteristics at various forward speeds**

| Working speed [km/h] | Vibration frequency [Hz] | Vibration acceleration [m/s$^2$] |
|---|---|---|
| 2 | 6.0 | 0.85 |
| 3 | 6.5 | 1.02 |
| 4 | 6.5 | 1.17 |
| 5 | 5.0 | 1.65 |
| 6 | 6.5 | 1.86 |

### *Results and range analysis of the orthogonal test*

The results of the test conducted per the orthogonal test design scheme are exhibited in Table 5.

**Table 5**

**Results of the three-factor and five-level orthogonal test**

| No. | *A* | *B* | *C* | Qualified rate [%] | Multiple rate [%] | Leakage rate [%] | Variation coefficient [%] |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 93.0 | 0.3 | 6.7 | 24.3 |
| 2 | 1 | 2 | 2 | 92.5 | 1.5 | 6.0 | 23.5 |
| 3 | 1 | 3 | 3 | 92.6 | 2.3 | 5.1 | 22.6 |
| 4 | 1 | 4 | 4 | 92.3 | 2.4 | 5.3 | 23.7 |
| 5 | 1 | 5 | 5 | 90.8 | 3.6 | 5.6 | 24.8 |
| 6 | 2 | 1 | 2 | 89.6 | 2.7 | 7.7 | 34.2 |
| 7 | 2 | 2 | 3 | 90.8 | 2.4 | 6.8 | 26.1 |
| 8 | 2 | 3 | 4 | 91.1 | 3.6 | 5.3 | 24.3 |
| 9 | 2 | 4 | 5 | 90.9 | 2.8 | 6.3 | 28.5 |
| 10 | 2 | 5 | 1 | 93.3 | 3.1 | 3.6 | 24.9 |
| 11 | 3 | 1 | 3 | 80.1 | 5.6 | 14.3 | 43.2 |
| 12 | 3 | 2 | 4 | 88.2 | 1.7 | 10.1 | 28.9 |
| 13 | 3 | 3 | 5 | 88.5 | 0.4 | 11.1 | 36.2 |
| 14 | 3 | 4 | 1 | 91.0 | 4.1 | 4.9 | 26.9 |
| 15 | 3 | 5 | 2 | 92.4 | 0.7 | 6.9 | 26.7 |
| 16 | 4 | 1 | 4 | 75.0 | 5.3 | 19.7 | 49.4 |
| 17 | 4 | 2 | 5 | 83.0 | 8.1 | 8.9 | 38.1 |
| 18 | 4 | 3 | 1 | 93.0 | 0.7 | 6.3 | 28.2 |
| 19 | 4 | 4 | 2 | 91.2 | 2.4 | 6.4 | 27.3 |
| 20 | 4 | 5 | 3 | 90.0 | 2.9 | 7.1 | 24.6 |
| 21 | 5 | 1 | 5 | 70.0 | 7.6 | 22.4 | 46.7 |
| 22 | 5 | 2 | 1 | 92.2 | 2.1 | 5.7 | 29.4 |
| 23 | 5 | 3 | 2 | 86.3 | 5.3 | 8.4 | 31.4 |
| 24 | 5 | 4 | 3 | 86.9 | 4.0 | 9.1 | 31.0 |
| 25 | 5 | 5 | 4 | 90.4 | 2.7 | 6.9 | 32.9 |

The range analysis of the orthogonal test results is illustrated in Table 6.

**Table 6**

**Range analysis of the orthogonal test results**

| Evaluation indicators | Factors | Levels | | | | | Extreme Difference | Optimal level | Optimal combination |
|---|---|---|---|---|---|---|---|---|---|
| | | $k_1$ | $k_2$ | $k_3$ | $k_4$ | $k_5$ | | | |
| Qualified rate | *A* | 92.24 | 91.14 | 88.04 | 86.44 | 85.16 | 7.08 | 1 | $A_1B_5C_1$ |
| | *B* | 81.54 | 89.34 | 90.30 | 90.46 | 91.38 | 9.84 | 5 | |
| | *C* | 92.50 | 90.40 | 88.08 | 87.40 | 84.64 | 7.86 | 1 | |
| Multiple rate | *A* | 2.02 | 2.92 | 2.50 | 3.88 | 4.34 | 2.32 | 1 | $A_1C_1B_2$ |
| | *B* | 4.30 | 3.16 | 2.46 | 3.14 | 2.60 | 1.84 | 3 | |
| | *C* | 2.06 | 2.52 | 3.44 | 3.14 | 4.50 | 2.44 | 1 | |
| Leakage rate | *A* | 5.74 | 5.94 | 9.46 | 9.68 | 10.50 | 4.76 | 1 | $A_1C_1B_5$ |
| | *B* | 14.16 | 7.50 | 7.24 | 6.40 | 6.02 | 8.14 | 5 | |
| | *C* | 5.44 | 7.08 | 8.48 | 9.46 | 10.86 | 5.42 | 1 | |
| Variation coefficient | *A* | 23.78 | 27.60 | 32.38 | 33.52 | 34.28 | 10.5 | 1 | $A_1B_5C_1$ |
| | *B* | 39.56 | 29.20 | 28.54 | 27.48 | 26.78 | 12.78 | 5 | |
| | *C* | 26.74 | 28.62 | 29.50 | 31.84 | 34.86 | 8.12 | 1 | |

According to the range analysis results shown in Table 6, the primary and secondary factors that determine the qualified rate of the spoon-wheel type seed-metering device are $B>C>A$, and the ideal combination is $A_1B_5C_3$. The major and secondary factors that affect the multiple rate are $C>A>B$, and the optimal combination is $A_1C_1B_2$. The main and auxiliary factors affecting the leakage rate are $B>C>A$, and the best combination is $A_1C_1B_5$. The initial and subsequent factors influencing the variation coefficient are $B>A>C$, with $A_1B_5C_1$ being an excellent combination. The results of the extreme difference analysis results also demonstrated that all evaluation indicators had the same desired levels for forward speed (*A*) and vibration acceleration (*C*), which are $A_1$ and $C_1$, respectively. The appropriate level of vibration frequency (*B*) is $B_2$ for the multiple rate, while $B_5$ is the preferred level for the other three evaluation indicators. When the acceleration of vibration remains constant, the vertical displacement of the seed-metering device will decrease as the vibration frequency increases. Consequently, whilst the vibration frequency is fixed, the seed-metering device behaves reasonably smoothly and the seeding performance is more stable under lower forward speed and vibration acceleration conditions.

Based on the detailed investigation, the ideal forward speed of the spoon-wheel maize seeder in the hilly and mountainous areas of southwest China is 2 km/h. At this particular time, the seeder is vibrating at a frequency of 10 Hz and an acceleration of 0.8 m/s$^2$.

### *Effect of forward speed, vibration frequency, and acceleration on the qualified rate*

As observed in Fig. 8, the qualified rate of the spoon-wheel seed-metering device significantly decreased as the forward speed increased, attending from 92.24% to 85.16%, while the qualified rate progressively evolved from 81.54% to 91.38% as the vibration frequency increased. When the vibration acceleration increases, there is a notable decline in the qualified rate from 92.5% to 84.64%.

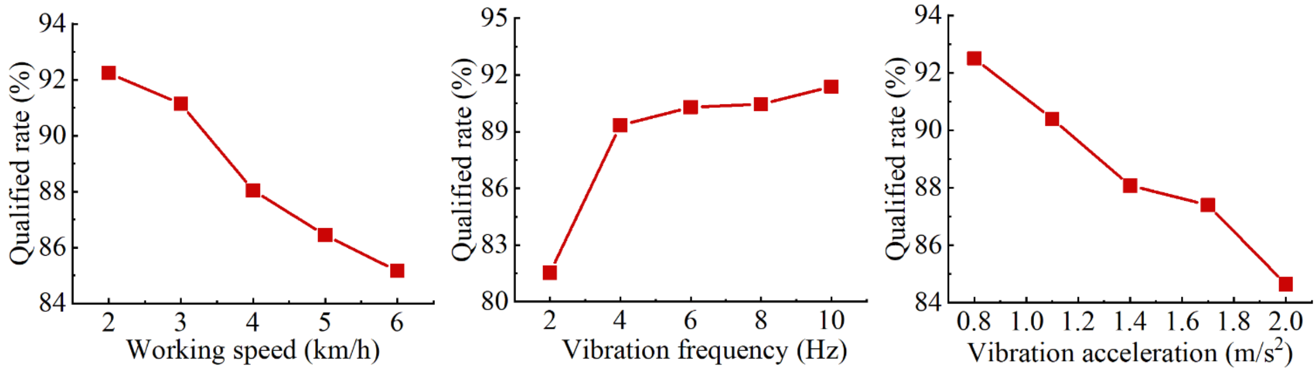


**Fig. 8 - Effect of the working speed, vibration frequency, and acceleration on the qualified rate**

### *Effect of forward speed, vibration frequency, and acceleration on the multiple rate*

As illustrated in Fig. 9, the multiple rate exhibited an overarching increasing tendency with an increase in forward speed and vibration acceleration. With the increase in forward speed, the multiple rate jumped from 2.02% to 4.34%, accompanied by an increase in vibration acceleration from 2.06% to 4.50%. As the vibration frequency increased, the multiple rate generally trended lessened dropping from 4.30% to 2.60%.

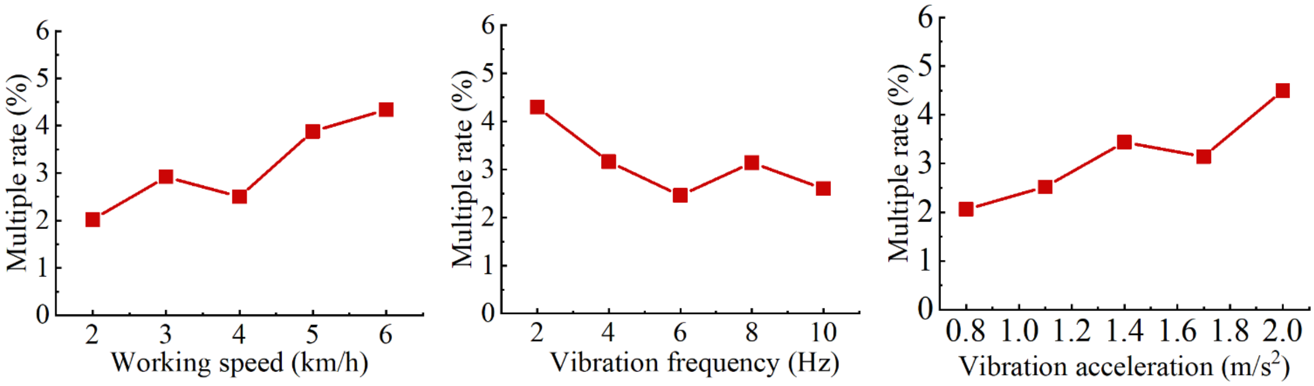


**Fig. 9 - Effect of the working speed, vibration frequency, and acceleration on multiple rate**

### *Effect of forward speed, vibration frequency, and acceleration on the leakage rate*

The leakage rate of the spoon-wheel seed-metering device exhibits an increasing trend given that the forward speed and vibration acceleration increase, as indicated in Fig. 10. There was a significant fluctuation in the leakage rate, which went from 5.74% to 10.5% with an increase in forward speed, and from 5.44% to 10.86% with a vibration acceleration increase. There was a discernible reduction in the leakage rate as vibration frequency increased from 14.16% to 6.02%.

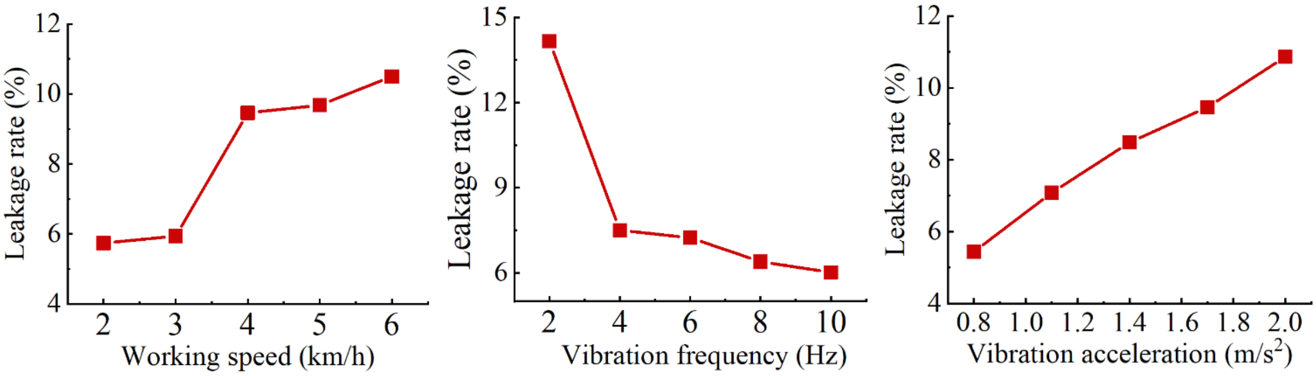


**Fig. 10 - Effect of the working speed, vibration frequency, and acceleration on leakage rate**

### *Effect of forward speed, vibration frequency, and acceleration on the variation coefficient*

The variation coefficient of the spoon-wheel seed-metering device exhibits an increasing trend when the forward speed and vibration acceleration increase as stated in Fig. 11. With an increase in forward speed, the variation coefficient increases from 23.78% to 34.28%, and from 26.74% to 34.86% with an increase in vibration acceleration, while it decreases from 39.56% to 26.78% with an increment in vibration frequency.

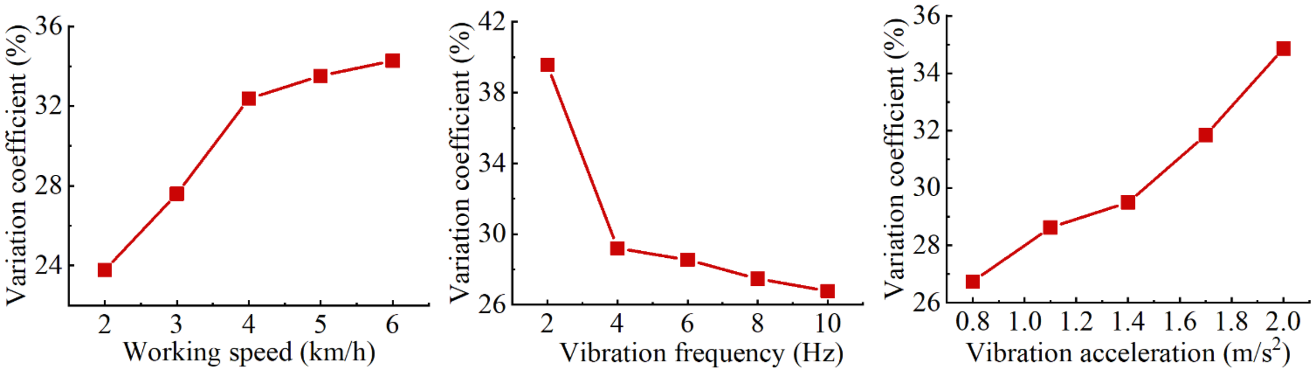


**Fig. 11 - Effect of the working speed, vibration frequency, and acceleration on variation coefficient**

An extensive assessment of the orthogonal test results revealed that the seeding performance of the spoon-wheel seed-metering device drastically deteriorated with rising forward speed. Which stipulates that the seeds in the spoon hole have a shorter seed-filling and cleaning duration. As a result, the seeds are filled and cleared earlier than they should, thereby boosting the probability of the multiple and leakage seeding. When the vibration acceleration serves as constant, the vertical displacement of the seed-metering device will decrease as the vibration frequency increases since the vibration frequency and acceleration manifest simultaneously. Consequently, the qualified rate increased and the leakage rate dropped as the vibration frequency increased. Leakage seeding occurs when the vibration acceleration increases and the vertical displacement of the seed-metering device increases, the seeds effortlessly break away from the spoon hole during the seed-filling and seed-cleaning processes and fall back to the seed-filling area again. The qualified rate, multiple rate, and leakage rate are strongly related to the variation coefficient. Hence, the variation coefficient will increase with advancements in forward speed and vibration acceleration.

### *Variance analysis of the orthogonal test*

To identify the major and secondary relationships between the contribution of the test factor to the evaluation indicators and the best level, the range analysis of the orthogonal test results is frequently utilized. The results of the orthogonal test were further subjected to variance analysis to ascertain the significance of the impact of the experimental variables on the evaluation indicator. The results of the variance analysis are presented in Table 7.

**Table 7**

**Variance analysis of the three-factor and five-level orthogonal test**

| Variables | Source of variance | Sum of squares | Df | Mean square | *F*-value | *P*-value | Significance |
|---|---|---|---|---|---|---|---|
| Qualified rate | *A* | 182.57 | 4 | 45.64 | 4.16 | 0.0024 | * |
| | *B* | 322.35 | 4 | 80.59 | 7.34 | 0.003 | ** |
| | *C* | 179.21 | 4 | 44.80 | 4.08 | 0.026 | * |
| | Error | 131.80 | 12 | 10.98 | | | |
| Multiple rate | *A* | 18.498 | 4 | 4.625 | 1.07 | 0.412 | - |
| | *B* | 10.498 | 4 | 2.625 | 0.61 | 0.664 | - |
| | *C* | 17.450 | 4 | 4.363 | 1.01 | 0.440 | - |
| | Error | 51.747 | 12 | 4.312 | | | |
| Leakage rate | *A* | 101.034 | 4 | 25.258 | 4.55 | 0.018 | * |
| | *B* | 224.526 | 4 | 56.131 | 10.10 | 0.001 | ** |
| | *C* | 87.966 | 4 | 21.991 | 3.96 | 0.028 | * |
| | Error | 66.673 | 12 | 5.556 | | | |
| Variation coefficient | *A* | 401.67 | 4 | 100.42 | 8.37 | 0.002 | ** |
| | *B* | 551.99 | 4 | 138.00 | 11.51 | 0.000 | ** |
| | *C* | 196.50 | 4 | 49.13 | 4.10 | 0.025 | * |
| | Error | 143.90 | 12 | 11.99 | | | |

**Note: * means significant influence in 95% confidence interval, ** means significant influence in 99% confidence interval, - means no significant influence.*

The deductions of the variance analysis indicated that forward speed had a generally significant influence on the qualified rate and leakage rate, as well as an exceedingly significant influence on the variation coefficient. Vibration frequency had an especially substantial effect on the qualified rate, leakage rate, and variation coefficient, while vibration acceleration typically had a general impact on these three evaluation indicators. There was no discernible influence of the three factors on the multiple rate. Thus, the seed-metering device has to conserve the qualified rate during the actual seeding operation, while minimizing the leakage rate.

## CONCLUSIONS

The vibration system model of the seeder in field operation was constructed and theoretically investigated by employing the spoon-wheel seeder as the study object. It is concluded that the quality of the seeding is affected by the construction of the seeder, forward speed, ground roughness, and other variables. The vibration characteristics of the seeder were tested and analyzed at a field speed of around 2 to 6 km/h.

The main conclusions are as follows:

(1) The time-domain investigation implies that the vibration accelerates with the forward speed and that the higher the forward speed, the more vibration it renders with increasing forward speed. The vibration properties of the seed-metering device at various operating speeds were determined through spectrum analysis.

(2) A three-factor and five-level orthogonal test was conducted with the development of a vibration seeding test stand, and the forward speed, vibration frequency, and vibration acceleration as test factors. The results concluded that the forward speed, vibration acceleration, and vibration frequency are the primary and secondary factors influencing the qualified rate of the spoon-wheel seed-metering device.

(3) The qualified rate increased regardless of the vibration frequency and decreased with increasing the forward speed and vibration acceleration. The leakage rate and variation coefficient increased with forward speed and decreased as the vibration frequency improved. The fluctuating trend of the multiple rate is generally consistent with the variation coefficient and the leakage rate.

(4) Both the qualified rate and the leakage rate are significantly impacted by the forward speed, which also has a highly substantial influence on the variation coefficient. The vibration frequency and vibration acceleration exhibited high and general effects on the qualified rate, leakage rate, and variation coefficient, respectively. Concerning the multiple rate, there was no substantial effect of any of the three factors on it. In the event of field vibration, the research in this paper can serve as a reference basis for optimizing and enhancing the spoon-wheel seed-metering device, as well as the seeding quality of the seeder.

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