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Sowing Performance of the Seeder Drill for the 2BYG-220 Type Combined Rapeseed Planter under Vibration Conditions

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Featured Application: Sowing Rapeseed.

Abstract: The direct sowing of rapeseed requires shallow tillage for stubble removal, which can cause significant vibrations that impact the seed metering device, thereby affecting the quality of seeding. This study focuses on a double-row hole-wheel-type seed metering device on the 2BYG-220 type combined rapeseed planter. Initially, vibrations experienced by the seed drill during field operations were measured and analyzed, revealing that the vibration frequencies during field operations predominantly ranged between 0 and 25 Hz. Consequently, an eccentric wheel–return-spring-type vibration seed metering test rig was designed, manufactured, and set up. By swapping out the eccentric wheel on the test rig, the amplitude was mainly concentrated within 3 mm. The test results indicate that amplitude had a minimal impact on the performance of the double-row hole-wheel-type rapeseed seed metering device, whereas vibration frequency had a more significant effect. When the vibration frequency was between 0 and 10 Hz, the seed metering device maintained a stable output between 7.6 and 8.2 g/min, with minimal impact from vibrations: the coefficient of variation for seeding uniformity ranged between 35.81% and 44.58%, indicating stability and good uniformity. However, when the vibration frequency ranged from 10 to 24 Hz, the output of the seed metering device decreased rapidly and exhibited a linear relationship with frequency changes, with a determination coefficient (R^2) of 0.92376. The coefficient of variation for seeding uniformity increased rapidly and also showed a linear relationship with frequency changes, with a determination coefficient (R^2) of 0.87973. Vibrations with frequencies greater than 10 Hz had a considerable impact on the performance of the seed metering device.

Keywords: rapeseed; seeder drill; vibration frequency; amplitude distribution; main frequency range; determination coefficient

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1. Introduction

Rapeseed is the largest oilseed crop in China, and it is mainly planted in the middle and lower reaches of the Yangtze River, where the terrain is complex and mostly bumpy [1]. Rapeseed seeds have an almost spherical appearance, and, collectively, their physical properties imitate those of a fluid. These characteristics make the seeds particularly prone to disruption by external forces during the planting process. When seed drills operate in the field, the native vibrations from the engine, vibrations caused by the tractor tires interacting with the soil, and vibrations from rototilling can all significantly impact the actual performance of the seeding equipment [2–4].

In order to investigate the effect of the vibration on the sowing performance of the seeding equipment, some methods were used to stimulate the field vibration and test the sowing uniform by test bench in the laboratory. Cujbescu et al. [5] simulated vibrations

under laboratory conditions, on the stand, by using rubber hemispheres with diameters between 30 and 100 mm. They analyzed the influence of the soil grinding degree on sowing precision in operating conditions with three working speeds: 4, 6, and 8 km·h^{-1}. Sowing precision was influenced by seedbed preparation and the working speed, which decreased as the seedbed developed larger irregularities. Wu et al. [6] measured seed-filling characteristics under vibration conditions with a frequency of 0–180 Hz, which had a significant impact on the target seed rate, the missing rate of seed filling, the multiple ratios of seed filling, the seed-filling angle, and the number of retained seeds when the speed of the seed metering wheel was 20 rpm. Yu et al. [7,8] investigated the effects of both internal and external excitation vibrations on the efficacy of a seed dispenser in a rice precision hole seeder using a six-degree spatial vibration tester. A decrease in accuracy and increase in dispersion were noted within the 70–130 Hz range. Wang et al. [9] studied the vibrational characteristics of finger pickup-type maize seed drills in field operations, indicating that an increase in the seed drill's working speed did not impact the distribution of vibrational energy in the frequency domain. Wang et al. [10] designed a chisel-type seeding opener with a contour-following roller to address issues such as uneven field surfaces and poor uniformity and stability in seeding depth due to wide-width seed drills.

The vibrational effect on the sowing performance was also investigated by simulation experiment, such as the discrete element method (DEM). Li et al. [11] employed the discrete element method to investigate the seed suction capability and degree of dispersion of a seed population using an air-suction-type vibratory seed metering device, discovering that the seed population entered a boiling state when the vibration frequency was 18 Hz and the amplitude 4.6 mm, which enhanced the seed suction effect. Chen et al. [12,13] studied the movement patterns of rice seeds when subjected to vibrations, finding that the dispersion of the seeds was optimal at frequencies of 11–12 Hz and amplitudes of 12–13 mm. They theoretically analyzed the motion of seeds inside an air-suction vibratory seeding test bench, noting that seeds would be cast out when the frequency exceeded 11.2 Hz. Wang et al. [14] focused on an air-suction-type super rice precision seedling seed drill and determined that vibration frequency was the main factor that affected the seed metering device's ability to pick up seeds. The "boiling" of a seed population under the influence of vibration facilitates effective seed suction, leading to the identification of an optimal combination of working parameters for seed layer thickness, hole spacing for double holes, and vibration frequency. Zhang et al. [15] conducted research on shovel-type precision maize seed drills, deriving a vibration model for the seed drill and analyzing the relationship between vibrations caused by field unevenness and the performance of the seed drill. The research highlighted that the structure of the seed drill, its operational speed, the distance between the inclined disc spoon-type maize precision seed metering device and the soil surface, and soil unevenness and soil stickiness are crucial factors influencing seed drill performance. The seed drill minimized vibration through its contour-following mechanism, stabilized the seeding depth, and achieved improved seed placement. Vibration significantly affects the performance of seed metering devices, but current research mainly focuses on air-suction seed metering devices and those for large seeds, with fewer studies conducted on the influence of vibrational effects on the performance of hole-type wheel rapeseed seed drills.

This study examined the vibrational characteristics of a double-row hole-wheel-type seed metering device used in the 2BYG-220 type combined rapeseed planter in rice stubble fields. According to the measured amplitude and frequency of the planter, an eccentric wheel-return-spring-type vibration seed metering test rig was designed, manufactured, and set up, to investigate the impact of field-induced vibrations on the seed metering device's performance, analyzing how different vibration amplitudes and frequencies affect seed metering as well as EDEM simulation experiment. The goal is to mitigate the detrimental effects of vibration on the device's performance.

2. Materials and Methods

2.1. Field Vibration Data Collection and Analysis

A test field where the surface was free of significant standing water and the rice had been recently harvested was chosen in Shaoshan, Hunan Province of China. A five-point sampling method was employed to measure the average height of rice stubble, moisture content, and soil firmness across the plot, selecting 1 m^2 areas from each of the four corners and the center of the field. On-site measurements revealed an average rice stubble height of 21.63 cm and a soil firmness of 864 kPa. Fresh, clean surface soil samples of about 100 g were collected from each area. The soil moisture content was determined using an oven-drying method, in which soil was dried in an oven set between 105 °C and 110 °C until its weight remained constant. The moisture content was calculated by dividing the mass of the dried soil by its pre-dried mass, and five sets of data were averaged to obtain a soil moisture content of 34.8% for the rice stubble field.

The 2BYG-220 type combined rapeseed planter [16], jointly developed by Hunan Agricultural University and Changsha Sanlaite Agricultural Machinery Equipment Co., Ltd., in Changsha, Hunan Province of China, was selected as the test equipment. The tractor matched with the seed drill had a power of 52.5 kW, overall dimensions of 160 cm× 244 cm × 165 cm, a working width of 220 cm, and six seeding rows. The seeding rate was 1.5–7.5 kg/ha, the fertilizer application rate was 0–1500 kg/ha, the productivity was 0.3–0.4 ha/h, and the operational speed was 0.56–0.83 m/s.

As shown in Figure 1, an accelerometer firmly attached to a flat surface in the middle of the seed drill with strong adhesive glue was used to capture vibration signals perpendicular to the ground. The accelerator's BNC cable harness was secured with tape to prevent significant movement during data collection and to avoid static electricity from friction between the cable and seed drill parts, which could cause cable noise. The wireless router was placed on the side of the seed drill to ensure minimal obstruction and stable data transmission; a transmission signal should avoid mobile phone frequency bands (1.6–2.8 GHz) to prevent electromagnetic interference. Other measuring instruments were securely taped in place and a small piece of plastic foam was placed underneath the instruments for cushioning. The power inverter was installed near the seed drill's 12 V battery and converted the 12 V DC to 220 V AC to power the vibration measurement system equipment.



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

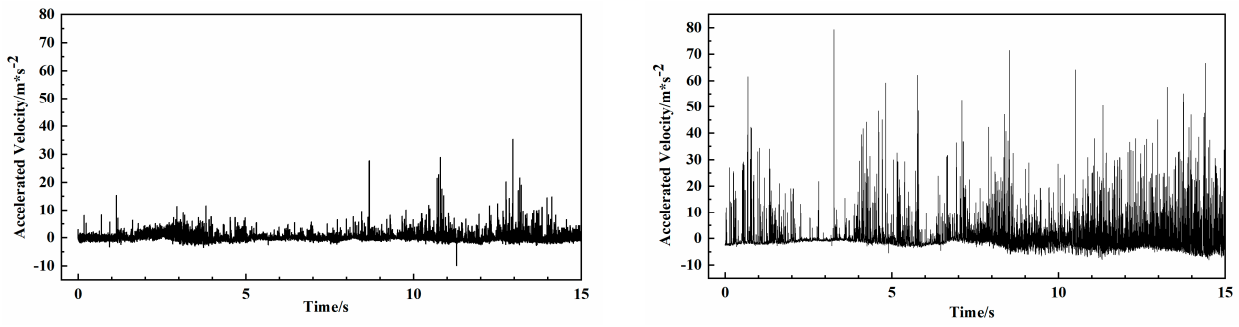
Figure 1. Seeder vibration test system with acceleration sensor test point location mounted on a 2BYG-220 type combined rapeseed planter (**a**) as well as the rice stubble field for test (**b**).

The vibration in the rice stubble field was categorized as a random analog signal. An accelerometer was used to convert the analog signal into an electrical one. The accelerometer captured a series of discrete data points, which lacked continuity, while the field vibration signal was continuous. Therefore, to ensure that the discrete signals did not suffer from

frequency aliasing, the accelerometer's acquisition of vibration signals had to adhere to the sampling theorem.

The 2BYG-220 type combined rapeseed planter was primarily subjected to vibrations from uneven ground and vibrations caused by the rotating components of the seed drill during operations such as rotary tilling, stubble removal, seeding, and fertilization. Given the seed drill's low advancement speed, the rotary tiller cutter shaft's rotation speed of 200–300 rpm, the machine was predominantly influenced by low-frequency vibrations; i.e., the highest frequency was less than 200 Hz. Therefore, a sampling frequency of 2000 Hz was selected to prevent frequency aliasing in the frequency domain and to avoid significant amplitude distortion in the time domain [17]. The experimental field was chosen for its uniform rice stubble height and the completeness of the field blocks in the stubble land. The experiment was conducted in two sets: first, the seed drill operated at a low speed of 0.56 m/s; second, it operated at a higher speed of 0.83 m/s. Each test lasted 20 min to satisfy the requirements for the subsequent spectral analysis of the signal length. During the tests, the vibration test system was powered up and the DAQami data collection and analysis software, which pairs with the E-1608 data acquisition card, was launched on a portable computer. The software was set up to connect to the wireless router network, and the sampling frequency was adjusted to 2000 Hz.

After subjecting the raw vibration signals to appropriate and rational mathematical treatment, we found that the minimum acceleration was -9.83944 m/s^2 and the maximum acceleration was 35.2845 m/s^2 in low-speed conditions, as seen in Figure 2. In high-speed conditions, the minimum acceleration was -9.04467 m/s^2 and the maximum acceleration was 79.26817 m/s^2. It is clear that the vibration intensity of the seed drill was significantly greater at high speeds than at low speeds. When installing the accelerometer, the vertically downward direction was designated as negative and the vertically upward as positive. As the seed drill performed shallow tilling and stubble removal, the blades cutting downward into the soil produced an upward reactionary force. This caused the seed drill to move upwards, resulting in an upward acceleration. Conversely, when gravity affected the seed drill on its descent, it experienced a downward acceleration. Due to the substantial rotational inertia of the rotary tiller blades at high speeds, the downward acceleration should be between 0 and -9.8 m/s^2, as evident in Figure 2.



(**a**) Low speed (**b**) High speed

Figure 2. Time domain signal diagram for the vibration acceleration of the seed drill at different speed.

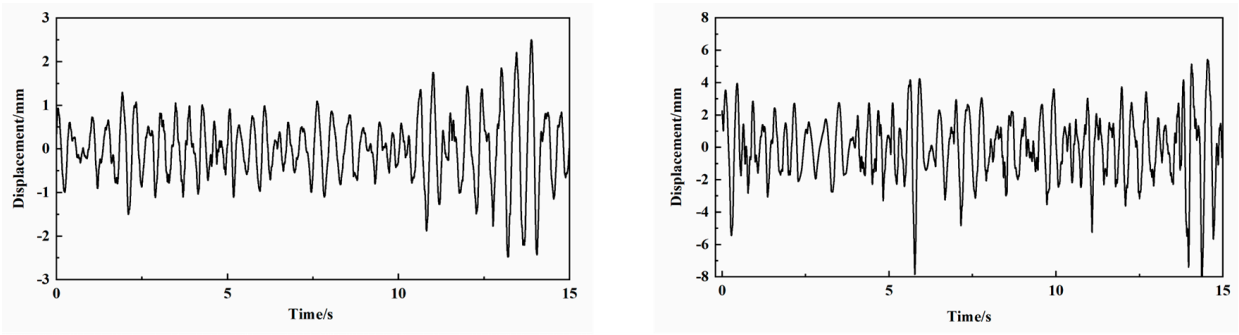
The vibration signals from the seed drill in the rice stubble field exhibit numerous discrete peaks. These are likely due to the rotary tiller blades encountering the tough rice stubble roots during rotary tillage for stubble removal, generating considerable reactionary forces when cutting through them. This phenomenon is particularly notable when the seed drill operates at high speeds. The vibrations of the seed drill on the rice stubble field were significant and markedly increased with the operational speed of the seed drill.

To process the acceleration signals gathered during the test, a frequency domain integration was performed. The formula for the numerical computation of the second integration in the frequency domain is as follows [18,19]:

$$y(r) = \sum_{K=0}^{N-1} -\frac{1}{(2\pi\kappa\Delta f)^2} H(k)X(k)e^{j2\pi kr/N} \quad (1)$$

Matlab 2018 was employed to carry out a Fourier transform on the vibration data, from which trend terms were removed [20]. The data underwent second-order integration in the frequency domain, and an inverse Fourier transform was then applied to obtain the vibration displacement as a function of time. The selected lower and upper cutoff frequencies were 2 Hz and 200 Hz, respectively.

As shown in Figure 3, the seed drill's maximum vibration amplitude reached 2.49 mm at low operational speeds; at high operational speeds, the maximum amplitude increased to 7.78 mm, indicating that the vibration amplitude escalated with the seed drill's working speed. There were sporadic sharp rises in the vibration amplitude of the seed drill within the first 15 s. This occurred because the 2BYG-220 type rapeseed combined seed drill performed rotary tillage for stubble removal. It shattered parts of the rice stubble that were embedded in the soil—roots and stalks—and were more robust than the soil itself. When the rotary tiller blades encountered difficulty in breaking the stubble smoothly, the vibrations from the tillage process increased abruptly. Hence, the seed drill experienced random surges in vibration amplitude. The vibration pattern of the seed drill in the rice stubble field is fundamentally composed of sinusoidal signals. Overall, when the 2BYG-220 type rapeseed combined seed drill is in operation, the majority of vibration amplitudes are concentrated within 3 mm.



(**a**) Low speed (**b**) High speed

Figure 3. Curve diagram of vibration displacement of the seed drill at under different speed.

For this analysis, the Welch function within Matlab was used to execute the Welch method for PSD estimation [18–20]. It is shown that the distribution of vibration power for the seed drill during both high-speed and low-speed operations spanned from 0 to 75 Hz, with a concentration within the 0 to 25 Hz range. The frequency range of the concentrated vibration remained highly consistent under both high-speed and low-speed conditions. The amplitude of vibration power was greater at high speeds than at low speeds, suggesting that while the working speed of the seed drill does not affect the frequency distribution of vibration power, it significantly impacts the amplitude of vibration power.

2.2. Test Bench and Method

The vibration fundamental of the seed drill working in a rice stubble field was identified as a sinusoidal wave based on the data collected. Consequently, this study employed an eccentric wheel mechanism to convert rotary motion into reciprocating motion at the equilibrium position, thereby generating vibrations.

The driven component maintained close contact with the eccentric wheel through the restoring force of a return spring. The rotation of the eccentric wheel drove the driven component in sinusoidal motion. The displacement, velocity, acceleration, and vibration frequency of the driven component were determined by the following equations:

$$S = e(1 - \cos \omega t) \tag{2}$$

$$v = e\omega \sin \omega t \tag{3}$$

$$a = e\omega^2 \cos \omega t \tag{4}$$

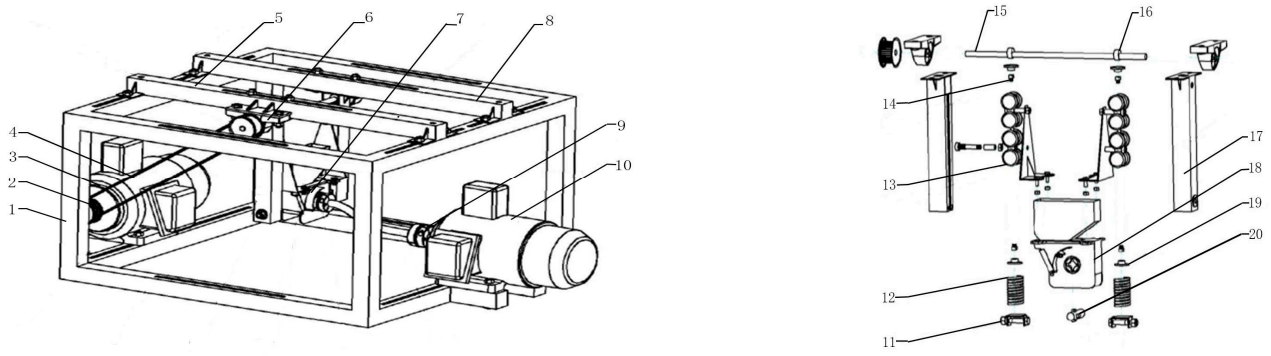
$$f = \frac{n}{60} = \frac{\omega}{2\pi} \tag{5}$$

where S is the displacement of the driven component, v is its velocity, a is its acceleration, e is the eccentricity, f is the vibration frequency of the driven component, and n is the rotational speed of the eccentric wheel.

Analysis of the motion laws of the driven component revealed that the amplitude of the vibration A = e; therefore, changing the eccentricity of the eccentric wheel can alter the amplitude of the driven component, and adjusting the rotational speed of the eccentric wheel can change its vibration frequency.

Considering that the vibration frequency experienced by the seed drill during field operations ranged from 0 to 25 Hz and the amplitude from 0 to 3 mm and that the mass of the driven component (the seed metering device) was 1.8 kg, numerical calculations performed using Matlab indicate that the stiffness of the return spring must be greater than 25.15 N/mm and that the maximum torque for the eccentric wheel shaft was 17.58 N·m.

As shown in Figure 4, The device consists of an eccentric wheel shaft with two pulley assemblies, which are connected to the shaft via return springs. The shaft is driven by a variable frequency motor, which rotates the eccentric wheels, causing the pulley assemblies to vibrate in a sinusoidal pattern. The amplitude and frequency of the vibrations can be adjusted by changing the settings of the variable frequency motor and the return springs. The distance between the two eccentric wheels can be adjusted using set screws, which affects the amplitude of the vibrations. The rotation speed of the variable frequency motor I can be changed to adjust the frequency of the vibrations.



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

Figure 4. Structure diagram of (**a**) the whole structure and (**b**) the exploded structure of the vibration test bench. 1. base frame; 2. variable frequency motor I; 3. timing belt; 4. timing belt; 5. top block I; 6. bearing; 7. coupler; 8. top block II; 9. steel wire flexible shaft; 10. variable frequency motor II; 11. limit switch; 12. return spring; 13. pulley assembly; 14. square head stud; 15. eccentric wheel shaft; 16. eccentric wheel; 17. slide slot; 18. the double-row hole-wheel-type seed metering device; 19. top plate; 20. seedmeter shaft.

During the bench test, we added about 96 g of rapeseed in the seed box, adjusted the speed of the seed shaft, placed the inoculation box in the seed filter outlet and timed it

with the stopwatch at the same time, vaccinated continuously for 5 min, used ME203E/02 balance quality (precision 0.001 g), repeated each test condition for 10 times, averaged the test results, and obtained the displacement of the seed filter per unit time per minute; this served as the data for subsequent analysis.

2.3. Simulation Test by Discrete Element Method

Based on the discrete element method and EDEM 2018 software (DEM Solutions Limited, Edinburgh, UK), the discrete element model of an eccentric wheel-return-spring-type vibration seed metering test rig for rapeseed was established to analyze the impact of field-induced vibrations on the seed metering device's performance, analyzing how different vibration amplitudes and frequencies affect seed uniformity, as shown in Figure 5. The geometric model of the test rig was established by using parametric three-dimensional software Pro/E 5.0 which was integrated into the EDEM. The Hertz-Mindlin (no-slip) model was chosen as the particle contact model with a hard-sphere model. The simulation parameters are shown in Tables 1 and 2, which were calibrated by the simulation test for the angle of accumulation. The model and simulation method can be found in our previous paper [21].

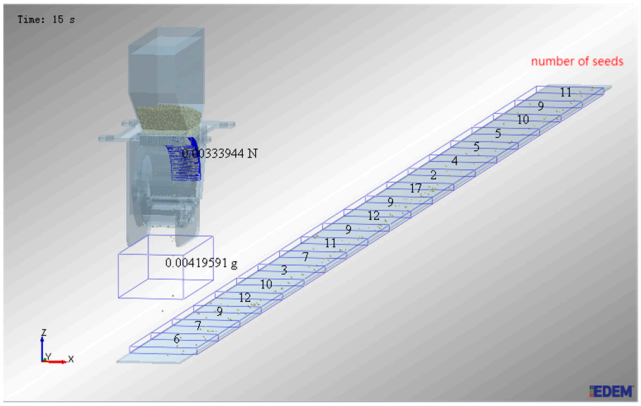


Figure 5. Scheme of the discrete element model of an eccentric wheel-return-spring-type vibration seed metering test rig for rapeseed.

Table 1. Material parameters used in the DEM simulations.

Material	Poisson's Ratio	Shear Modulus/MPa	Density/kg·m^3
Rapeseed	0.28	11.0	0.28
PMMA	0.3	177.0	11.0
Nylon	0.4	102.0	1060
Belt conveyor	0.32	7.8	1240

Table 2. Contact parameters used in the DEM simulations.

Interaction	Coefficient of Restitution	Coefficient of Static Friction	Coefficient of Rolling Friction
Rapeseed—Rapeseed	0.6	0.5	0.1
Rapeseed—PMMA	0.5	0.5	0.1
Rapeseed—Nylon	0.6	0.5	0.1
Rapeseed—Belt conveyor	0.001	0.999	0.999

During the simulation test, the total quality of rapeseed was adjusted in the pellet factory and consistent with the bench test. Through the mass sensor set in the 5 s–15 s module, the total mass of rapeseed seeds was obtained and the unit time displacement of the seed filter under each test condition was calculated. The seed metering shaft speed was set at 40 r/min to ensure an optimal seed discharge rate per unit time and seed metering

uniformity coefficient for the device and also to study the impact of vibration on the seed metering performance of the double-row hole-wheel seed metering device. Table 3 shows the experimental parameters of the test bench for the sowing uniform test of the double-row hole-wheel seedmeter. The seed metering device's discharge rate and the coefficient of variation in seed metering uniformity was measured and calculated, respectively.

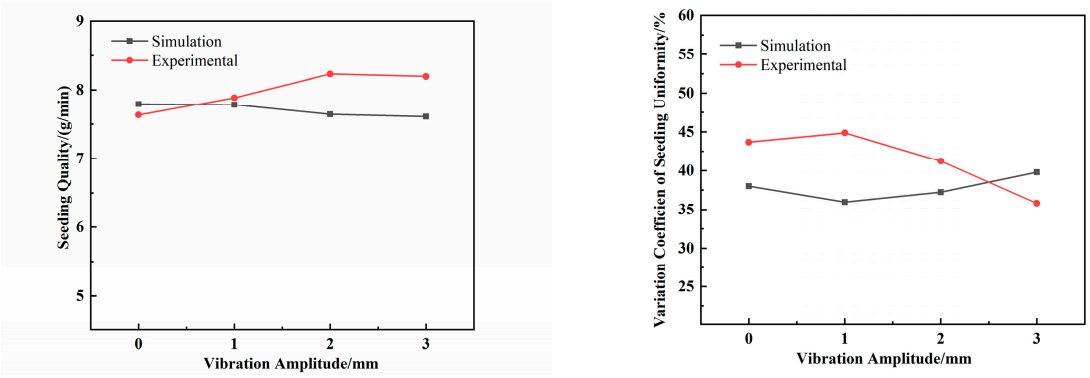
Table 3. Experimental parameters of the test bench for the sowing uniform test of the double-row hole-wheel-type seed metering device under vibration.

Test Plan	Vibration Amplitude/mm	Vibration Frequency/Hz
A	0, 1, 2, 3	6
B	3	2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24

3. Results

3.1. The Impact of Vibration Amplitude on the Performance of Seeder Drill

As shown in Figure 6, under the influence of vibrations with a frequency of 6 Hz and an amplitude of 0–3 mm, the seed metering device exhibited gradual changes in the seed discharge rate per unit time and in the variation coefficient of seed metering uniformity, maintaining relative stability. This indicates that under these conditions, the seeds within the seed metering device remained relatively calm without detaching from the hole-wheel. The simulation and experimental results are basically stable, with their curves intersecting, indicating that the simulation and experimental results are largely consistent. Thus, within this amplitude range, the vibration magnitude has little effect on the performance of the seed metering performance of the device.



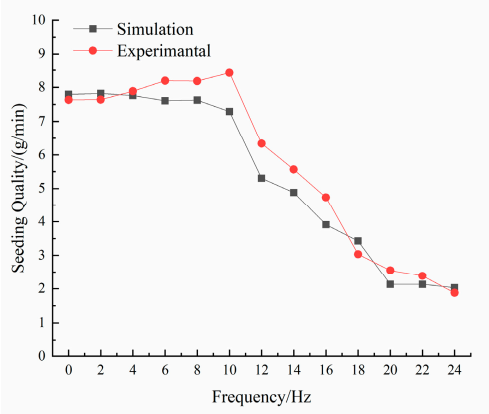
(**a**) Relationship between vibration amplitude and seeding quality

(**b**) Relationship between vibration amplitude and seeding uniformity variation coefficient

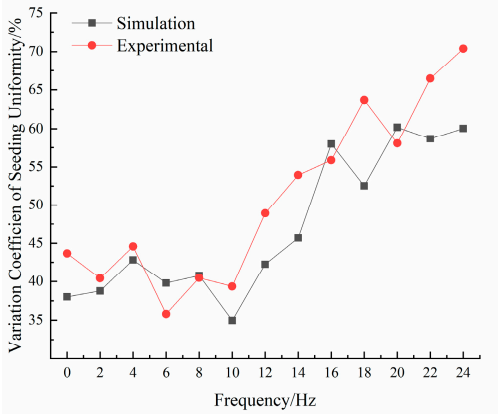
Figure 6. Sowing performance based on the relationship between vibration amplitude and (**a**) seeding quality and (**b**) the seeding uniformity variation coefficient.

3.2. The Impact of Vibration Frequency on the Performance of the Seeder Drill

As depicted in Figure 7, compared to the impact of amplitude on the performance of the seed metering device, the vibration frequency had a more significant effect. Analyzing the experimental results of the relationship between the device's vibration frequency and discharge rate, it can be seen that the seed discharge rate of the device remained stable between 7.6 and 8.2 g/min when the vibration frequency was between 0 and 10 Hz, with minimal impact from the vibration. However, as the vibration frequency increased from 10 to 24 Hz, the seed discharge rate of the device decreased rapidly and exhibited a linear relationship with the frequency change, with the linear equation given by $y = 0.45476x + 12.09349$ and a coefficient of determination $R^2 = 0.92376$.



(**a**) Relationship between vibration frequency and seeding quality



(**b**) Relationship between vibration frequency and seeding uniformity variation coefficient

Figure 7. Sowing performance based on the relationship between vibration frequency and (**a**) seeding quality and (**b**) the seeding uniformity variation coefficient.

Regarding the seed metering uniformity coefficient, the variation coefficient fluctuated between 35.81% and 44.58% when the vibration frequency was between 0 and 10 Hz, indicating stable and favorable uniformity. When the vibration frequency was between 10 and 24 Hz, the variation coefficient of seed metering uniformity increased rapidly and showed a certain linear relationship with frequency, with the equation given by y = 1.93577x + 24.1756 and a coefficient of determination R^2 = 0.87973. Given that field operations of the seed drill require the variation coefficient of seed metering uniformity to be ≤45%, vibration frequencies greater than 10 Hz significantly impact the performance of the seed metering device.

4. Discussion

From a theoretical perspective, one can initially ignore the inter-seed interaction forces and consider the seeds inside the seed metering device as a single seed population to analyze the motion patterns of seeds within a seed metering device. Thus, the problem is simplified to the interaction between the seed population and the seed metering device. Because the seed metering device undergoes sinusoidal vibration due to the action of the eccentric wheel and return spring, its acceleration can be described by the following equation:

$$a = A\omega^2 \cos \omega t \tag{6}$$

where a represents the acceleration of the seed metering device; A is the amplitude of the seed metering device's vibration; ω is the angular frequency; and t is time. The seed population inside the seed metering device is subject to the forces of gravity and the vibrational excitation of the seed metering device. If the vibration-induced acceleration exceeds gravitational acceleration, it may cause the seed population to detach from the hole-wheel. This condition is satisfied when the following relationship holds:

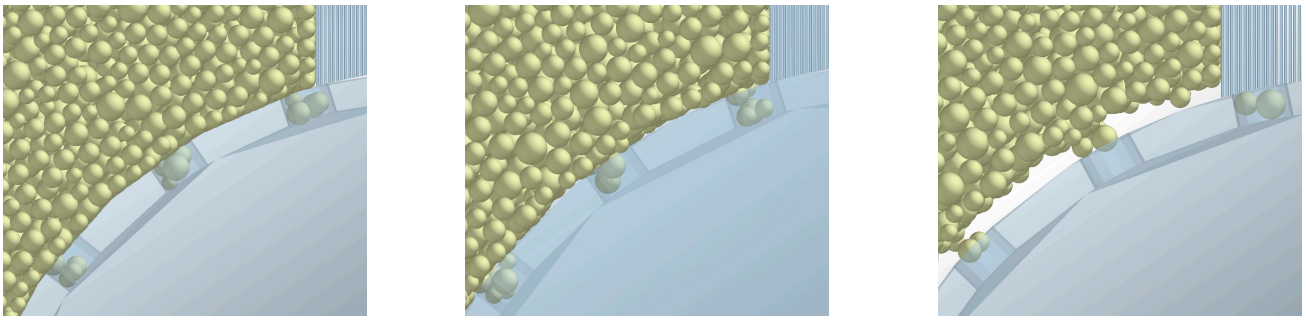
$$A\omega^2 \cos \omega t > g \tag{7}$$

Here, g represents the gravitational acceleration acting on the seed population. Since $\omega = 2\pi f$, we can express the relationship as follows:

$$f > \sqrt{\frac{g}{4\pi^2 A}} \tag{8}$$

where f is the vibration frequency of the seed metering device.

The seed metering process of the hole-wheel-type seed metering device involves three stages: filling, clearing, and sowing. When the seed metering device operates, the hole-wheel rotates upward in the filling zone. Driven by the rotating hole-wheel, rapeseed seeds form a dynamic circulating seed mass. Under the combined action of gravity, centrifugal force, the support force of the hole-wheel on the rapeseed seeds, the friction between the hole-wheel and the rapeseed seeds, and the pushing force between the seeds, the seeds enter the holes in the wheel in two ways: "filling space" and "scooping". Therefore, when the vibration frequency of the seed metering device meets the above relationship, the seed population inside the device is intermittently ejected, losing contact with the hole-wheel and creating "voids" between the seed mass and the wheel. This causes the seeds that have already filled the holes to be "flung out", preventing the wheel from making contact with the seeds and causing it to fail to complete the filling process. Consequently, the discharge rate of the seed metering device decreases, leading to missed seeding and reduced uniformity in seed metering. When the vibration frequency of the seed metering device exceeds 10 Hz, the simulation process clearly shows that seeds are repeatedly ejected from the holes, resulting in a reduced discharge rate as the hole-wheel fails to fill adequately, as shown in Figure 8.



(**a**) (**b**) (**c**)

Figure 8. Sketch map of rapeseed movement in the test rig with different vibration frequencies (**a**) at 8 Hz, (**b**) at 10 Hz, and (**c**) at 12 Hz.

Based on the research content of this article, the amplitude of vibration for the seed metering device is 3 mm. Inserting this value into the formula, one can calculate that the seed population inside the device will be intermittently ejected when $f > 9.096$ Hz. However, due to the interaction forces within the seed population and the friction between the seed population and the seed metering device, the actual vibration frequency needs to be slightly higher than the calculated theoretical vibration frequency to cause intermittent ejection of the seed population. According to the results of the vibration test bench, 10 Hz is the minimum vibration frequency at which the seed population is ejected, which corresponds highly with the theoretical calculations and experimental conclusions. Chen et al. [12,13] also found that the dispersion of the seeds was optimal at frequencies of 11–12 Hz and amplitudes of 12–13 mm for rice seeds when subjected to vibrations and theoretically analyzed the motion of seeds inside an air-suction vibratory seeding test bench, noting that seeds would be cast out when the frequency exceeded 11.2 Hz.

5. Conclusions

A field vibration measurement system centered around an accelerometer was constructed, utilizing the tractor's power source for operation. The system is capable of wirelessly transmitting vibration data and effectively meets the field data collection requirements, with a sampling frequency of 2000 Hz. The vibrational frequencies of the seed drill during field operations are concentrated within the range of 0–25 Hz, with amplitudes primarily within 3 mm. Changes in the working speed of the seed drill do not affect the distribution of vibrational power across frequencies and mainly influence the amplitude of

the vibrational power. Amplitude has less of an impact on the seed metering performance of the double-row hole-type rapeseed seed metering device, whereas vibration frequency has a more significant effect. When the vibration frequency is between 0 and 10 Hz, the seed metering device's discharge rate remains stable between 7.6 and 8.2 g/min, with minimal influence from vibration. The coefficient of variation in seed metering uniformity is between 35.81% and 44.58%, indicating stable and favorable uniformity. When the vibration frequency is between 10 and 24 Hz, the seed metering device's discharge rate decreases rapidly, exhibiting a linear relationship with frequency change and a coefficient of determination R^2 of 0.92376. The coefficient of variation in seed metering uniformity also rises quickly and shows a certain linear relationship with frequency change, with a coefficient of determination R^2 of 0.87973. Theoretical analysis was conducted on the causes of seed ejection from the population, and we provide a formula to calculate the minimum frequency at which seed ejection from the hole-wheel surface occurs: $f > \sqrt{\frac{g}{4\pi^2 A}}$.

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References

1. Hu, Q.; Hua, W.; Yin, Y.; Zhang, X.; Liu, L.; Zhao, Y.; Qin, L.; Chen, C.; Wang, H. Rapeseed research and production in China. *Crop J.* **2017**, *5*, 127–135. [CrossRef]
2. Liao, Q.; Lei, X.; Liao, Y.; Ding, Y.; Zhang, Q.; Wang, L. Research progress of precision seeding for rapeseed. *Trans. CSAM* **2017**, *48*, 1–16.
3. Li, H.; He, J.; Wang, C.; Yang, W.; Lin, H.; Wang, Q.; Yang, H.; Tan, L. Research Progress on the Development of the Planter Unit for Furrowing Control and the Depth Measurement Technology. *Appl. Sci.* **2023**, *13*, 11884. [CrossRef]
4. Lei, X.; Wu, W.; Chang, C.; Li, T.; Zhou, Z.; Guo, J.; Zhu, P.; Hu, J.; Cheng, H.; Zhou, W.; et al. Seeding Performance Caused by Inclination Angle in a Centralized Seed-Metering Device for Rapeseed. *Agriculture* **2022**, *12*, 590. [CrossRef]
5. Cujbescu, D.; Găgeanu, I.; Persu, C.; Matache, M.; Vlădut, V.; Voicea, I.; Paraschiv, G.; Biris, S.S.; Ungureanu, N.; Voicu, G.; et al. Simulation of Sowing Precision in Laboratory Conditions. *Appl. Sci.* **2021**, *11*, 6264. [CrossRef]
6. Wu, W.; Chang, C.; Li, T.; Hu, H.; Zhou, Z.; Yang, W.; Guo, J.; Zhu, P.; Li, J.; Hu, J.; et al. Seed-Filling Characteristics of a Centralized Seed-Metering Device for Rapeseed Caused by Vibration. *Agriculture* **2022**, *12*, 965. [CrossRef]
7. Yu, D.Y.; He, J.F.; Peng, F.H.; Qian, C.; Zang, Y.; Zhang, M.; Yang, W.; Zeng, G.; Chen, J.; Qin, W.; et al. Study on Vibration Characteristics of Paddy Power Chassis under Different Driving Conditions. *Agriculture* **2023**, *13*, 1842. [CrossRef]
8. Yu, D.; Peng, F.; Zeng, Z.; Zhang, M.; Yang, W.; Zang, Y.; He, J.; Huang, Y.; Wu, Y.; Zhong, W.; et al. Vibrational Dynamics of Rice Precision Hole Seeders and Their Impact on Seed Dispensation Efficacy. *Agriculture* **2024**, *14*, 324. [CrossRef]
9. Wang, Q.; Zhu, L.T.; Li, M.W.; Huang, D.Y.; Jia, H.L.; Zhuang, J. Vibration characteristics of finger clip no-tillage precision corn planter and its effect on seed metering performance. *Trans. CSAE* **2019**, *35*, 9–18.
10. Wang, L.; Liao, Y.T.; Zhang, Q.S.; Yao, L.; Fu, Y.K.; Liao, Q.X. Study on profile chisel trench opener for oil and wheat dual-purpose precision wide-width no-tillage planter. *Trans. CSAM* **2019**, *50*, 1–12.
11. Li, Y.M.; Zhao, Z.; Chen, J. Discrete Element Method Simulation of Seeds Motion in Vibrated Bed of Precision Vacuum Seeder. *Trans. CSAM* **2009**, *40*, 56–59+76.
12. Chen, J.; Zhou, H.; Zhao, Z.; Li, Y.M.; Gong, Z.Q. Analysis of Rice Seeds Motion on Vibrating Plate Using EDEM. *Trans. CSAM* **2011**, *42*, 79–83+100.
13. Chen, J.; Li, Y.M. Study on Seeds Movement Law in Sowing Test Stand with Suction and Vibration. *Trans. CSAM* **2002**, *1*, 47–50.

14. Wang, C.H.; Ma, X. Vibrating Measurement and Analysis of Seeds Layer on Precision Seedling Planting Partsf or Super Hybrid Rice. *Trans. CSAM* **2010**, *41*, 68–72.
15. Zhang, X.D.; Li, C.H.; Li, J.Q.; Zou, M. Mathematic Vibration Model of Spade Punch Planter of Maize. *Trans. CSAM* **2014**, *45*, 88–98.
16. Wu, M.L.; Guan, C.Y.; Tang, C.Z.; Chen, S.Y.; Luo, H.F.; Wang, G.H.; Xie, F.P.; Li, X.; Yang, W.M. Experimental research on 2BYF-6 type no-tillage rape combine seeder in paddy stubble field. *Trans. CSAE* **2007**, *23*, 172–175.
17. Xu, L.Z.; Li, Y.M.; Xun, P.P.; Pang, J. Vibration measurement and analysis of tracked-whole feeding rice combine harvester. *Trans. CSAE* **2014**, *30*, 49–55.
18. Zhang, T.; Liu, F.; Zhao, M.Q.; Liu, Y.Q.; Li, F.L.; Chen, C.; Zhang, Y. Movement law of maize population in seed room of seed metering device based on discrete element method. *Trans. CSAE* **2016**, *32*, 27–35.
19. Wang, J. *MATLAB Signal Processing*; Tsinghua University Press: Beijing, China, 2017.
20. Lin, Q. Frequency Weight Power Spectrum Analysis Method Based on Hanning Window Interpolation FFT. *China Instrum.* **2014**, 72–76.
21. Liu, Y.F.; Wu, Z.L.; Nie, Y.Z.; Liu, F.P.; Wu, M.L. Seeding performance of double hole-wheel seedmeter for rapeseed based on EDEM. *J. Hunan Agric. Univ.* **2019**, *45*, 554–559.

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