PERFORMANCE ANALYSIS AND TESTING OF A CONICAL DEFLECTOR-TYPE SEED-METERING DEVICE UNDER VIBRATION
/
振动工况下锥面导流式排种器性能分析与试验

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ABSTRACT
To address the deterioration in the seed-metering performance of mechanical seed-metering devices caused by vibration during field operation, a conical deflector-type seed meter was selected as the research object. A vibration-system model of the seed meter under field operating conditions was established, and the principal operating parameters affecting seed-metering performance were determined. The seed-metering process under vibration was then simulated using the discrete element method to investigate changes in the working angle of the seed population and its dynamic characteristics. In addition, vibration bench tests were conducted to evaluate the effects of vibration on seed-metering performance. The main results were as follows: (1) seed-filling efficiency, seed-clearing efficiency, and horizontal seed-throwing displacement were significantly affected by operating speed, vibration acceleration, and vibration frequency; (2) the adverse effect of vibration on seed-metering performance increased with increasing vibration acceleration but decreased with increasing operating speed or vibration frequency; and (3) when the vibration acceleration was below 0.63 g and the vibration frequency exceeded 4.28 Hz, the qualified-seed rate was greater than 95%, and the coefficient of variation of seed spacing was less than 20%. This study clarified the effects of vibration parameters on seed-metering performance and identified appropriate operating ranges, thereby providing theoretical support for the vibration-resistant design and optimization of mechanical seed meters.

ABSTRACT
针对机械式排种器在田间作业过程中易受振动影响导致排种性能下降的问题，选取锥面导流式排种器为研究对象，建立了排种器田间作业振动系统模型，推导出对排种性能产生影响的主要工况参数。运用离散元法对排种器振动工况下工作过程进行仿真试验，研究种群工作角度和动力学特性的变化规律，并通过振动台架试验测试了排种性能受到的影响。结果表明：1）排种器的充、清种效率及水平方向投种位移均受到作业速度、振动加速度和振动频率的显著影响；2）排种性能受到的负面影响随振动加速度的提升而增大，随作业速度和振动频率的提升而减小；3）当振动加速度小于 0.63g，振动频率大于 4.28Hz 时，排种器的合格率高于 95%，粒距均匀性变异系数低于 20%。研究阐明了振动参数对排种性能的影响规律及其合理范围，为机械式排种器的抗振设计改进提供了理论支撑。

INTRODUCTION
High-speed precision seeding technology has become the development direction and trend of modern seeding technology due to its outstanding advantages, such as cost-saving, efficiency enhancement, and wide application (*Cujbescu et al., 2021; Emrah et al., 2021; Cay A. et al., 2018; Hijam J.S. et al., 2016*). As one of the carriers to realize high-speed and precision seeding technology, the mechanical precision metering device is still widely used in many countries because of its simple structure, low cost and easy maintenance (*Ibrahim et al., 2022; Shen et al., 2021; Karayel et al., 2022*).

By virtue of its inclined conical surface that guides seeds into the compound holes with reduced orientation requirements and randomness, the conical deflector-type seed-metering device enhances filling efficiency and thus qualifies as a high-speed precision mechanical seed-metering device for soybean planting.

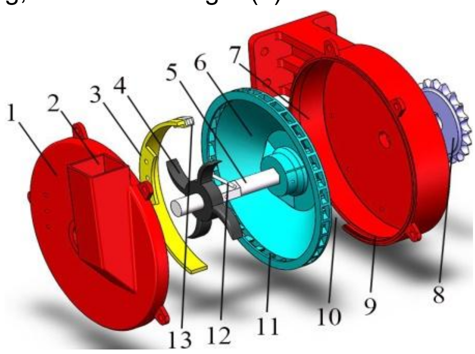
Through the design and optimization of its structure, the optimal structure of the seed-metering device is obtained, and verifies its excellent seed metering performance under the high-speed operation conditions through indoor bench test. Its qualified rate is higher than 97% when the operation speed is 6-12km/h (*Dong, 2021*). At present, studies had shown that the operation of seed-metering device suffers vibrations loads when the planter was working at high speed in the field (*Ku et al., 2021; Muhammad et al., 2021*). In this case, the working performance of the seed-metering device will be seriously affected, which may result in the deterioration of its working quality (*Zhang et al., 2016; Hao et al., 2017*). In order to improve the field operation performance of the planter, it is necessary to further research the influence of vibration on seed-metering device.

However, most studies on seed-metering devices have focused primarily on structural optimization, the effects of structural parameters on seed motion, and seed-metering performance under ideal laboratory conditions *(Chen et al., 2021; Liu et al., 2021; Zhao et al., 2026)*. By contrast, the motion state of seeds and their interaction with the seed-pickup mechanism under high-speed and vibrational operating conditions remain insufficiently understood. Consequently, the effects of vibration on the seed-metering process and performance have not yet been clearly established. Therefore, this study investigates the variation in seed-group motion and seed-metering performance under vibration.

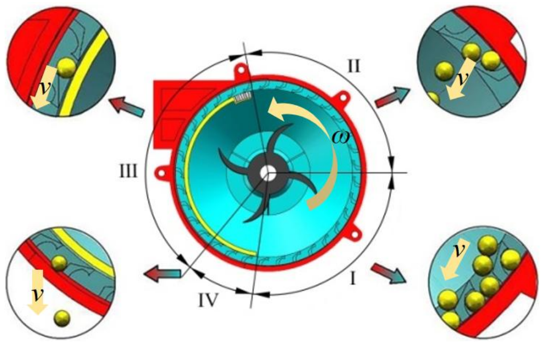
MATERIALS AND METHODS

Conical deflector-type seed-metering device

The conical deflector-type seed-metering device mainly consisted of a seed-metering disc, rotating shaft, deflector, seed baffle, housing, and seed-feed tube, as shown in Fig. 1(a). The seed-metering disc, deflector, and rotating shaft were assembled as an integrated rotating unit driven by an external power source. The operating cycle comprised four stages: I, seed filling; II, seed clearing; III, seed carrying; and IV, seed throwing, as shown in Fig. 1(b).



a. Components of the seed-metering device



b. Operating principle of the seed-metering device

Fig. 1 - Structure and operating principle of the conical deflector-type seed-metering device

1. Front housing 2. Seed-feed tube 3. Seed buffle 4. Deflector 5. Rotating shaft 6. Seed-metering disc 7. Rear housing 8. Sprocket 9. Arc-shaped guide rail 10. Seed outlet 11. Compound hole 12. Pin 13. Brush Ⅰ-Seed filling, Ⅱ-Seed clearing, Ⅲ-Seed carrying, and Ⅳ-Seed throwing

Vibration-system model of the seed-metering device

During field operation, the planter is subjected primarily to random vertical vibration loads *(Liu, 2016; Huang, 2018)*. Assuming that the excitation caused by tillage-surface unevenness can be represented by a sinusoidal waveform and that the planter remains in continuous contact with the ground during operation, the spring stiffness k and viscous damping coefficient c were treated as linear parameters *(Gao et al., 2021)*. Based on these assumptions, the field vibration model of the seed-metering device was simplified, as shown in Fig.2.

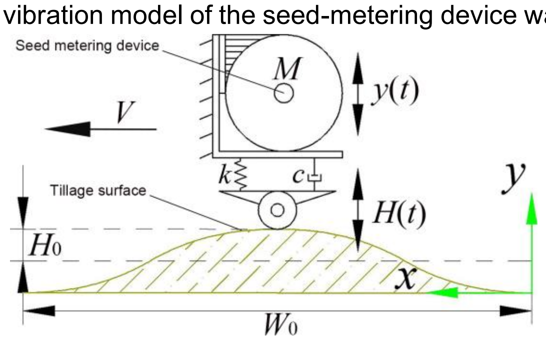


Fig. 2 - Field vibration-system model of the seed-metering device

As shown in Fig.2, the instantaneous displacement excitation in the vertical direction of the planter frame is expressed as follows:

$$H(t)=H_0\sin\omega_0 t \tag{1}$$

where: ω_0 is the frequency of displacement excitation in the vertical direction (Hz), H_0 is the undulation amplitude of the cross section of the tillage surface compared with the reference plane (m).

Based on Eq. (1) the second derivative can be obtained, the acceleration excitation in the vertical direction of the planter frame is as follows:

$$H''(t)=\left|\frac{d^2H(t)}{dt^2}\right|=H_0\omega_0^2\sin\omega_0 t \tag{2}$$

According to Eq. (2), the dynamic equilibrium equation of the vibration system of the seed-metering device is as follows:

$$M\frac{d^2y(t)}{dt^2}+c\frac{dy(t)}{dt}+ky=MH_0\omega_0^2\sin\omega_0 t^2 \tag{3}$$

where: M is mass of seed metering system (kg).

From Eq. (3), the following expression is obtained:

$$\frac{d^2y(t)}{dt^2}+2\zeta\omega_n\frac{dy(t)}{dt}+\omega_n^2y=\omega_n^2H_0\omega_0^2\sin\omega_0 t \tag{4}$$

where: ω_n is natural frequency of seed metering system (Hz), ζ is the viscous damping ratio of the system.

By solving the steady-state response equation of sinusoidal excitation with frequency ω (4), a specific solution Eq. (5) is obtained, where the amplitude A and phase φ are given by the standard forced vibration amplitude / phase expression.

$$\begin{cases}\omega_0=2\pi V/W_0\\ y(t)=A\sin(\omega_0 t+\varphi_0)\\ A=\dfrac{H_0\omega_0^2}{\omega_n^2\sqrt{(1-\dfrac{\omega_0^2}{\omega_n^2})^2+(2\zeta\dfrac{\omega_0}{\omega_n})^2}}\\ \varphi_0=\arctan\dfrac{2\zeta\omega_0\cdot\omega_n}{\omega_n^2-\omega_0^2}\end{cases} \tag{5}$$

where: A is system displacement response amplitude (m), and φ_0 is phase difference of system displacement response (rad), V is operating speed of planter (km/h), and W_0 is wavelength of tillage surface section (m).

From Eq. (5):

$$\begin{cases}V_z(t)=\left|\dfrac{dy(t)}{dt}\right|=A\omega_0\sin(\omega_0 t+\varphi_0)\\ a_z(t)=\left|\dfrac{d^2y(t)}{dt^2}\right|=A\omega_0^2\sin(\omega_0 t+\varphi_0)\end{cases} \tag{6}$$

where: V_z(t) is the inertial velocity generated by vibration (m/s), and a_z(t) is the inertial acceleration generated by vibration (m/s^2).

From Eq. (5) and (6), it can be concluded that the seed-metering device was mainly affected by vibration acceleration, vibration frequency and operating speed in the field working environment.

Simulation test

Simulation model and parameter setting

During the vibration process of the seed-metering device, the particle motion characteristics cannot be directly measured. The discrete element method is one of the methods to observe the seed motion characteristics during the vibration process. Therefore, the discrete element method is used in this study. To analyze the influence of vibration condition parameters on different working processes of seed-metering device, a 3D model of seed-metering device was established by using CAD software, and imported into EDEM software for simulation (Fig. 3).

The physical parameters and interaction parameters among the simulation model, the seed model and the material were consistent with the result of the previous research (*Dong, 2021*).

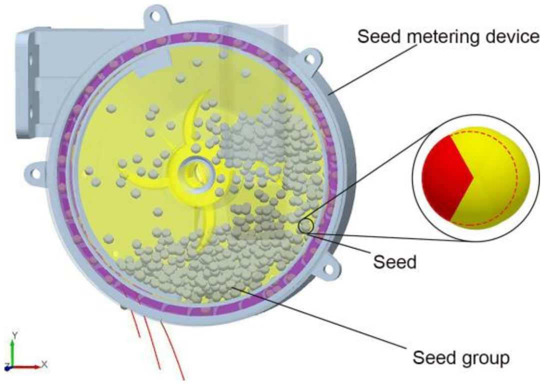


Fig. 3 - Simulation model of seed-metering device

Test method

According to the preliminary experimental results, the simulation was carried out at the speed of 6, 8, 10 and 12km/h (8km/h and above were classified as high-speed operation conditions), and the corresponding rotation speeds were 31.6, 40.8, 50.5, and 60.6r/min, respectively. The parameter value range of acceleration and frequency under vibration conditions were selected (*Wang et al., 2019; Zhang et al., 2016; Liu et al., 2016*). A total of 300 particles were generated in the simulation. The total simulation time was 3 s, and the data were recorded every 0.01 s.

Table 1

Simulation condition parameters

Working parameters	Numerical value	Fixed value
Operating speed [km·h^{-1}]	6; 8; 10; 12	10
Vibration acceleration [*g*]	0.3; 0.5; 0.7; 0.9;1.1	0.7
Vibration frequency [Hz]	3; 5; 7; 9; 11	7

The operating process of the seed-metering device under different vibration conditions was simulated using DEM software, and the velocity vectors of the seed particles were obtained, as shown in Fig.4.

In this study, a smaller seed-filling angle, θ (defined as the angle between the vertical direction and the position at which a seed is about to enter the compound hole) indicated higher seed-filling efficiency. Similarly, a larger seed-clearing angle, φ (defined as the angle between the vertical direction and the position at which the seed to be cleared leaves the compound hole) indicated higher seed-clearing efficiency. A larger seed-throwing angle, δ (defined as the angle between the position at which the seed completely leaves the compound hole and the edge of the seed outlet) indicated a greater horizontal seed-throwing distance.

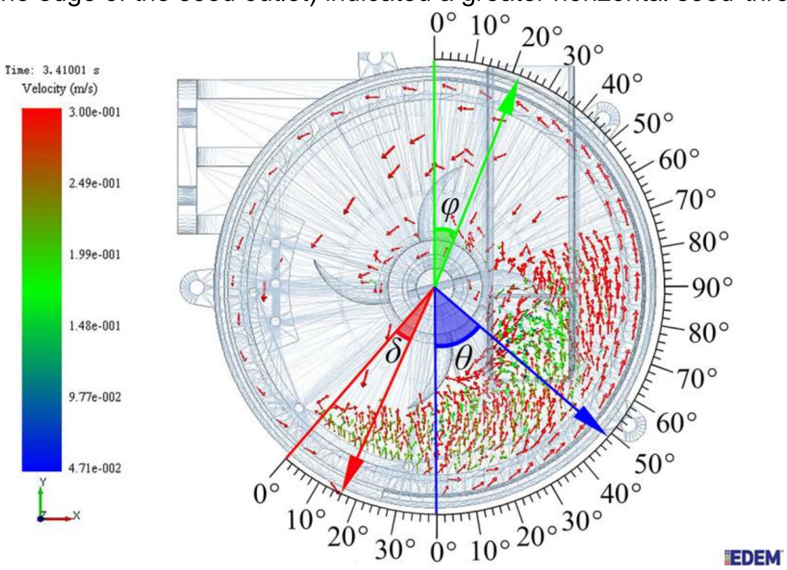


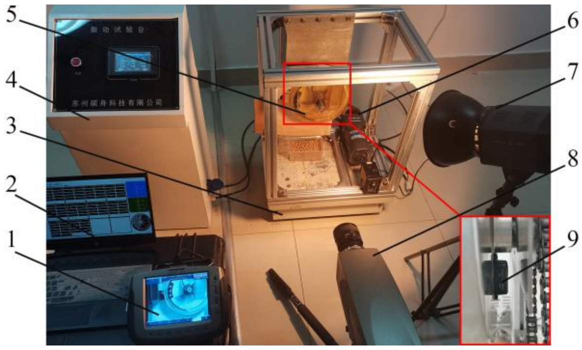
Fig. 4 - Working-angle distributions of seed particles under vibration

Vibration bench test

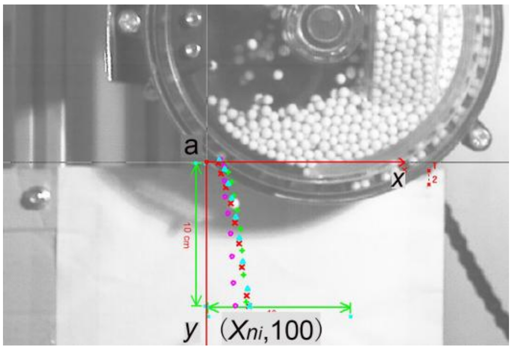
Test condition

To investigate the effects of vibration conditions on seed-metering performance, a vibration test bench was established in the Agricultural Machinery Laboratory at Northwest A&F University.

The vibration test bench consisted of a conical deflector-type seed-metering device, a mounting frame, a speed-control system, a vibration-excitation system, and an image-acquisition system, as shown in Fig. 5. The speed-control system comprised a 120 W variable-speed motor with an output torque of 8.5 N·m, a planetary gear reducer with a reduction ratio of 1:15, and a motor controller. The vibration-excitation system comprised a variable-frequency electromagnetic vibration table, a vibration-signal controller with a sinusoidal frequency range of 1-2000 Hz, and a vibration sensor equipped with Bluetooth 5.0 wireless transmission, a triaxial acceleration range of ±16 g, a frequency range of 0.2-200 Hz, and an output error not exceeding 1%. The image-acquisition system comprised a high-speed camera (Olympus i-SPEED 3), a computer running i-SPEED Suite software, a spatial grid panel, and a marker pen. Soybean seeds of the cultivar 'Suinong 26' were used in the tests. The thousand-seed mass was 0.21 kg, and the seed density was 1.267 g/cm^3.



a. Vibration test bench



b. Seed-position coordinate measurement

Fig. 5 - Vibration bench test of the conical deflector-type seed-metering device

1. Image-acquisition unit; 2. Monitoring computer; 3. Vibration table; 4. Vibration-signal controller; 5. Conical deflector-type seed-metering device; 6. Drive unit; 7. High-intensity lam; 8. High-speed camera; 9. Vibration sensor

Test method

To evaluate the effects of the selected factors on seed-metering performance, a three-factor, three-level Box-Behnken design was employed. The seed-metering performance under different combinations of factor levels was measured using the vibration test bench for the seed-metering device. The factor levels were selected based on the significance of each factor observed in the simulation analysis of the different operating stages of the seed-metering device, as shown in Table 2. Each experimental treatment was repeated three times, and the mean value was used for analysis.

Table 2

Coded levels of the test factors

Level	Test factors		
	Rotational speed X1 [r·min^{-1}]	Vibration acceleration [*g*]	Vibration frequency [Hz]
-1	31.6	0.7	6
0	46.1	1.1	9
1	60.6	1.5	12

The response variables were the qualified-seed rate, Y_1, and the coefficient of variation of seed spacing, Y_2, as defined in Eq. (7). In the high-speed image-processing software, point "a" at the seed outlet was set as the coordinate origin, and the theoretical seed-throwing height was set to 100 mm. A seed i was classified as qualified when its spacing, X_i, ranged from 5 to 15 cm. The values of Y_1 and Y_2 were then calculated accordingly *(Shen et al., 2021)*.

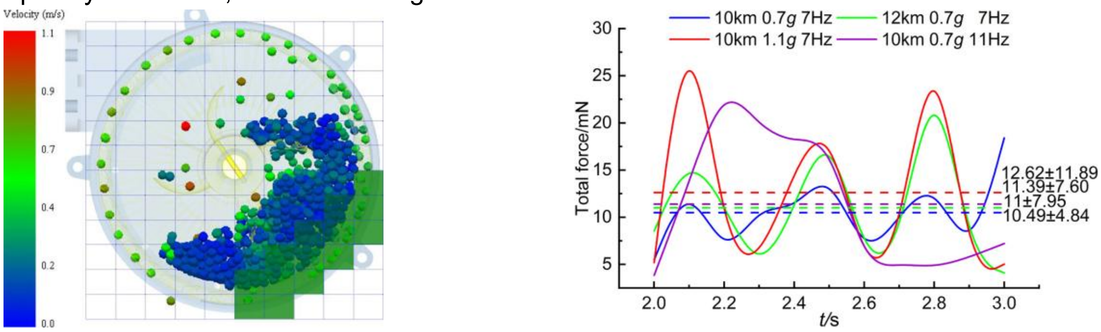
$$\begin{cases} Y_1 = \dfrac{N_1}{N} \times 100\% \\ X_i = X_{Ni} - X_{Ni\text{-}1} + S \\ \bar{X} = \dfrac{1}{N} \sum_{i=1}^{N+1} X_i \\ Y_2 = \dfrac{\sqrt{\dfrac{1}{N} \sum_{i=1}^{N} \left(X_i - \bar{X} \right)^2}}{\bar{X}} \times 100\% \end{cases} \tag{7}$$

where: Y_1 is the qualified-seed rate (%), $\bar{X}$ is the mean seed spacing (mm), Y_2 is the coefficient of variation of seed spacing (%), N_1 is the number of qualified seeds, N is the total number of seeds included in the statistical analysis, X_{Ni} is the abscissa of the i-th recorded seed, $X_{Ni\text{-}1}$ is the abscissa of the preceding recorded seed, S is the theoretical seed spacing, equal to 100 mm, and X_i is seed spacing of qualified seeds (mm).

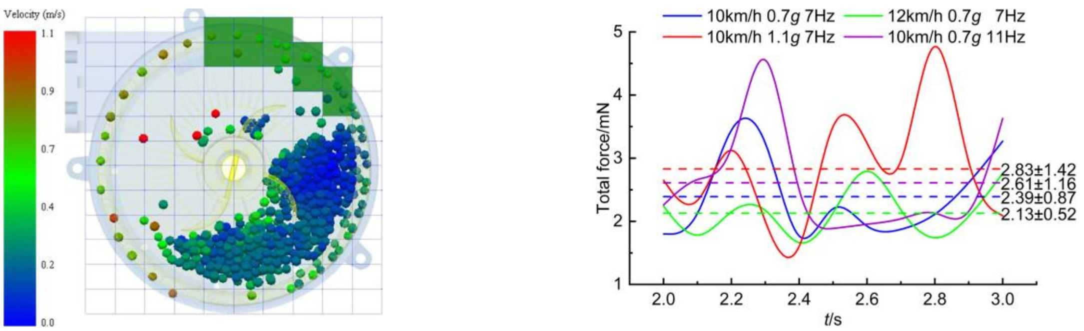
RESULTS AND DISCUSSION

Simulation results

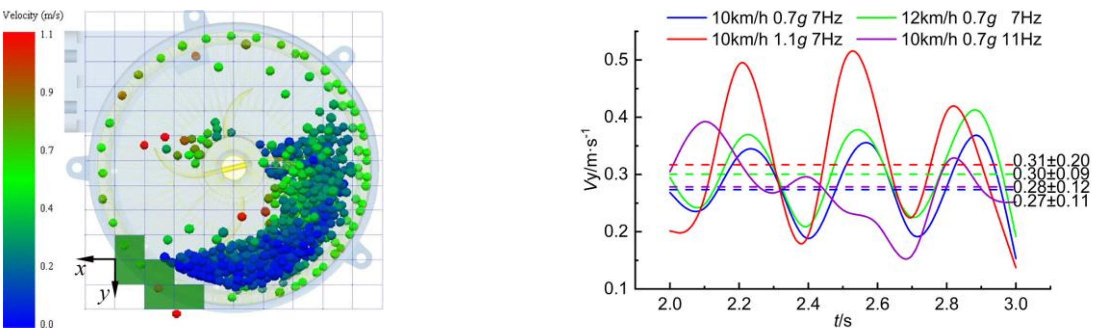
During post-processing of the simulation data, the external forces acting on the seeds in the seed-filling and seed-clearing zones and the downward vertical velocities of the seeds in the seed-throwing zone were statistically analyzed over the 2–3 s interval, as shown in Fig.6. For each simulation run, the seed-filling angle θ, seed-clearing angle φ, and seed-throwing angle δ were recorded from 1 to 5 s at intervals of 0.05 s. At each sampling time, the maximum value of each angle was selected, and the corresponding mean values were subsequently calculated, as shown in Fig.7.



a. Total force acting on the seed group in the seed-filling zone



b. Total force acting on the seed group in the seed-clearing zone



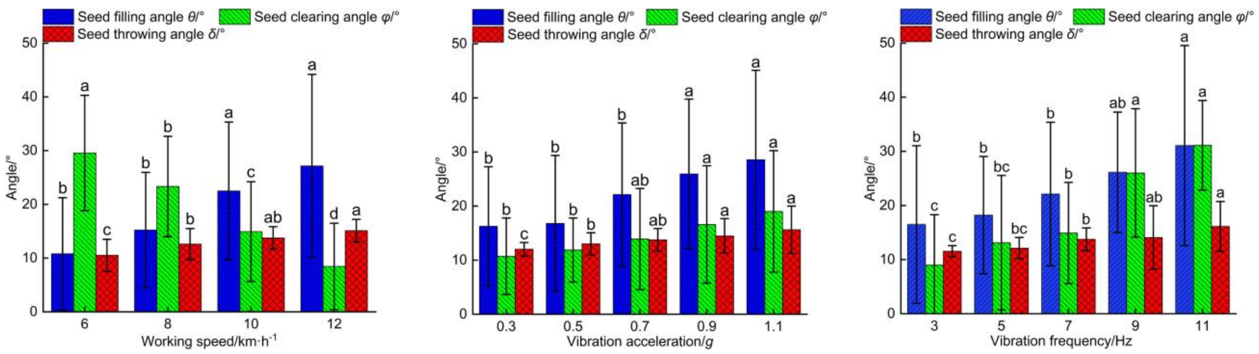
c. Vertical velocity of the seed group in the seed-throwing zone

Fig. 6 - Effects of vibration on seed-group dynamics

As vibration acceleration, vibration frequency, or operating speed increased, the fluctuations in the resultant force acting on the seeds in the seed-filling zone became more pronounced, and the seed-filling zone expanded, as shown in Fig. 6(a). Meanwhile, the mean seed-filling angle, θ, increased, as shown in Fig.7.

Increasing the vibration acceleration or vibration frequency intensified the fluctuations in the resultant force acting on the seeds in the seed-clearing zone and expanded this zone, as shown in Fig. 6(b). Correspondingly, the mean seed-clearing angle, φ, increased, as shown in Fig. 7(b) and (c), indicating improved seed-clearing efficiency. By contrast, increasing the operating speed reduced the force fluctuations and narrowed the seed-clearing zone. The mean value of φ also decreased, as shown in Fig. 7(a), indicating a reduction in seed-clearing efficiency. The vertical seed velocity, Vy, generally increased with operating speed, as shown in Fig. 6(c). The horizontal velocity, Vx, also increased, resulting in a larger mean seed-throwing angle, δ, and greater horizontal seed-throwing displacement, as shown in Fig. 7.

Overall, seed-filling efficiency, seed-clearing efficiency, and horizontal seed-throwing displacement were significantly affected by operating speed, vibration acceleration, and vibration frequency. Increasing any of these three factors reduced seed-filling efficiency and increased horizontal seed-throwing displacement. However, their effects on seed-clearing efficiency differed: increasing vibration acceleration or vibration frequency improved seed-clearing efficiency, whereas increasing operating speed reduced it.



a. Operating speed *b. Vibration acceleration* *c. Vibration frequency*

Fig. 7 - Effects of operating conditions on the seed-filling, seed-clearing, and seed-throwing angles

Bench test result

Establishment of regression model

The experimental results presented in Table 3 were subjected to analysis of variance (ANOVA), and the results are summarized in Table 4. As shown in Table 4, the model *P*-values for both Y_1 and Y_2 were less than 0.01, whereas the lack-of-fit *P*-values were greater than 0.05. These results indicate that the regression models were highly significant and that the lack of fit was not significant. The coded regression equations relating Y_1 and Y_2 to the test factors were established as follows:

$$Y_1 = 73.17 + 11.20X_1 - 18.68X_2 + 10.99X_3 + 6.22X_1X_2 - 4.16X_1X_3 + 9.09X_2X_3 - 1.62X_1^2 + 4.76X_2^2 + 2.49X_3^2 \tag{8}$$

$$Y_2 = 24.01 - 3.81X_1 + 6.29X_2 - 1.09X_3 - 4.44X_1X_2 + 3.11X_1X_3 - 0.89X_2X_3 - 0.87X_1^2 - 0.19X_2^2 + 0.36X_3^2 \tag{9}$$

Based on the *F*-values of the individual factors, their effects on both Y_1 and Y_2 were ranked in descending order as follows: vibration acceleration, operating speed, and vibration frequency.

Table 3

Test result

Test number	Factors			Y_1[%]	Y_2[%]
	X_1[r·min^{-1}]	X_2[g]	X_3[Hz]		
1	-1	-1	0	91.33	14.47
2	1	-1	0	99.47	18.35
3	-1	1	0	40.7	36.42
4	1	1	0	73.73	33.73
5	-1	0	-1	44.27	22.56
6	1	0	-1	76.8	17.28

Test number	Factors			Y_1[%]	Y_2[%]
	X_1[r·min^{-1}]	X_2[g]	X_3[Hz]		
7	-1	0	1	79.6	23.5
8	1	0	1	95.5	23.48
9	0	-1	-1	99.3	18.42
10	0	1	-1	44.6	31.28
11	0	-1	1	98.07	17.84
12	0	1	1	79.73	29.15
13	0	0	0	72.93	26.78
14	0	0	0	74.13	19.23
15	0	0	0	75.6	27.61
16	0	0	0	72.27	18.61
17	0	0	0	70.93	21.81

Table 4

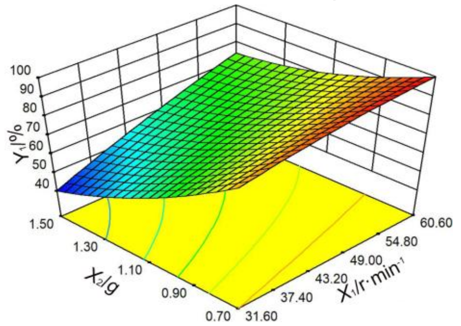
Variance analysis

Source	Y_1[%]				Y_2[%]			
	df	Mean Square	F	P	df	Mean Square	F	P
Model	9	605.38	59.40	<0.0001	9	62.92	7.24	0.0081
X_1	1	1003.52	98.47	<0.0001	1	115.90	13.33	0.0082
X_2	1	2790.42	273.81	<0.0001	1	316.64	36.41	0.0005
X_3	1	966.46	94.83	<0.0001	1	9.55	1.10	0.3295
$X_1 X_2$	1	154.88	15.20	0.0059	1	78.68	9.05	0.0197
$X_1 X_3$	1	69.14	6.78	0.0352	1	38.63	4.44	0.0730
$X_2 X_3$	1	330.51	32.43	0.0007	1	3.15	0.36	0.5662
X_{12}	1	11.10	1.09	0.3314	1	3.16	0.36	0.5656
X_{22}	1	95.36	9.36	0.0184	1	0.15	0.018	0.8977
X_{32}	1	26.19	2.57	0.1530	1	0.53	0.061	0.8115
Lack of fit	3	19.54	6.15	0.0559	3	62.92	0.70	0.5995
Pure error	4	3.18			4	6.98		

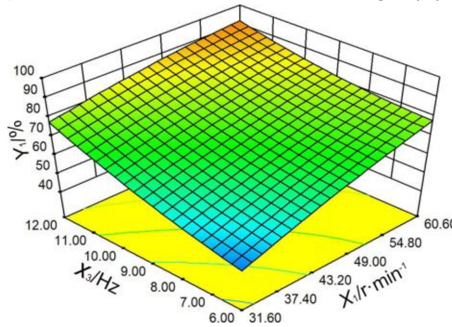
Values of P less than 0.05 indicate model terms are significant.

Response surface analysis

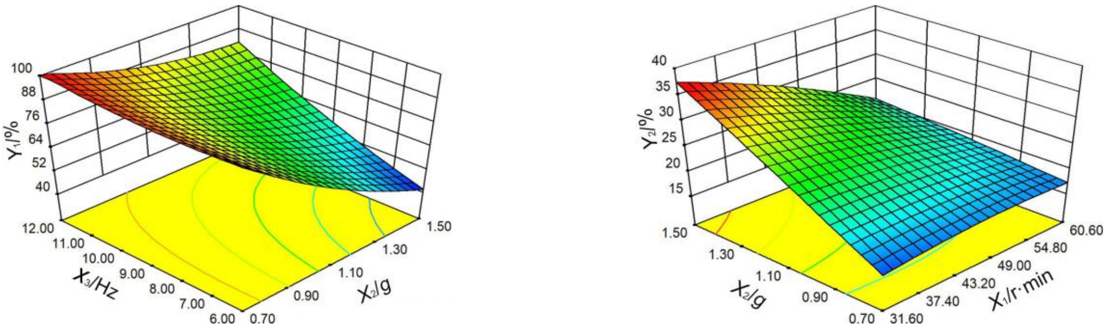
Design-Expert software was used to generate response surfaces illustrating the interactions between pairs of factors, as shown in Fig.8. The qualified-seed rate decreased with increasing vibration acceleration, although this decline became less pronounced as rotational speed increased, as shown in Fig.8(a). The qualified-seed rate increased with increasing vibration frequency, but the rate of increase decreased as rotational speed increased, as shown in Fig. 8(b). Similarly, the qualified-seed rate decreased with increasing vibration acceleration, while the magnitude of this decrease was reduced at higher vibration frequencies, as shown in Fig.8(c). The coefficient of variation of seed spacing increased with increasing vibration acceleration, although this increase became less pronounced as rotational speed increased, as shown in Fig.8(d).



a. $Y_1 = f(X_1, X_2, 9)$



b. $Y_1 = f(X_1, 1.1, X_3)$



c. $Y_1 = f(46.9, X_2, X_3)$ d. $Y_2 = f(X_1, X_2, 9)$

Fig. 8 - Response surfaces showing the effects of factor interactions on the response variables

The analysis indicated that increasing vibration acceleration intensified fluctuations in the external forces acting on the seeds and increased radial runout. During seed clearing, these effects promoted premature seed removal and increased variability in the seed-throwing trajectories. By contrast, increasing rotational speed or vibration frequency mitigated these effects.

Accordingly, the adverse effect of vibration on seed-metering performance increased with increasing vibration acceleration but decreased with increasing operating speed or vibration frequency.

To ensure satisfactory seed-metering performance over the tested range of operating speeds, the regression models were subjected to multi-objective optimization using a qualified-seed rate, Y_1, greater than 95% and a coefficient of variation of seed spacing, Y_2, less than 20% as constraints. The objective function is given in Eq. (10):

$$\begin{cases} Y_1(X_1, X_2, X_3) \geq 95\% \\ Y_2(X_1, X_2, X_3) \leq 20\% \\ 31.6\text{r/min} \leq X_1 \leq 60.6\text{r/min} \\ \max X_2(X_2 \leq 1.5\text{g}) \\ \min X_3(X_3 \leq 12\text{Hz}) \end{cases} \tag{10}$$

According to Eq. (10), the optimal parameter ranges were X_2<0.63 g and X_3>4.28 Hz. To verify the reliability of the optimization results, validation tests were conducted at rotational speeds (X_1) of 31.6, 46.1, and 60.6 r·min⁻¹. The qualified-seed rate, Y_1, exceeded 98.8%, while the coefficient of variation of seed spacing, Y_2, remained below 17.31%. These results satisfied the optimization objectives.

CONCLUSIONS

This study quantified the relationships between field vibration parameters and the performance of a mechanical conical deflector-type seed-metering device, a device type whose vibration behavior has received limited attention compared with pneumatic and finger-type seed meters. By linking seed-scale DEM simulations with bench-test measurements, the combined effects of vibration acceleration, vibration frequency, and operating speed on the seed-filling, seed-clearing, and seed-throwing processes were determined, and threshold conditions for acceptable seed-metering performance were identified.

1. Seed-filling efficiency, seed-clearing efficiency, and horizontal seed-throwing displacement were significantly affected by operating speed, vibration acceleration, and vibration frequency. Increasing any of these three factors reduced seed-filling efficiency and increased horizontal seed-throwing displacement. Increasing operating speed also reduced seed-clearing efficiency.

2. Based on the *F*-values of the main-effect terms, the effects of the factors on the qualified-seed rate and the coefficient of variation of seed spacing were ranked in descending order as follows: vibration acceleration, operating speed, and vibration frequency. The adverse effect on seed-metering performance increased with increasing vibration acceleration but decreased with increasing operating speed or vibration frequency.

3. Multi-objective optimization showed that when the vibration acceleration was below 0.63 g and the vibration frequency exceeded 4.28 Hz, the qualified-seed rate was greater than 95%, and the coefficient of variation of seed spacing was less than 20%.

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