EFFECT OF TRANSPLANTER VIBRATION ON PARTICLE MOVEMENT VELOCITY OF SANDY LOAM SOIL BY USING DEM
/
移栽机振动对沙壤土颗粒运动速度的影响分析

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ABSTRACT
The sandy loam soil has complex movement characteristics during hole formation by hanging cup transplanters. In order to better investigate this point, the paper aims to investigate the disturbance pattern of transplanter vibration on sandy loam soil and the movement characteristics of soil particles by the discrete element method. The vibration characteristics of the transplanter operating on sandy loam soil were tested and analyzed, and the motion law of vibration parameters on sandy loam soil was investigated with the help of the discrete element method and soil bin test. The results showed that the vibration acceleration of the transplanter increased with the forward speed, the primary vibration frequency range was from 0 to 12 Hz, and the vibration amplitude increased linearly in the field of 1.21 to 9.19 mm. The Central Composite test resulted in the regression equations of vibration amplitude and vibration frequency on the average movement velocity of the particles. The response surface analysis showed that the effect of vibration amplitude on the average movement velocity of particles was greater than the effect of vibration frequency on the average movement velocity of particles. At the same time, the average movement velocity of the particles tends to increase significantly under the interaction of the two. This study provides data to support the design of planters for sandy loam soils, which is beneficial to promote seedling transplanting technology further.

摘要
吊杯式移栽机成穴过程中，砂壤土运动特性复杂。为更好地探究这一问题，本研究通过离散元法研究移栽振动对沙壤土的扰动规律和土壤颗粒的运动特性。对移栽机的振动特性进行了测试和分析，并借助于离散元仿真和土槽试验研究了振动参数对沙壤土颗粒速度的影响规律。结果表明，插秧机的振动加速度随前进速度的增加而增加，振动频率范围为 0～12Hz，振动振幅在 1.21～9.19mm 的范围内线性增加。中心组合试验得到振动振幅和振动频率对颗粒平均移动速度的回归方程，响应面分析表明，振动幅度对颗粒平均移动速度的影响大于振动频率对颗粒平均移动速度的影响。同时，在两者的相互作用下，颗粒的平均运动速度有明显增加的趋势。本研究为沙壤土移栽机的设计提供了数据支持，有利于进一步推广育苗移栽技术。

INTRODUCTION
In the past five years, the vegetable industry in China is developing steadily, and the use of transplanters can overcome labor shortages. It is worth mentioning that soil type is also a key factor in the performance of transplanters. However, scholars have not paid attention to the disturbance of transplanting machine on sandy loam soil. Part of the soil flows back into the hole, creating an uneven bottom and seriously affecting seedling growth and planting efficiency (*Frasconi et al., 2019; Mamun et al., 2020; Awuah et al., 2022*). In order to investigate the planting mechanism and optimize the structure of the planters, it is necessary not only to analyze the morphology of the holes formed by the planters but also to investigate the dynamic disturbance of the soil particles by the planters (*Bhambota et al., 2018*). In addition, vibrations caused by complex excitation in the field will accelerate the velocity of soil particle flow. None of the existing studies considered the effect pattern of soil disturbance by transplanter vibration caused by complex excitation in the field, and the field experiments failed to better reveal the disturbance pattern of soil particles by transplanter vibration.

Qiang Su, D. Eng; Xuying Li, Prof. Eng; Fandi Zeng, D. Eng; Hongbin Bai, M. S. Eng; Junyue Wang, D. Eng.

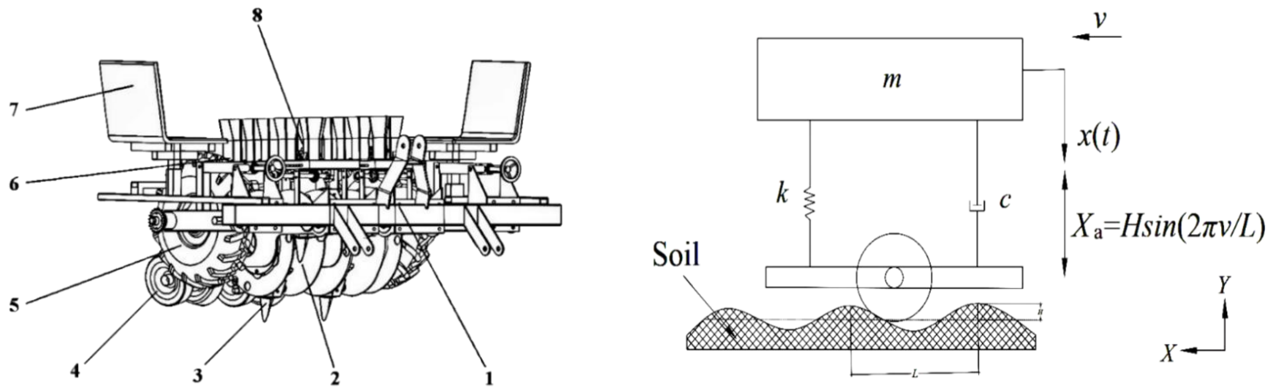
The discrete element method (DEM) is a numerical method that is suited to analyze the microscopic behavior of granular media. Tanaka used DEM to simulate the tillage process of a vibrating subsoiler. The soil profiles simulated by the deep vibrating subsoiler were compared with field tests. The areas of disturbance were very consistent, indicating that DEM can be used to study microscopic soil movement under the action of vibratory tools (*Tanaka et al., 2010*). The effect on operational performance in the case of agricultural machine vibration has been analyzed by related scholars using the discrete element method. Moreover, the interaction between the two was analyzed by considering the soil. For example, the working process of deep loosening machine vibration deep loosening and no vibration deep loosening was simulated (*Ma et al., 2020*), exploring the influence of a vibrating digging shovel on the range of soil disturbance (*Shi et al., 2021*). The cup-soil contact movement in the planting operation process can be simulated and the planter's complex kinematics characteristics under the action of the soil can be studied. Yang Qizhi analyzes the hole planting process of a hanging cup planter of a high speed hanging auto-transplanter to study the kinematic characteristics of the hanging cup planter under the more realistic action of soil and the interaction mechanism with the soil (*Yang et al., 2022*). Above studies provide ideas for this study.

Our research group conducted vibration tests on the transplanting machine in the early stage (*Su et al. 2022*), and conducted experimental research on hole parameters (*Zeng et al., 2023*). In summary, this study is based on theories such as vibration mechanics and discrete element method and combines vibration testing techniques, soil bin tests and discrete element simulation to analyze the effect law of transplanter vibration on sandy loam soil particles. The vibration test was carried out on the transplanter under complex excitation, and the collected vibration signals were analyzed. The vibration frequency and amplitude were introduced into the discrete element model of the contact action between the transplanter and soil to examine the influence law of the transplanter on the sandy loam soil under vibration.

MATERIALS AND METHODS

Hanging-cup transplanter structure and working principle

It consists of the seat, the three-point suspension, the ground wheel drive assembly, the transplanting assembly and the planting depth adjustment device, shown in Fig. 1a). The transplanting assembly mainly consists of a chain-row seedling feeder, a support plate, an eccentric disc, a cup transplanter, a single support frame and a mulching ballast wheel. The two transplanting units are fastened to the three-point suspension by U-bolts. The two ground wheel drive assemblies are fastened to the left and right sides of the three-point suspension, transmitting power to the chain feeder and the eccentric disc planting mechanism using a chain drive system. During operation, the tractor pulls the transplanter forward, and the ground wheel transmits the power to the seedling feeding mechanism and the planting mechanism, both of which work in a specific ratio; the seedlings are manually placed into the seedling feeding cup, and when the planting device rotates to a specific position above, it catches the seedlings falling from the seedling feeding cup and the planting device then drives the seedlings down. As the planter rotates into the soil, the planter opens up, and the seedlings fall into the expanded hole. Then the planter continues to rotate for the next planting. For the randomness of the complex excitation of the transplanter, the soil surface unevenness is regarded as the main source of transplanter vibration (*Su et al., 2022)*, as shown in Fig. 1b).



a) Structural of hanging cup transplanters *b) Vibration modeling of hanging cup transplanters*

Fig. 1 – Structural and vibration modeling of hanging cup transplanters

1 - Three-point hanging mechanism; 2 - Planting mechanism; 3 - Driving wheel; 6 - Planting depth adjustment mechanism; 7 - Seat; 8 - Chain feeding mechanism

Test conditions and test protocol

The test site was the soil bin laboratory at Inner Mongolia Agricultural University, equipped with an intelligent soil-machine-plant technology platform to carry out transplanting trials by the transplanting standard (JB-T 10291-2013 Dryland Planting Machinery) for tomato cavity tray seedlings.

The test machines and soil related physical parameters are shown in Table 1. The vibration signal acquisition equipment of the hanging cup transplanter is shown in Fig. 2.

Table 1

Main parameters of field trials

Item		**Value**
2ZP-2 type hanging-cup transplanter	Weight / [kg]	346
	Number of transplanted rows	2
	Row spacing / [mm]	500
	Spacing / [mm]	436
	Forward speed / [km/h]	0.8~2.4
Technology platform for intelligent soil-machine-plant systems	Rated speed / [km/h]	0.5~10
	Traction / [t]	1.5
	Power / [kW]	70
Soil parameters	Soil type	Sandy loam soil
	Moisture content / [%]	13.6
	Solidity / [MPa]	0.821
	Weight capacity / [g/cm^3]	1.26

This experiment uses the accelerometer installation position, as shown in Fig. 2, which can simultaneously test the vibration acceleration in three directions (*Wang et al., 2021*). The X-axis is defined as the transplanter forward direction, the Y-axis is defined as the transplanter lateral direction, and the Z-axis is defined as the direction of the transplanter perpendicular to the ground. The vibration characteristics of the transplanter were tested at 0.8, 1.2, 1.6, 2.0 and 2.4 km/h in a single factor test. The soil was rotated, levelled and suppressed before each test, and the planting depth was 60 mm. After the transplanter had stabilized, the vibration signals were collected for 8 s for each set of tests, and the average of three replicate tests was taken for analysis.

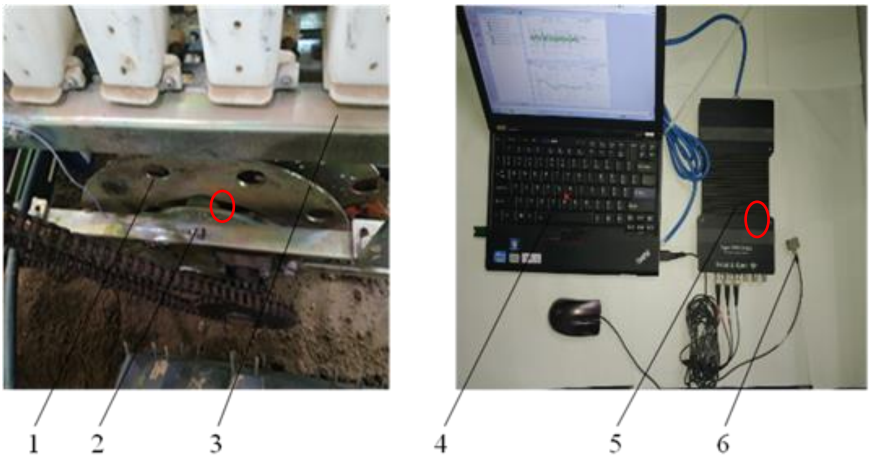


Fig. 2 - Vibration data acquisition diagram of transplanter

1 - planting mechanism; 2 - three-directional acceleration sensor attachment position; 3 - seedling feeding mechanism; 4 - computer with pulse software; 5 - data acquisition card; 6 - three-directional acceleration sensor.

Vibration test data analysis methods

The mean square value can describe the average energy or power of the vibration process. The positive square root of the mean square value is called the root mean square value of acceleration (RMS), or the practical value can better reflect the transplanter vibration, and the expression is:

$$\mathrm{RMS} = \left|\sqrt{\psi_x^2}\right| = \left|\frac{1}{\mathrm{N}}\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{x}_{\mathrm{i}}^2\right| \tag{1}$$

where:

X_i is the vibration signal; ψ_x^2 is the mean square value of the acceleration; N is the average number of vibration signals.

Power Spectral Density (PSD) is a measure of the mean square value of a random variable that represents the variation of energy per unit frequency band of a signal with frequency.

The power spectral density is defined as follows:

$$G_{xx}(f) = \frac{1}{\Delta f} \lim_{f \to \to \infty} \frac{1}{T} \int_0^T x^2(t, f, \Delta f) dt \tag{2}$$

Soil bin validation tests

Validation trials were carried out in the soil bin laboratory at Inner Mongolia Agricultural University, equipped with an intelligent soil-machine-plant technology platform and contains less straw, weeds and other debris. The soil was a sandy loam, prepared according to the macroscopic properties such as moisture content and firmness that the soil model has in the EDEM simulation model, and pretreated by sprinkling, rototilling and ballasting. Considering the planting depth requirement of tomato seedlings in cavity trays, the planting depth was set at 60 mm and soil parameters were measured in the 0-60 mm soil layer in the test area. The average soil moisture content was controlled at around 13±2%, and the average soil firmness was 643.8 kPa.

At the end of the test, several sets of measurement points were selected at equal intervals in the test area. The hole depth and longitudinal length were obtained at once using a hole plotter, as shown in Fig. 3, which consisted of a grid coordinate paper, an acrylic rod and a base made of acrylic sheets. To measure, the top layer of soil is scraped off, the hole plotter is placed directly above the hole, the acrylic rod is inserted along the circular hole in the base until it touches the soil, and the position of the top point of the rod on the grid coordinate paper is marked in turn with a marker to read the coordinates of each marked point.

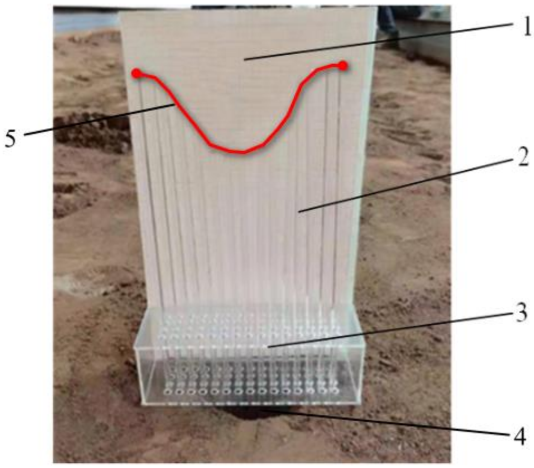
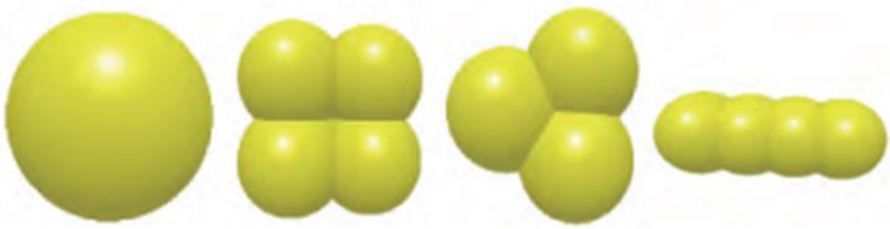


Fig. 3 - Hole plotter

1 - grid coordinate paper; 2 - acrylic rod; 3 - base made of acrylic sheet; 4 – hole; 5 - hole contour

Discrete element simulation analysis of transplanting process

In order to ensure that the simulated soil can accurately represent the actual soil conditions, the determination of relevant physical parameters and the calibration of simulation parameters have been completed for the sandy loam soil in Inner Mongolia (*Zeng et al., 2021*), as shown in Table 2. The simplification is carried out separately for the structural characteristics of sandy loam soils. Fig. 4 shows the different types of sandy loam particles, including spherical particles, nucleated particles, blocky triangular particles and columnar particles. Particle size is normally distributed.



a) spherical particles *b) nucleated particles* *c) blocky triangular particles* *d) columnar particles*

Fig. 4 - Soil particle discrete element model

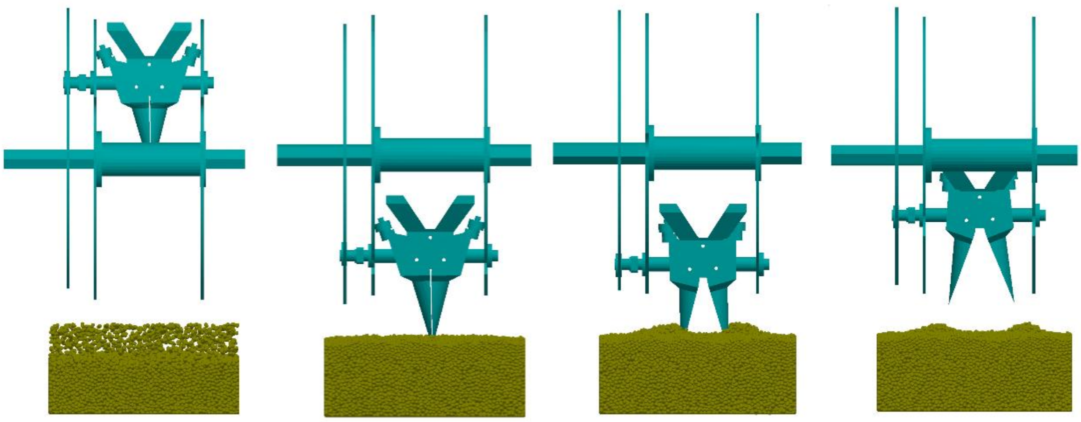
The mutual contact model between the planting device and the soil was set as Hertz–Mindlin (no slip) with a generation ratio of 1:1:1:1 (*Lv et al., 2021; Ma et al., 2021; Sun et al., 2018*). The particles were deposited by gravity after generation.

Table 2

Basic parameters of discrete element model

Simulation parameters	Value
Density of steel / [kg/m^3]	7850
Density of soil particles / [kg/m^3]	1452
Poisson's ratio of soil	0.42
Poisson's ratio of steel	0.3
Young's modulus of soil / [MPa]	10^6
Young's modulus of steel / [MPa]	7×10^{10}
Soil-soil restitution coefficient	0.45
Soil-steel restitution coefficient	0.35
Soil-soil static friction coefficient	0.4
Soil-steel static friction coefficient	0.85
Soil-soil rolling friction coefficient	0.3
Soil-steel rolling friction coefficient	0.13
Soil particle generation time / [s]	5
Simulation time / [s]	8
Time step	25%

A simulated soil trough of 1400 mm long, 500 mm wide and 300 mm high was used in the simulation, as shown in Fig. 5. In order to reduce the simulation time, only the individual planters were simulated, and the model of the planting mechanism was constructed using Pro/E and imported into the center of the working interface of the EDEM discrete element simulation software.



a) b) c) d)

Fig. 5 - Planter positions at different times

a) soil model generation; b) planter in contact with soil; c) generate pores; d) the planter leaves the soil

Based on the vibration data analyzed in the previous section, vibration frequencies of 0, 4, 8, 12 and 16 Hz and vibration amplitudes of 0, 3, 6, 9 and 12 mm were set for the transplanting simulation tests. Based on the agronomic requirements of transplanting and related research, the transplanter was set to a speed of 18.2 r/min (i.e. λ=1.22), a planting depth of 60 mm and a simulation time of 8 s.

Soil bin validation test

At the end of the simulation, the critical curve of the movement velocity of soil particles was plotted as the contour of the pitshaped cross section of soil disturbance, conditional on whether the soil has movement velocity, and the contour of soil accumulation on the surface was used as the contour of the monopoly-shaped cross section of soil disturbance. The holes were measured using a hole mapper, and the measured contour data points were curve fitted and compared with the simulation results, as shown in Fig.6.

In the soil bin test, the skidding of the transplanter tires caused the misalignment of the two fitted curves. The statistical analysis of the difference between the actual measurement points and the simulated points in the figure shows that the maximum misalignment value is 6 mm and the minimum is 0 mm, where the average value is 2.22 mm and the average difference is 1.35 mm.

The soil trough test fitted pore contours are consistent with the simulated pore contour crosssection in a V-shape. In order to further evaluate the consistency of the simulated and soil bin test values, the relevant parameters of the hole were compared.

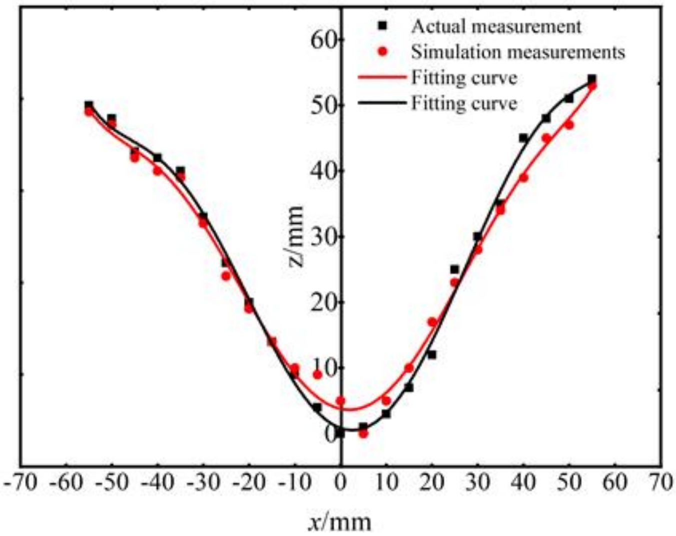


Fig. 6 - Measurement results of hole section

In order to further demonstrate the accuracy of the simulation experiment, the key parameters of the holes were analyzed. From Table 3, the experimental values of longitudinal length and width of the hole were larger than the simulated values, and the relative errors between the experimental and simulated results were within a reasonable range, which proved the reasonableness of the simulated data. The relative error of effective depth is 9.54%, which is probably due to the accumulation of errors in the measurement and software fitting process, and the relative error of hole width is 0.86%.

This also proves the reliability of using discrete element methods for research. In the future, the discrete element method will be further used for analysis.

Table 3

Comparison of the results of simulation and soil bin test

Indexes	Simulation values [mm]	Test values [mm]	Relative errors [%]
Longitudinal length of the hole / [mm]	102	104	1.92
Width of the hole / [mm]	57.6	58.1	0.86
Effective depth / [mm]	52.3	48.5	9.54

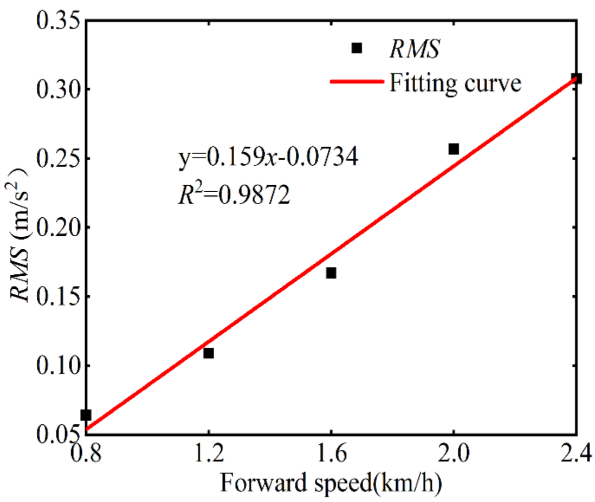
RESULTS

Analysis of vibration test results

Based on the time domain signal of the transplanter, the relationship between its forward speed and the Root Mean Square (*RMS*) value of acceleration can be solved, as shown in Fig. 7.

As can be seen from Fig. 6, the root mean square values of acceleration in the *X*, *Y* and *Z* directions increase as the forward speed increases, and when the forward speed of the transplanter is 0.8-2.4 km/h, the root-mean-square values of vibration acceleration in X-direction range from 0.06 to 0.31 m/s^2, in the Y-direction from 0.23 to 0.77 m/s^2, and in the *Z*-direction from 0.29 to 0.95 m/s^2.

The regression results show that there are linear correlation between the root mean square and forward speed.



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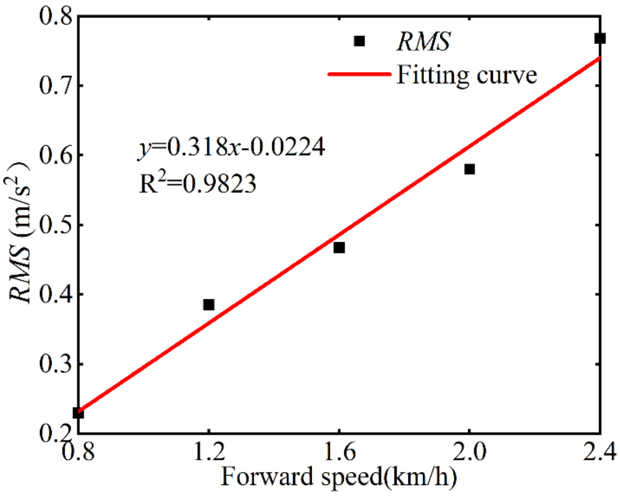

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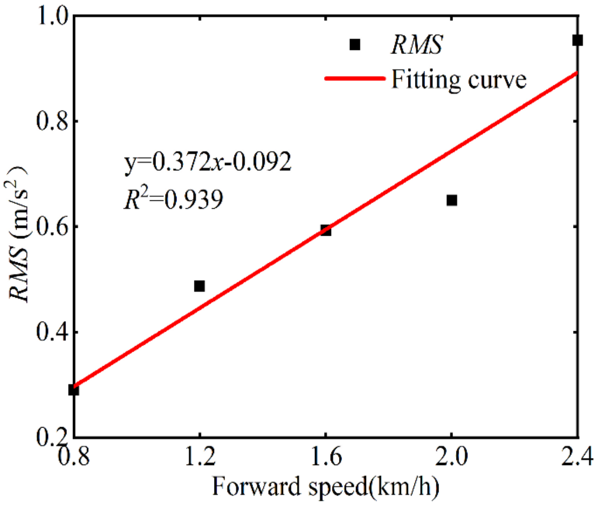
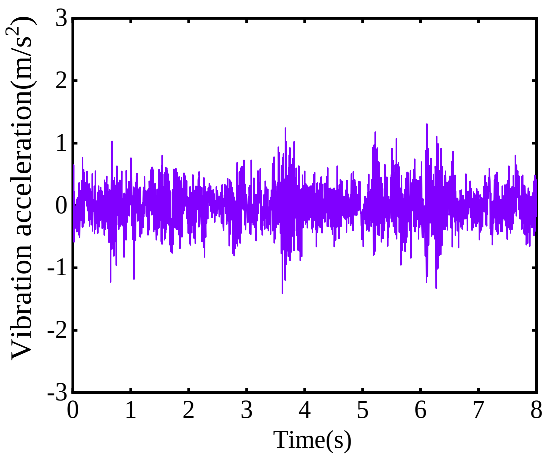


c)

Fig. 7 – Distribution of root mean square acceleration of transplanter

a) X direction; b) Y direction; c) Z direction

The time domain signal of *Z*-direction vibration is shown in Fig. 8. The vibration is most intense in the direction perpendicular to the soil. This conclusion is consistent with the vibration test results in this article.



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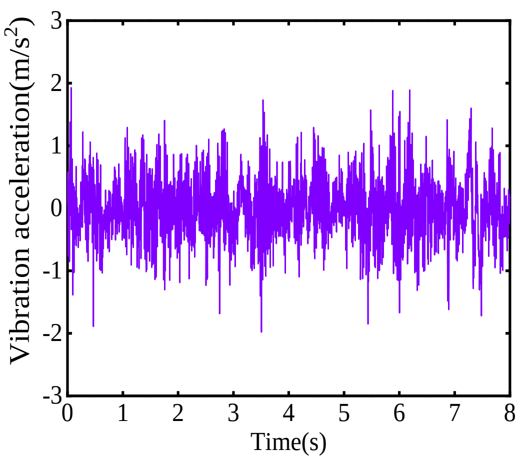

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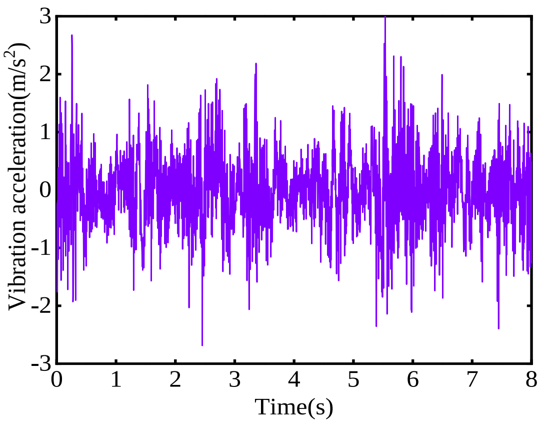

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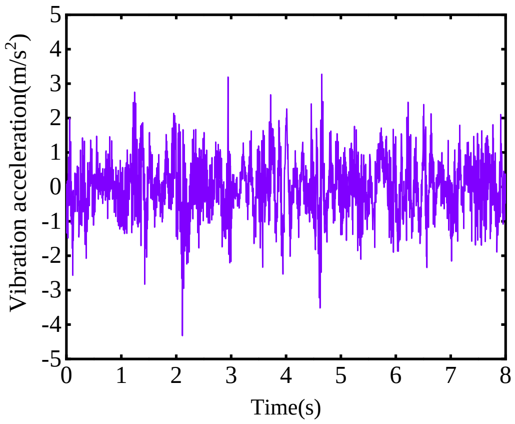

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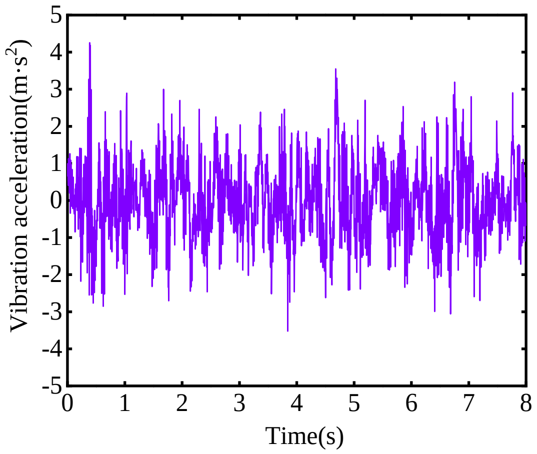


e)

Fig. 8 - Time domain signals of vibration at different forward speeds of the transplanter

a) v=0.8 km/h; b) v=1.2 km/h; c) v=1.6 km/h; d) v=2.0 km/h; e) v=2.4 km/h

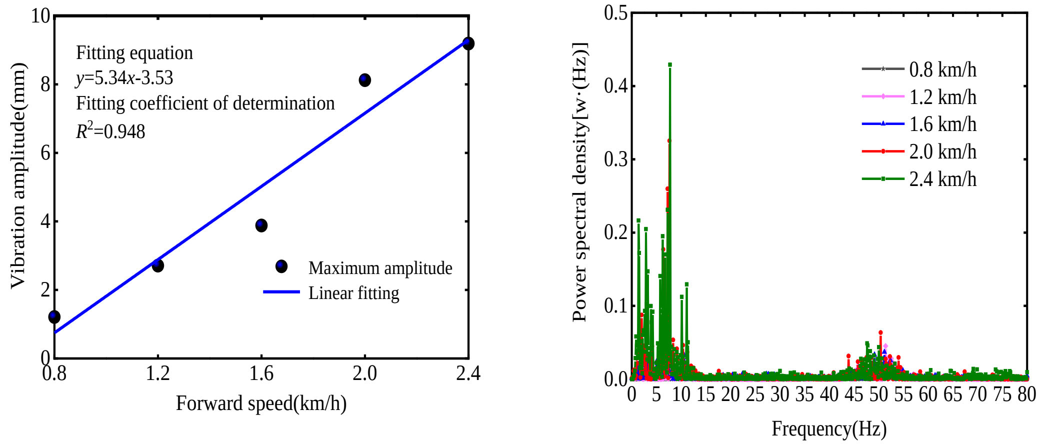
As shown in Table 4, with the increase of the forward speed, the maximum value, variance, standard deviation and effective value of the vibration acceleration tended to be increased. This shows a trend of positive correlation with forward speed.

Table 4

Time domain parameters statistics table

Forward Speed / [km/h]	Vibration data statistics/[m/s^2]						
	Maximum Values	Minimum Values	Mean Value	Variance	Standard Deviation	Median	Valid Value
0.8	1.3070	-1.4116	-0.0016	0.1141	0.3379	-0.0013	0.2931
1.2	1.9276	-1.9807	-0.0068	0.2629	0.5128	-0.0226	0.4870
1.6	3.1437	-2.6875	-0.0085	0.4514	0.6719	-0.0063	0.5932
2.0	3.2731	-4.3245	-0.0093	0.7177	0.8472	-0.0086	0.6489
2.4	4.2535	-3.5225	0.0018	1.0504	1.0249	-0.0210	0.9526

The time-amplitude curve is obtained by quadratic integration of the time-domain signal, as shown in Fig.9a), where the maximum amplitude becomes more significant as the forward speed increases. The vibration amplitude increases significantly at a forward speed of 2 km/h. The power spectrum density curve was obtained by a fast Fourier transform of the time domain signal. According to the power spectrum density curve in Fig.9b), the vibration of the transplanter is primarily low-frequency vibration, and the frequency distribution of vibration energy is mainly concentrated in the frequency range of 1-12 Hz. The greater the forward speed, the more intense the vibration will be, but there will be no effect on the frequency distribution of the vibration energy range.



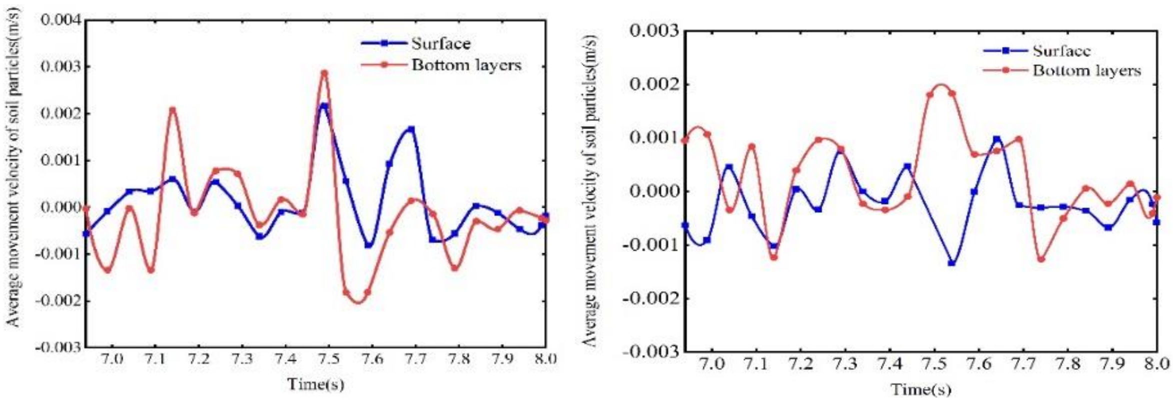
a) b)

Fig. 9 - Vibration test results

a) Fitting line between forward velocity and maximum amplitude; b) Power spectral density curves

Discrete element simulation results

Vibration increases the soil fragmentation effect and will accelerate the flow of soil particles (*Awuah et al., 2022*). When seedlings enter the soil, soil flow increases, and the planting depth of seedlings becomes shorter. The effect of machine vibrations on soil particles affects the quality of seedling planting. The simulated soil was divided into two layers and used to analyze the variation of soil movement velocity in the area where the transplanter operated. The average movement velocity variation curve of soil particles at a vibration frequency of 8 Hz and vibration amplitude of 6 mm were selected for analysis, as shown in Fig. 10. The movement trend of the two layers of soil is similar, but the movement speed is not the same. The movement speed of soil particles on the surface is significantly lower than that of the bottom particles.



a) b)

Fig. 10 - Soil average movement velocity contrast graph

a) Vibration frequency is 8Hz; b) Vibration amplitude is 6 mm

Parametric regression orthogonal test

Central composite design

Combined with the design principle of orthogonal test, vibration frequency and vibration amplitude were selected as the test factors. The test factors are coded as shown in Table 5.

Table 5

Horizontal coding of test factors

Horizontal coding	Factors	
	A: Vibration amplitude [mm]	B: Vibration frequencies [Hz]
-1.414	0	0
-1	3	4
0	6	8
1	9	12
1.414	12	16

According to the above analysis, the vibration parameters have the most significant effect on the average movement velocity of the particles in *Z*-direction. Therefore, the subsequent study will be conducted with the average movement velocity of the particles in *Z*-direction as the indices. An orthogonal test of two factors and five levels was designed using the Design Expert 11 software (STAT-EASE Inc., Minneapolis, USA). A total of 13 test combinations were conducted, and each combination was repeated several times, and the test results are shown in Table 6.

Table 6

Test design and results

No.	Test Factors and Levels		Target Value
	Vibration amplitude [mm]	Vibration frequencies [Hz]	Average movement velocity of soil particles [m/s]
1	1	1	0.0486
2	0	0	0.0183
3	0	0	0.0204
4	0	0	0.0189
5	-1	1	0.0321
6	1	-1	0.0289
7	0	-1.414	0.0170
8	0	0	0.0172
9	0	0	0.0212
10	-1.414	0	0.0295
11	1.414	0	0.0399
12	-1	-1	0.0253
13	0	1.414	0.0214

Establishment and significance analysis of regression model

Eq. 3 is a multiple regression fitting curve equation for the average movement velocity (*V*) of the particle with respect to the vibration amplitude (*A*) and vibration frequency (*B*).

$$V = 0.0152 + 0.0087A + 0.0036B + 0.0032AB + 0.0049A^2 + 0.0137B^2 \tag{3}$$

The Design Expert software was used to conduct the multiple regression fitting and variance analysis on the data from average movement velocity of soil particles, and the results are shown in Table 7.

Table 7 shows that the overall P-value of the model is less than 0.01, which indicates that the model is highly significant and R^2=0.9576 indicates a better fitting. The lack of fit term is non-significant (P=0.3296>0.05) indicating that the model can analyze and predict the change of average movement velocity of soil particles. The factors affecting the magnitude of average movement velocity of soil particles are vibration amplitude (*A*) and vibration frequency (*B*) in that order.

Table 7

Variance analysis of the regression model

Source	Sum of Squares	Freedom	Mean Square	F-value	p-value
Model	0.0021	5	0.0004	31.59	0.0001**
A	0.0006	1	0.0006	45.21	0.0003**
B	0.0001	1	0.0001	7.86	0.0264*
AB	0.0000	1	0.0000	3.08	0.1228
A^2	0.0002	1	0.0002	12.29	0.0099**
B^2	0.0013	1	0.0013	96.77	< 0.0001**
Residual	0.0001	7	0.0000		
Lack of Fit	0.0001	3	0.0000	1.56	0.3296
Pure Error	0.0000	4	0.0000		
Cor Total	0.0022	12			

*Note: * means significant (P < 0.05), and ** means extremely significant (P < 0.01).*

Fig. 11 shows the response surface of the influence of vibration amplitude and frequency on the average movement velocity of soil particles. When the vibration frequency is constant, the average motion speed of particles increases with the increase of vibration amplitude. When the vibration amplitude is constant, the average movement velocity of soil particles first decreases and then increases with the increase of vibration frequency. In the case of interaction between the two, there is a clear upward trend in the average motion speed of particles.

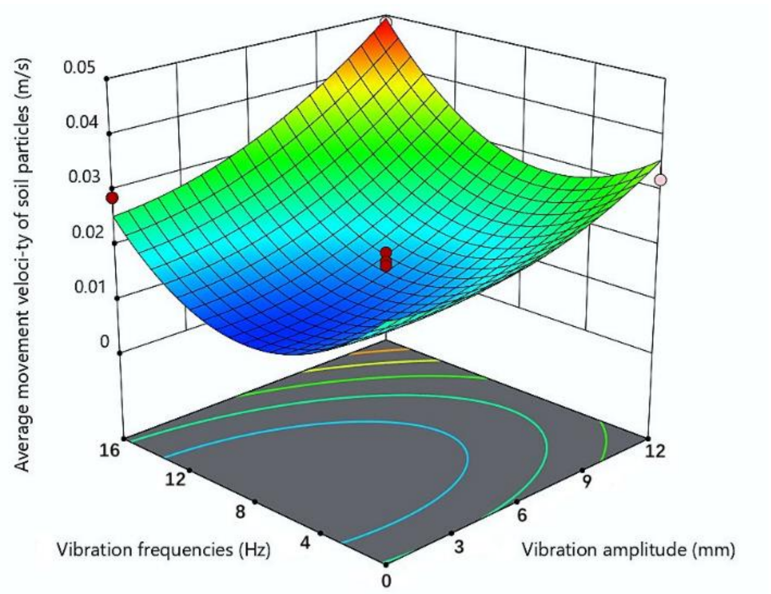


Fig. 11 - Response surface plots of interaction of two factors on average movement velocity of soil particles

CONCLUSIONS

This study used theoretical analysis, vibration testing experiments, discrete element simulation, and other methods to analyze the impact of transplanting machine vibration on the movement speed of soil particles in holes.

At an operating speed of 0.8-2.4 km/h, the vibration acceleration of the 2ZP-2 type hanging-cup transplanter increases with the forward speed, the frequency distribution of the vibration energy ranges from 1 to 12 Hz in the low-frequency band, and the vibration amplitude increases linearly in the range of 1.21-9.19 mm.

The Central Composite test resulted in the regression equations of vibration amplitude and vibration frequency on the average movement velocity of the particles. The response surface analysis showed that the effect of vibration amplitude on the average movement velocity of particles was greater than the effect of vibration frequency on the average movement velocity of particles. At the same time, the average movement velocity of the particles tends to increase significantly under the interaction of the two. In order to be more suitable for transplanting in sandy loam soil, the vibration amplitude of the transplanting machine should be as small as possible. And ensure the smoothness of the soil.

In addition, the use of transplanters to carry out the planting process has been known widely. Reviews related to productivity performance from these tools are closely related to topographic conditions, soil types, land area, plant species, community culture, the purpose of use, and the technology included as an added value to the tool. In the future studies, the plant species, water content and other factors deserve further experimental studies. Our test bench is already under development, and test methods for controlling variables are being proposed.

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