VIBRATION CHARACTERISTICS TEST AND ANALYSIS OF HANGING CUP TRANSPLANTER
/
吊杯式移栽机振动特性测试与分析

Qiang SU[1)], Xuying LI*[1)], Fandi ZENG[1)], Junyue WANG[1,2)], Yongzhi ZHANG[1)], Hongbin BAI[1)], Lei WU[1)], Jie WANG[1)]
[1)]Inner Mongolia Agricultural University, College of Mechanical and Electrical Engineering, Hohhot/China;
[2)] Hohhot Branch of Chinese Academy of Agricultural Mechanization Science Co., Ltd, Hohhot/China
Tel: +86-0471-4309215; E-mail: suqi5199@163.com
DOI: https://doi.org/10.35633/inmateh-66-28

Keywords: *hanging cup transplanter, uneven soil surfaces, vibration characteristics, root-mean-square acceleration, power spectrum*

ABSTRACT
The vibration of the hanging cup transplanter affected the hole size and tray seedling quality. This paper takes the 2ZP-2 hanging cup transplanter as the research object, studies the vibration characteristics of the transplanter when it works, deduces the mathematical model of the transplanter-soil vibration characteristics, and solves the steady-state vibration response. The Danish B&K vibration test system carried out the vibration test. Studies have shown that the vertical vibration of the transplanter is greater than that of the lateral vibration and the forward vibration. The main factors affecting the vertical vibration of the transplanter are the forward speed of the transplanter, the soil compaction, and the planting depth. When the forward momentum of the transplanter is in the range of 0.8~2.4 km/h, the vertical vibration acceleration increases with increasing forward speed of the transplanter. According to the power, spectral density curve, and spectral curve, the spectrum range of the vertical vibration energy peak is 0~10 Hz, the vibration frequency is between 4.5~5.5 Hz, and the corresponding vibration acceleration amplitude is 0.03~0.33 m/s^2. The research results can provide a reference for improving the operating speed, comfort, and structural optimization.

摘要
针对吊杯式移栽机受复杂激励产生振动影响栽植孔穴参数、穴盘苗栽植质量的问题，本文以 2ZP-2 型吊杯式移栽机为研究对象，对移栽机工作时的振动特性进行研究，推导了移栽机-土壤振动特性数学模型，求解了稳态振动响应；利用丹麦 B&K 振动测试系统进行了振动测试试验。研究表明移栽机垂直振动大于横向振动和前进方向振动，影响移栽机垂直振动的主要因素是移栽机前进速度、地表坚实度和栽植深度；当移栽机前进速度在 0.8~2.4 km/h 范围内时，随移栽机前进速度增加，垂直振动加速度也增加，由功率谱密度曲线和频谱曲线可知，垂直振动能量峰值出现的频谱区间为 0~10 Hz，振动主频位于 4.5~5.5 Hz 之间，所对应的振动加速度幅值范围为 0.03~0.33 m/s^2。研究结果可以为提高移栽机作业速度、舒适性和结构优化提供参考。

INTRODUCTION
Seedling transplanting technology carried out in the Bayannaoer area of Inner Mongolia can avoid natural disasters in spring, prevent pests and weeds, and improve the survival rate of seedlings. Seedling transplanting plays an essential role in warming, heat preservation, soil moisture conservation, and increased crop yield (*Hu et al., 2021)*. At present, hanging cup transplanters are the leading equipment suitable for transplanting on the film *(Wang et al., 2016)*, duckbill-type transplanting machines (*Zhao et al., 2017*), and water wheel film transplanters (*Xu et al., 2021*). The hanging cup transplanter can complete the punching, planting, covering soil, and pressing operations all at once. It has high transplanting efficiency, significantly saves the labor force, and reduces the impact on a farmland's ecological environment. Therefore, in the Inner Mongolia Bayannaoer region hanging cup transplanter is widely used. During the field transplanting operation, the transplanting machine had random vibrations due to the complex field conditions. The random vibration affected the planting performance of the transplanter. It reduced the riding comfort of the seedling feeders, which was one of the crucial factors inhibiting the large-scale promotion of the transplanter.

In recent years, scholars at home and abroad have improved planting efficiency and planting qualification rates. Research on the hanging cup transplanters mainly aims to optimize the structure of the transplanter (*Zhang et al., 2015*), perform planting performance tests (*Jin Seok Jo. et al., 2018*), explore the law of seedling throwing (*Liu et al., 2018*), and transplant trajectory (*Liu et al., 2019*).

Finite element analysis software was used to conduct the modal test on the transplanter (*Wout W et al., 2014*). Lingxin Geng carried out vibration characteristics tests on the seedling picking device of the transplanter (*Geng et al., 2021*). Scholars in China and abroad have performed many studies on the relationship between the vibration caused by soil surface roughness and the operation performance of agricultural machinery. For example, Hildebrand studied the vibration of vehicles passing through rough or undulating dry and soft road surfaces and established a vehicle-soil system vibration model (*Hildebrand R., 2008, G.V.P. Kumara et al., 2011*). Rabbani MA predicted the vibration characteristics of a semi-crawler tractor by establishing a vibration model (*Rabbani M A. et al., 2002*). Xiaodong Zhang studied the relationship between vibrations caused by uneven farmland excitation, the shovel corn precision seeder and the sowing performance, deducing the steady-state response mathematical model (*Zhang et al., 2014*). Based on the above literature, we can see that there have been achievements in the study of vibration caused by agricultural machinery field roughness and in the research of agrarian machinery structure and operation performance. Nevertheless, research on the combination of soil surface roughness excitation and vibration characteristics of transplanting machines is limited.

This study intends to conduct theoretical analysis and vibration tests on the vibration generated by the bucket transplanter under different working conditions. The test determines what factors affect the vibration characteristics of the transplanter. This study provides a reference for selecting the working parameters of hanging cup transplanters and improving the design of planting mechanisms.

MATERIALS AND METHODS

• **Structure and working principle of hanging cup transplanter**

The 2ZP-2 hanging cup transplanter is mainly composed of a three-point suspension frame, a planting assembly, a covering soil pressing mechanism, a chain feeding seedling assembly, and a ground wheel transmission mechanism, as shown in Figure 1. The planting assembly is fixed on the three-point suspension frame by two parallel support frames; two driving wheels drive the power to the seedling cup and the hanging cup planting device by chain transmission. When the transplanter operates, it is necessary to put the plug seedlings into the seedling feeding cup, given the chain drives the seedling feeding cup to throw the plug seedlings into the planter. The planter rotates around the transplanting spindle at the same time as the transplanter moves horizontally. The transplanter is always perpendicular to the ground and is punched when it comes into contact with the soil.

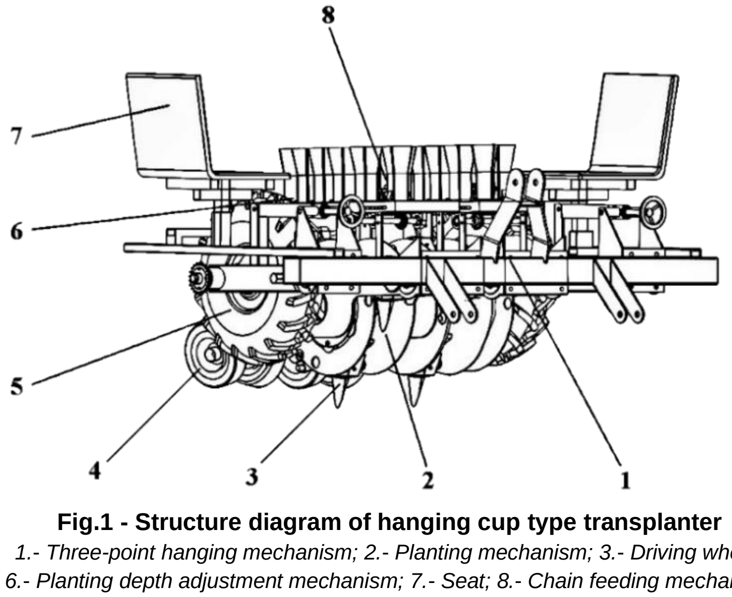


Fig.1 - Structure diagram of hanging cup type transplanter

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

• **Establishment of a Vibration Characteristic Model of Transplanters**

Vibration is common in mechanical structures. Because the working environment of the transplanter is complex, the vibration caused by surface roughness and mechanical design is complex. Vibration affects the ride comfort of seedling feeders and the planting quality of plug seedlings, quickly leadings to structural damage due to resonance. Our research group measured and analyzed the surface roughness (*Liu et al., 2019*).

The surface morphology of the hanging cup transplanter working ground simplifies into a sine curve as shown in Figure 2. The longitudinal ground curve is the height of the ground relative to reference level H. The distance viewed between the two peaks is the soil roughness function (length L of the transplanter walking along the forward direction). Taking into account the influence of the speed of the transplanter on the vibration of the system, the variation of the road height with the road length is used to describe the soil roughness excitation. In the analysis, considering the influence of the transplanter speed on the system vibration, the soil roughness excitation is described by the change of the road height with the road length. When studying the vibration characteristics of the transplanter, considering the influence of the transplanter speed on the system vibration, the soil roughness excitation is described by the change in the road height with the road length (*Zhang et al., 2014*). To better analyze the vibration characteristics of the transplanter, the transplanter model is simplified, so that the whole system is a continuous linear system. Before establishing the model, we make the following assumptions: (1) The transplanter framework, planting assembly, and chain-row seedling feeding assembly are all rigid bodies. (2) The stiffness of the transplanter planting assembly and the stiffness of the ground wheel are linear functions of displacement. (3) The damping caused by the interaction between the planter, the ground wheel, and the soil is a linear function of speed. (4) The ground wheel keeps in contact with the soil without bouncing. The established model is the vertical vibration model of the transplanter without considering the lateral vibration (*Wang et al., 2019, Liu, 2016*). The mathematical model for transplanter-soil vibration based on soil roughness is as follows:

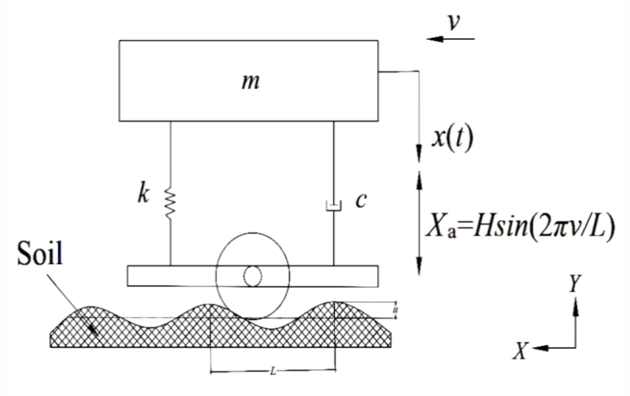


Fig. 2 - Hanging cup transplanter-soil system vibration model

Based on the soil surface roughness, the transplanter is excited by a $\omega=2\pi\frac{vt}{L}$ harmonic.

$$X_a = H\sin\left(\frac{2\pi vt}{L}\right) \tag{1}$$

where: v—advance speed of transplanter, [m/s],

t—working time of transplanter, [s].

The absolute displacement of transplanter is $x(t)$, so the vibration balance equation is:

$$\mathrm{m}\ddot{x}(t) + \mathrm{c}\left[\dot{x}(t) - \dot{X}_a(t)\right] + \mathrm{k}[x(t) - X_a(t)]=0 \tag{2}$$

Substituting Formula (1) into Formula (2):

$$\mathrm{m}\ddot{x}(t)+\mathrm{c}\dot{x}(t)+\mathrm{k}x(t)=\mathrm{c}\dot{X}_a(t)+\mathrm{k}X_a(t)=\mathrm{k}X_a\cos\omega t\text{-}\mathrm{c}\omega X_a\sin\omega t \tag{3}$$

Equation (3) is simplified, and the motion equation for the vibration system under the operating conditions is:

$$\mathrm{m}\ddot{x}(t)+\mathrm{c}\dot{x}(t)+\mathrm{k}x(t)=X_a\sqrt{\mathrm{k}^2+(\mathrm{c}\omega)^2}\sin\left[\omega t+\tan^{-1}\left(\frac{\mathrm{c}\omega}{\mathrm{k}}\right)\right] \tag{4}$$

The letter in Formula (4) gives the following meanings:

$$\begin{cases} Y_d=X_a\sqrt{\mathrm{k}^2+(\mathrm{c}\omega)^2} \\ \alpha=tan^{-1}\left(\frac{c\omega}{k}\right) \end{cases} \tag{5}$$

Arrange Formula (4) into the following formula:

$$m\ddot{x}(t)+c\dot{x}(t)+kx(t)=Y_d\sin(\omega t+\alpha) \tag{6}$$

Dividing both sides of the formula by m, where:

$$\begin{cases} 2\xi\omega_n=\frac{c}{\mathrm{m}} \\ \omega_n^2=\sqrt{\frac{\mathrm{k}}{\mathrm{m}}} \\ \delta=\frac{Y_d}{m} \end{cases} \tag{7}$$

The above vibration equation can simplify the following equation:

$$\ddot{x}(t)+2\xi\omega_n\dot{x}(t)+\omega_n^2x(t)=\delta\sin(\omega t+\alpha) \tag{8}$$

- **Steady-state response of transplanter under harmonic excitation**

The steady-state response equation of the bucket transplanter is as follows:

$$\mathrm{X}(t)=X\sin(\omega t\text{-}\varphi) \tag{9}$$

where: φ——initial phase,
X——amplitude.

Substitute Formula (7) into Formula (6) to obtain the following procedure.

$$X[(\omega_n^2\text{-}\omega^2)\cos(\omega t+\alpha\text{-}\varphi)\text{ -}2\xi\omega_n\omega(\omega t+\alpha\text{-}\varphi)]=\delta\sin(\omega t+\alpha) \tag{10}$$

Combine trigonometric functions in Formula (8) and obtain the following:

$$\begin{cases} X=\frac{X_a\sqrt{1+(2\xi\lambda)^2}}{\sqrt{\left(1\text{-}\lambda^2\right)^2+(2\xi\lambda)^2}} \\ \varphi=\tan^{-1}\frac{2\xi\lambda}{1\text{-}\lambda^2} \end{cases} \tag{11}$$

In the formula, λ is the ratio of the excitation force-frequency ω to the natural frequency ω_n of the system without damping. Therefore, the steady-state solution of the transplanter vibration system is as follows:

$$\mathrm{X}(t)=\frac{X_a\sqrt{(2\xi\lambda)^2}}{\sqrt{(1-\lambda^2)^2+(2\xi\lambda)^2}}\sin\left[\omega t+\tan^{-1}\frac{c\omega}{k}\text{-}\tan^{-1}\frac{2\xi\lambda}{1-\lambda^2}\right] \tag{12}$$

Therefore, we can derive the influencing factors from the vibration characteristics and steady-state response of the transplanter. The main factors affecting the vibration of the cup transplanter are forward speed, external excitation, soil surface condition, and structural characteristics of the whole machine.

- **Vibration Test on Transplanter**

The orthogonal vibration test on the hanging cup transplanter explores the main factors influencing the vibration characteristics of the hanging cup transplanter.

The experiment was performed in the intelligent soil-machine-plant laboratory of Inner Mongolia Agricultural University.

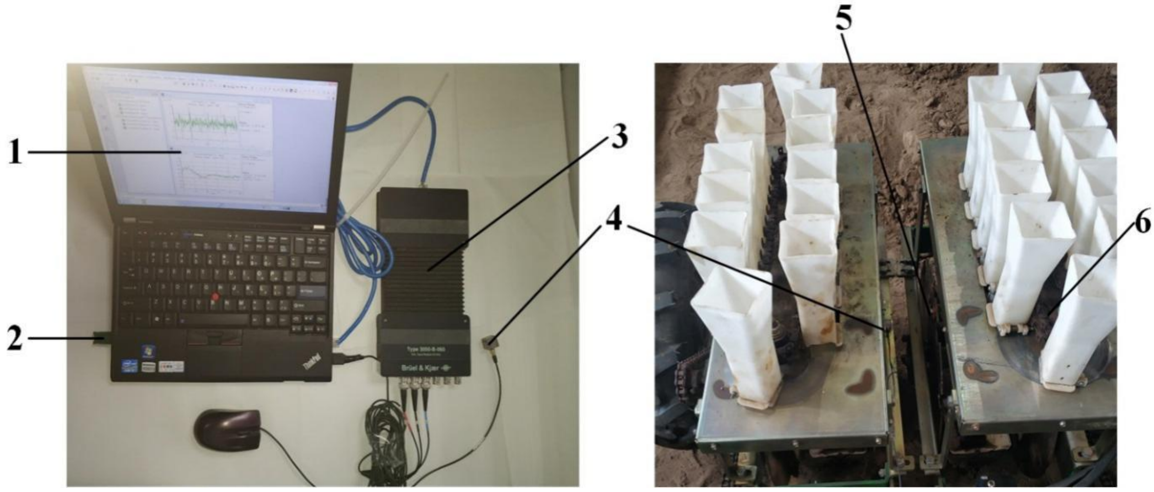
We used a 2ZP-2 hanging cup transplanter as the research object to transplant tomato plug seedlings. The test methods refer to JB-T 10291-2013 “Dryland Planting Machinery” and GB/T 5667-2008 “Agricultural Machinery Production Test Method” to ensure the planting performance of the transplanter. Before each test, the soil was subjected to rotary tillage, leveling, compaction, and other operations. The test machine and soil-related physical parameters are shown in Table 1.

Table 1

Test equipment and soil parameters

Item		Data
Intelligent Soil-Machine-Plant Laboratory System Technology Platform	Rated speed [km/h]	0.5~10
	Tractive force [t]	1.5
	Maximum traction speed [km/h]	4
Soil physical characteristics	Soil type	Clay loam
	Averaging of water saturation [%]	13.6
	Averaging of volumetric weight [g/cm^3]	1.2

The test equipment for the vibration signal acquisition of a hanging cup transplanter includes Pulse software of B&K Company of Denmark, a 4506B series triaxial acceleration sensor, and a 3050-B-060 six-channel Pulse LAN-XI data acquisition card. The three-axis acceleration sensor is in the spindle position of the planting mechanism. The *X*-axis direction is the forward direction of the transplanter, the *Y*-axis direction is the horizontal direction of the transplanter, and the *Z*-axis direction is the vertical direction of the transplanter. The sensor connects the data acquisition instrument. The data acquisition instrument processes the analog-to-digital conversion, amplification, filtering and so on, and the voltage signal is transformed the analog signal using analog-to-digital conversion, amplification, and filtering, the voltage signal is converted into a digital signal (*Wang et al., 2021*). After the transplanter runs smoothly, the vibration signal is collected for 8 s in each group of experiments and repeated for three times to take the average value which is taken for analysis.



a) Vibration data acquisition system *b) Sensor installation position*

Fig. 3 - Field vibration data collection of transplanter

1.- Electronic key; 2.- Computer; 3.- Data acquisition card of type 3050-B-060; 4.- Sensor;
5.- Planting mechanism; 6.- Feeding mechanism

This experiment used a soil tanker instead of a tractor-drawn cup transplanter for orthogonal vibration experiments. Vibration signal processing and statistical functions are often used to describe its essential characteristics. The root mean square (*RMS*) can explain the strength of vibration signals.

$$\Psi_x^2 = \lim_{T\to\infty} \frac{1}{T}\int_0^T X^2(t)dt \tag{13}$$

The expression is expressed by finite discrete variables as follows.

$$\Psi_x^2 = \lim_{n\to\infty} \frac{1}{n}\sum_{k=1}^{n} X_k(t_i)^2 \tag{14}$$

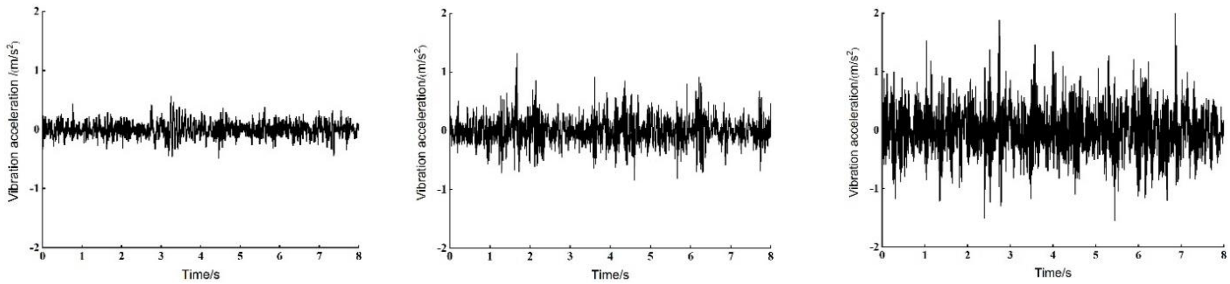
According to the Box-Behnken experimental principle, three factors and three levels orthogonal experiments were designed.

A total of 17 practical points were included, including 5 zero estimation errors, and each experiment was repeated three times. The root means square used a fair value for the vibration acceleration, given the evaluation index for the vibration amplitude of the transplanting machine. The effects of forward speed, planting depth, and soil solidity on the vibration characteristics of the transplanting machine were analyzed. This experiment does not consider the structural parameters of the cup-type transplanter and the transplanting plug seedlings. Each experimental factors and the levels of each facet are shown in Table 2.

Table 2

Experimental factors and levels

Levels	Forward speed A	Depth of planting B	Soil compaction C
	[Km/h]	[mm]	[N/cm^2]
-1	0.8	50	50~70
0	1.4	70	90~110
1	2.0	90	130~150



a) Developing direction *b) Vertical orientation* *c) Horizontal direction*

Fig. 4 - Time domain signal with advance speed of 1.2 km/h and planting depth of 70 mm

The Z-axis acceleration amplitude is much larger than the amplitudes for the X-axis and Y-axis. The test data of different acceleration sensor channels are analyzed. Figure 4 shows the time domain signal of the acceleration sensor in the *X*, *Y*, and *Z* directions when the planting depth is 70 mm and the speed is 1.2 km/h. It shows that the vertical vibration of the hanging cup transplanter is the most intense. The root suggests a square value for the vibration acceleration for a short pulse on the transplanter should be emphatically analyzed.

RESULTS

The test results are shown in table 3, in which *A*, *B* and *C* are the factor coding values for the transplanting machine planting depth, forward speed, and surface firmness respectively.

Table 3

Vibration test scheme and results

Test serial number	*A*	*B*	*C*	*RMS*
	[Km/h]	[mm]	[N/cm^2]	[m/s^2]
1	0	1	1	1.23
2	1	1	0	0.95
3	0	1	-1	0.82
4	0	-1	-1	0.43
5	1	-1	0	0.46
6	-1	-1	0	0.36
7	0	0	0	0.67

Table 3
(Continuation)

Vibration test scheme and results

Test serial number	*A*	*B*	*C*	*RMS*
	[Km/h]	[mm]	[N/cm^2]	[m/s^2]
8	0	0	0	0.69
9	0	0	0	0.72
10	-1	0	1	0.98
11	1	0	1	0.82
12	1	0	-1	0.53
13	-1	0	-1	0.63
14	0	-1	1	0.69
15	0	0	0	0.51
16	-1	1	0	0.84
17	0	0	0	0.85

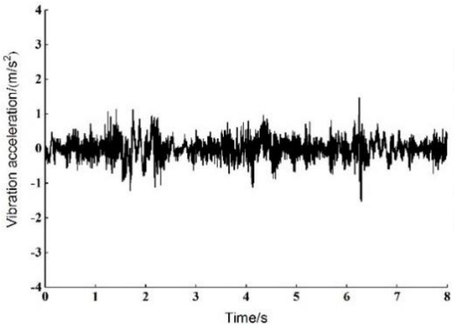
Table 4 shows the variance analysis results. It shows that the overall *P value* of the model was less than 0.05, indicating the model was significantly different. In addition, $R^2 = 0.83$, indicating that the fitting was good. The unremarkable missing fitting term (P=0.7584>0.05) suggests that the model can analyze and predict the change in *RMS*. Since the forward velocity (P<0.0001) and the surface solidity (P=0.0006) have P values less than 0.01, the influence of forwarding velocity and soil solidity on the vertical vibration of the transplanter is significantly different. However, the effect of planting depth on the vertical vibration of the transplanter is not entirely different. Therefore, the factors that affect the size of the *RMS* are the transplanter forward speed, the surface firmness, and the planting depth. When the bold speed changes, the vibration of the transplanter will be more prominent due to the excitation of the soil surface roughness.

Table 4

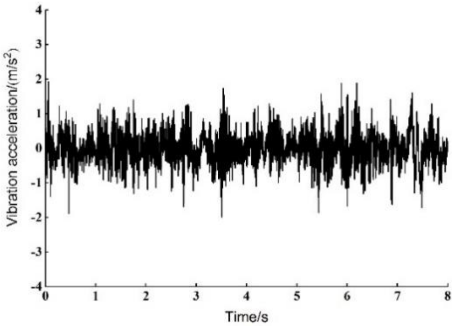
Analysis of variance of regression equation

Source	Quadratic sum	DF	MS	FValue	PValue
Model	0.6661	3	0.222	20.69	<0.0001
A	0.0003	1	0.0003	0.0291	0.8670
B	0.4513	1	0.4513	42.05	<0.0001
C	0.2145	1	0.2145	19.99	0.0006
Residual error	0.1395	13	0.0107		
Misfit term	0.0802	9	0.0089	0.6015	0.7584
Pure error	0.0593	4	0.0148		
Summation	0.8056	16			

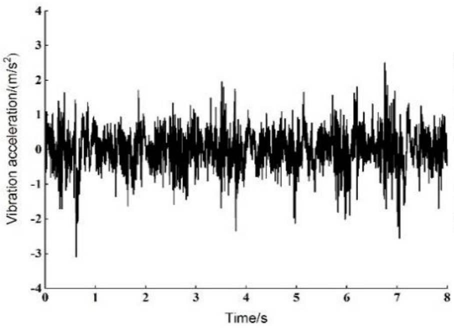
According to the orthogonal test, the main factor affecting the vibration characteristics of the transplanter is the forward speed. To determine the vibration characteristics of the transplanter, a comparative test was conducted at different speeds on the transplanter. The test allowed for time-frequency domain analysis and power spectral density analysis of the measured vibration signals. Figure 5 shows that in the range of 0.8~2.4 km/h, the forward velocity and the vibration acceleration increase.



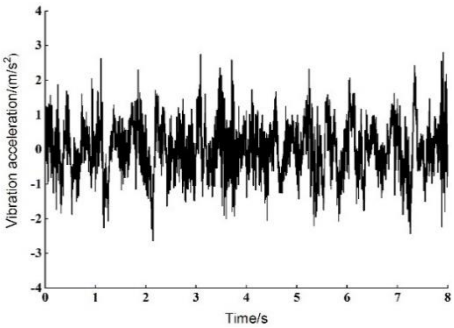
a) v=0.8 **km/h**



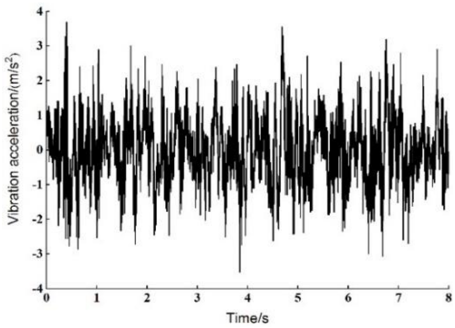
b) v=1.2 **km/h**



c) v=1.6 **km/h**



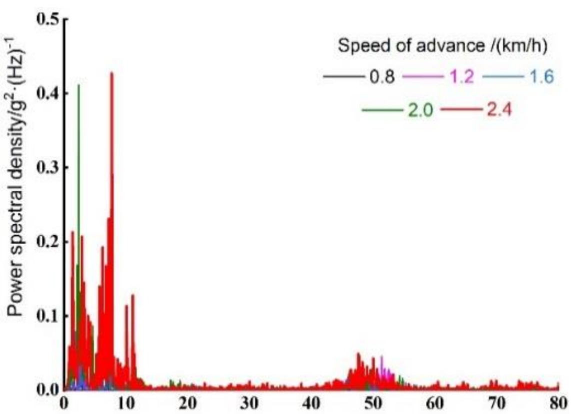
d) v=2.0 **km/h**



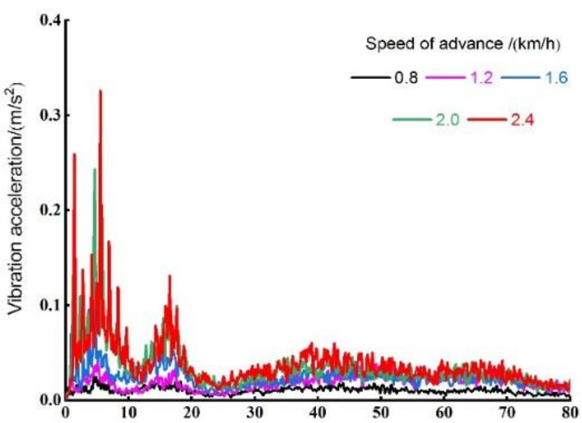
e) v=2.4 **km/h**

Fig. 5 - Vibration time domain diagram at different speeds

The power spectrum represents the energy component of the vibration signal in the specific frequency band. The power spectrum density curve in Figure 6(a) shows that the main frequency components of the vertical vibration energy for the transplanter concentrate in a low-frequency range of 0~10 Hz, there is also high vibration energy near the 50 Hz frequency band. At the same time, the greater the forward speed of the transplanter, the more intense the vibration. It does not affect the frequency distribution of vibration energy.



a) Power spectral density



b) Frequency spectrum

Fig. 6 - Vibration frequency analysis of cup transplanter

The vibration characteristics at different speeds can be extracted from the spectrogram of Figure 6(b), as shown in Table 5. When the forward speed is in the range of 0.8~2.4 km/h, the central frequency of vibration is distributed between 4.5~5.5 Hz. As the forward speed increases. The acceleration range corresponding to the primary frequency of oscillation is 0.03~0.33 m/s^2.

Table 5

Vibration characteristics corresponding to different velocity levels

Forward speed	Vibration frequency	Vibration acceleration
[km/h]	[Hz]	[m/s^2]
0.8	4.5	0.03
1.2	5.0	0.04
1.6	4.6	0.12
2.0	4.6	0.24
2.4	5.5	0.33

CONCLUSIONS

1) The mathematical model for transplanting machine-soil vibration under complex excitation is established and obtains the steady-state response of the transplanter. According to the vibration equation and the derivation process of the steady-state response, the forward speed of the transplanter determines the vibration characteristics, the external excitation, the soil surface condition, the machine structure characteristics, and other factors.

2) The vibration test shows that the vertical vibration of the transplanter is the strongest. According to the RMS value for vibration acceleration under different working conditions, the main factors influencing vertical vibration are the forward speed of the transplanter, surface solidity, and planting depth.

3) When the forward speed changes in the range of 0.8~2.4 km/h, the forward speed of the transplanter increases. The vertical vibration acceleration also increases, according to the analysis for the power spectral density curve and the spectrum curve. The main frequency components of sheer vibration energy during transplanting operation are between 0 and 10 Hz. The central frequency of transplanting vibration is in the range of 4.5~5.5 Hz, and the acceleration range corresponding to the primary frequency of oscillation is 0.03~0.33 m/s^2.

ACKNOWLEDGEMENTS

This project was funded by the National Natural Science Foundation of China (32160423) and the Natural Science Foundation of the Inner Mongolia Autonomous Region of China (2019MS05031 and 2020MS05055).

REFERENCES

[1] Geng Lingxin, Li Kang, Pang Jing, et al. (2021). Test and analysis of vibration characteristics of transplanting machine based on time frequency and power spectral density (基于时频和功率谱密度的移栽机振动特性测试与分析), *Transactions of the Chinese Society of Agricultural Engineering*, 37(11), 23-30. https://doi.org/10.11975/j.issn.1002-6819.2021.11.003

[2] Hu Fei, Guo Dong, Chen Cairong, et al. (2021). Design and experiment on compound crank Rocker double-row planting device of vegetable plug seedling up-film transplanter (复合曲柄摇杆式蔬菜膜上双行栽植装置设计与试验). *Transactions of the Chinese Society for Agricultural Machinery*, 1-11. http://kns.cnki.net/kcms/detail/11.1964.S.20210712.1439.027

[3] Hildebrand R., Keskinen E., Romero J.N. (2008) Vehicle vibrating on a soft compacting soil half-space: Ground vibrations, terrain damage, and vehicle vibrations. *Journal of Terramechanics*, 45, 121-136. https://doi.org/10.1016/j.jterra.2008.09.003

[4] Jin Seok Jo, Frank Gyan Okyere, et al. (2018). A study on improving the performance of the planting device of a vegetable transplanter, *Journal of Biosystems Engineering*, 43(3), 202-210. https:/i.org/10.5307/JBE.2018.43.3.202

[5] Kumara G.V.P., Raheman H. (2011). Development of a walk-behind type hand tractor powered vegetable transplanter for paper pot seedlings, *Biosystems Engineering*, 110(2), 189-197. https://doi.org/10.1016/j.biosystemseng.2011.08.001

[6] Liu Yang, Mao Hanping, Wang Tao, et al. (2018). Collision optimization and experiment of tomato plug seedling in basket-type transplanting mechanism (吊杯式移栽机构中番茄穴盘苗运动分析优化与试验). *Transactions of the Chinese Society for Agricultural Machinery*, 49(5), 143-151. https://doi.org/10.6041/j.issn.1000-1298.2018.05.016

[7] Liu Yang, Wang Shiguo, Mao Hanping, et al. (2019). Trajectory optimization and test of basket-type planting devices (*吊杯式栽植器运动轨迹优化与试验*). *Agricultural Research in the Arid Areas*, vol. 37(3), 291-298. https://doi.org/10.7606/j.issn.1000-7601.2019.03.38

[8] Liu Xuening, Li Xuying, Zhang Yongzhi. (2019). The design and experimental research of measuring device about 3D surface topography of tillage soils (耕作土壤地表三维形貌测量装置设计与试验研究). *Journal of Agricultural Mechanization Research*, 41(7), 85-89. https://doi.org/10.3969/j.issn.1003-188X.2019.07.016

[9] Liu Yueqin, Liu Fei, Zhao Manquan, et al. (2016), Analysis of vibration test and vibration theory of air-suction no-tillage planter (气吸式免耕播种机的振动测试与振动理论分析), *Journal of China Agricultural university*, 21(10), 109-116. https://doi.org/10.11841/j.issn.1007-4333.2016.10.14

[10] Rabbani M A, Tsujimoto T, Mitsuoka M, et al. (2011). Prediction of the vibration characteristics of half-track tractor considering a three-dimensional dynamic model, *Biosystems Engineering*, 110(2):178-188. https://doi.org/10.1016/j.biosystemseng.2011.07.013.

[11] Wang Yongwei, Tang Yanhai, Wang Jun, et al. (2016). Parameters optimization for the dibble-type planting apparatus of vegetable pot seedling transplanter in high-speed condition (蔬菜钵苗高速移栽机吊杯式栽植器参数优化). *Transactions of the Chinese Society for Agricultural Machinery*, 47(1), 91-100. https://doi.org/10.6041/j.issn.1000-1298.2016.01.013

[12] Wout W, John L, Christof D., et al. (2014). Dealing with periodical loads and harmonics in operational modal analysis using time-varying transmissibility functions, *Mechanical Systems and Signal Processing*, 49(1/2), 154-164. https://doi.org/10.1016/j.ymssp.2014.04.008

[13] Wang Qi, Zhu Longtu, Li Mingwei, et al. (2019). Vibration characteristics of corn no-tillage finger-type precision planter and its effect on seeding performance (指夹式玉米免耕精密播种机振动特性及对排种性能的影响). *Transactions of the Chinese Society of Agricultural Engineering*, 35(9), 9-18. https://doi.org/10.11975/j.issn.1002-6819.2019.09.002

[14] Wang Li, Li Shuo, Lv Dianji, et al. (2021). Multi-sensor signal acquisition and data processing analysis of combine harvester. *INMATEH Agricultural Engineering*, 63(2), 335-344. https://doi.org/10.35633/inmateh-63-34

[15] Xu Gaowei, Qiu Xuyun, Zhu Mengxia et al. (2021). Research progress and analysis of transplanting machinery on film (膜上移栽机械研究进展及与分析) *Agricultural equipment and vehicle engineering*, 59(02): 23-26+30. https://doi.org/10.3969/j.issn.1673-3142.2021.02.006

[16] Zhao Xiong, Cui Haiyang, Dai Li, et al. (2017). Kinematic Analysis and Experimental Research on the Seedling Pick-Up Mechanism of a Second-Order Free Noncircular Planetary Gear System, *Applied Engineering in Agriculture*, 33(2): 169-179. https://doi.org/10.13031/aea.11852

[17] Zhang Xiaodong, Li Chenghua, Li Jianqiao, et al. (2014). Mathematic Vibration Model of Spade Punch Planter of Maize (*铲式玉米精密播种机振动特性模型建立与试验*). *Transactions of the Chinese Society for Agricultural Machinery*, 45(2), 88-93. https://doi.org/10.6041/j.issn.1000-1298.2014.02.015.

[18] Zhang Shuo, Chen Qingyu, Liu Jinyi, et al. (2021). Research on design and experiment of multifunctional vegetable field machine. *INMATEH Agricultural Engineering*, 63(2), 434-442. https://doi.org/10.35633/inmateh-63-44