TEST AND ANALYSIS OF VIBRATION CHARACTERISTICS OF VIBRATION SUBSOILER
/
深松机振动特性试验与分析

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ABSTRACT

In this paper, the vibration characteristics of the 1ST-460 vibration subsoiler was analyzed. In order to solve the problem of vibration imbalance caused by the vibration component under the action of multiple groups of vibration shovels, the optimal combination mode of the vibration component under the interaction of multiple groups of shovels was obtained. Piezoelectric accelerometers are fixed symmetrically on the frame of the subsoiler to measure the vibration at different positions. TST5910 dynamic signal test and analysis system is used to collect and process the acceleration data. Non-load tests were carried out with different initial eccentric phase angle combination. Results showed that the combination of [0°, 180°, 180°, 0°] (symmetrically up and down staggered vibration) for the eccentric vibration component of four shovels is the optimal initial phase combination, which can lead to the minimum adverse vibration on the frame. Further tests were conducted under different vibrating frequency and amplitude/eccentric with optimal phase combination. The results showed that, when amplitude/eccentricity ratio was 2.0 and 2.5, frequency of vibration was 6.7 and 8.3 Hz, the required traction force of the subsoiler was stable and significantly reduced, which can reduce the harmful vibration on the tractor.

摘要

为研究1ST-460型振动深松机振动特性，解决在多组振动铲作用下因激振装置的惯性载荷引起的振动不平衡问题，获取多组铲交互作用下激振装置的优化组合方式。采用TST5910动态信号测试分析系统对1ST-460型振动深松机机架的振动响应特性进行了试验与分析。研究了在不同相位角组合下机架振动位移变化规律和牵引力特性，得到最优起始相位角组合为[0°,180°,180°,0°]；在最优相位角组合下，研究了振动深松机在不同振幅/偏心距比和不同振动频率下的振动特性和牵引力特性，结果表明，当振幅/偏心距比为2.0～2.5，振动频率为6.7～8.3 Hz时，深松机减阻效果显著且振动影响较小。

INTRODUCTION

Vibrating subsoiling has an advantage of decreasing tillage resistance, but if the vibration of the vibration subsoiler transfers to the tractor, it will cause harmful effect to both the tractor and driver, restricting the popularization of vibration subsoiler (*Yuan et al., 2020; Sun et al., 2018; Qiu & Li, 2000; Cui et al., 2016; Wang et al., 2018; Zhao et al., 2017; Liu et al., 2017*). With the agricultural equipment's modernization and the requirement of agricultural equipment's comfort and the continuously increasing reliability from custom, the study of vibrating deep loosen comfort and reliability, especially the effective way to reduce the bad effect caused by vibration, which is based on the foundation of decreasing the vibrating subsoiling resistance, has practical significance (*Yang et al., 2017*).

Researchers have done quite as much research on the aspects of vibrating drag reduction and vibration characteristics (*Nagasaki et al., 1996; Liu et al., 2017; Sakai et al., 2010*).

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Radite et al., (2016), studied the application of vibration in reducing the drag of subsoiling, meanwhile, they compared and analyzed the vibration characteristics of different types of subsoiling shovels when doing an operation.

Wang et al., (2020), studied electric–hydraulic control technology to improve the adaptability of the vibrating subsoiler to various soil conditions by adjusting the working pressure of the excitation element. *Hilal et al., (2021),* studied deep loader vibrating and non-vibrating wings and two penetration angles (45°and 55°) in soil at speeds of 2.88, 3.6 and 4.5 km/h. The results showed that the wing vibration had a positive dominance in the Slip, Critical Depth and Depth Stability Ratio, while a negative increase was achieved in the vibration of the driver's seat of agricultural tractors (VDS).

Based on the relevant research results, the vibration characteristics of 1ST-460 vibration subsoiler were studied by using TST5910 dynamic signal test and analysis system. Pre-experiments were carried out on vibration subsoiler with different phase angle combinations, and the initial eccentric phase angle combinations under smaller vibration were obtained. These combinations were tested in soil grooves with different initial phase angles, and the vibration characteristics under different eccentric phase angle combinations were analyzed. Taking the main vibration displacement characteristics and traction characteristics as the optimization indexes, the optimal phase angle combination under the minimum vibration was obtained. Under the optimal phase angle combination, the amplitude/eccentricity ratio and vibration frequency were changed respectively, and the optimal parameter combination was obtained by taking the vibration displacement and traction characteristics as the indexes, so that the optimal combination mode of the vibration components under the interaction of multiple groups of shovels was obtained. In a word, scholars have not studied the vibration characteristics of this kind of combined frame subsoiler, so this paper carried out analysis on the relevant vibration characteristics from this kind of vibration subsoiler with unique structure, as well as the related innovation in the vibration measurement method and treatment, which has certain research value.

MATERIALS AND METHODS

Structure

The structure of model 1ST-460 vibrating subsoiler is shown in Fig. 1. It is mainly composed of gear box, hanger, coupling, vibration components, frame and soil loosening components. The frame connected by the profile is connected by welding, such as the hanger 2 and the frame 5, and the other parts are connected with the frame by anti-loosening bolts and nuts with washers.

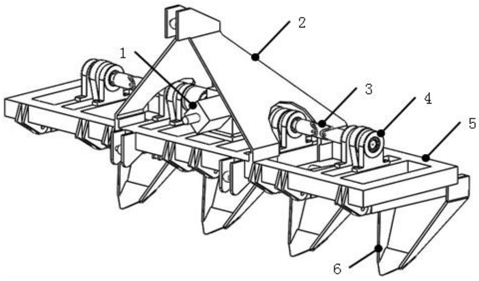


Fig. 1 - 1ST-460 vibration subsoiler

1– Gear box; 2– Hanger; 3– Coupling; 4–Vibration components; 5– Frame; 6–Soil loosening components

Working principle

The machine adopts the active vibration operation mode, the vibration components adopt the eccentric connecting rod excitation device, and the power is transmitted by the rear power output shaft of the tractor, which is connected with the power input shaft of the gear box through the universal joint and the power input shaft of the gear box, and the power is changed by the bevel gear of the reversing box. It is transversely transmitted to the groups II and III of vibration components on both sides, and the connection here is made by a flexible coupling, which allows a certain deviation in the centerline of the two axes. It has the ability to compensate the relative offset of the two axes. Because the working parts of groups I and IV are far apart, the universal coupling is used in the middle transmission part, which allows the two axes to have a large angular offset. The transmission design reduces the positioning accuracy requirements for four groups of vibration components in the installation process, and can achieve simple and reliable transmission, as shown in Fig. 2. The soil loosening components is a frame-type deep-loose shovel, which can reduce the resistance and improve the quality of deep-loose work.

The method to regulate the phase angle

The balance performance and traction resistance of subsoiler will be affected by a different phase angle combination of four groups of vibration shovel. The phase angle is adjusted by universal coupling. The way power is transferred through vibration shovel is shown in Fig. 2. I, II, III and IV, are the four groups of subsoiler shovels respectively. The gear box's output shaft is close to the adjacent vibration component, so it is connected by a double row roller chain coupling (flexible coupling), and between the vibration device and the vibration device is connected by a universal coupling.

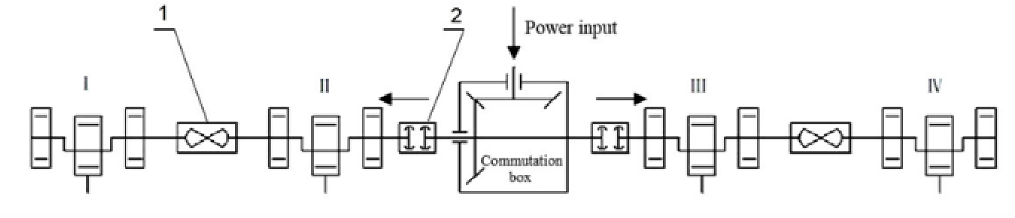


Fig. 2 - Combination configuration of shovels
1– Universal coupling; 2– Hanger Double row roller chain coupling

When adjusting the phase angle between the four groups of vibration components, it is not necessary to disassemble and assemble the shaft and the bearing housing components, the only thing that needs to be done is loosening the locked screw of the universal coupling, disassemble and assemble the universal coupling on the short shaft side. In this way, the relative phase angle between adjacent eccentric vibration components can be adjusted efficiently, the adjustment process is shown in Fig. 3.

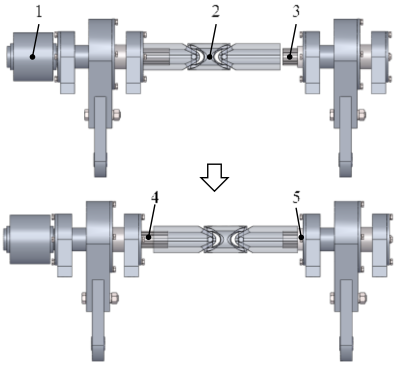


Fig. 3 - Schematic diagram of long and short shaft adjustment method
1- Double row roller chain coupling; 2– Universal coupling; 3– Short shaft;
4– Long shaft; 5– Space

When adjusting the initial phase angle, it is realized by changing the relative rotation teeth of the two sprockets of the roller chain coupling. For every relative rotation of two teeth, the corresponding initial phase angle changes 45°, that is, the first-order initial phase angle is adjusted. The double row roller chain coupling is of KC-4016 type, as shown in Fig. 4, and the starting phase angle of the eccentric sleeve can be adjusted by eight levels with 16 links.

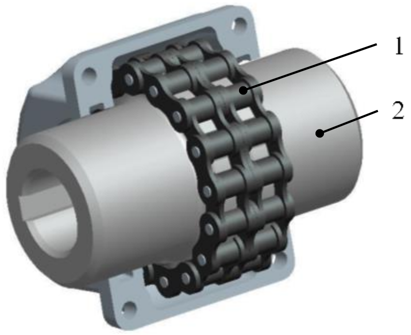


Fig. 4 - Double row roller chain coupling
1– Double row roller chain; 2–Sprocket

The vibration test facility is shown in Fig. 5 (*Wang et al., 2021; Su et al., 2022*). The carrier is used for placing the TST5910 dynamic signal tester and the computer. The traveling wheel of the carrier is a universal wheel, which is connected to the soil bin tester. During the test, the carrier can run both forwardly and backwardly, and one end of the IEPE signal line is connected to the dynamic signal tester, and the other end is connected to the accelerometer.

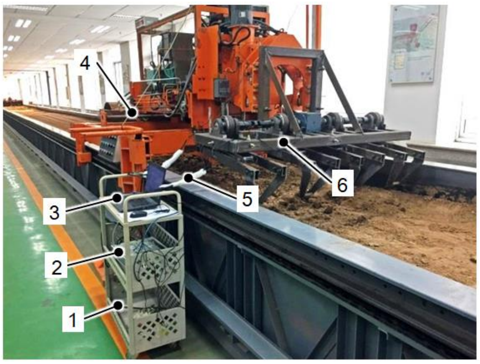


Fig. 5 - Test facility

1– Carrier; 2– Dynamic signal tester; 3– Computer; 4– Soil bin tester; 5– Signal line; 6– Vibration subsoiler

The acceleration curve of each position of the vibrating bulldozer frame was tested by using the TST5910 dynamic signal test and analysis system. The acceleration test adopts the voltage source piezoelectric accelerometer. The vibrating bulldozer is connected behind the soil bin trolley, and the vibrating bulldozer is symmetrical on both sides, so the sensor is only arranged on the left side and the middle position of the bulldozer, which is located in the position of the symmetrical cross section of the loosening parts, where the vibration is caused by the vibration of the loosening parts. In addition, a sensor is placed at the connection between the frame and the parts to measure the vibration of the connecting position, and the sensor is also placed on the force measuring frame. It is used to measure the vibration transmitted to the soil bin trolley. The position of the sensor measuring point is arranged as shown in Fig. 6.

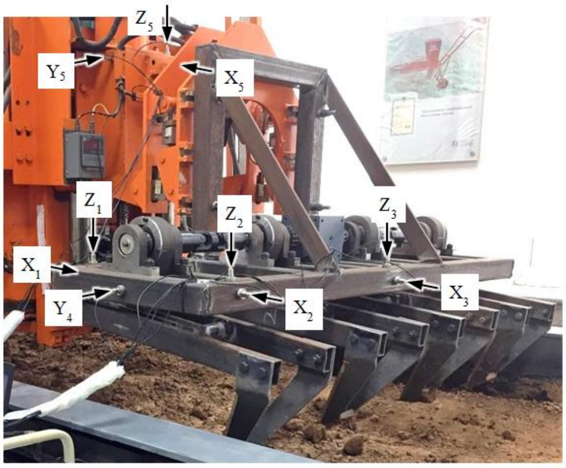


Fig. 6 - Placements of sensors

Test preparation

In the soil bin laboratory of China Agricultural University, the soil of the soil bin was pre-treated before the test. Firstly, the sprinkler function of the TCC electric four-drive soil bin test rig was used to evenly sprinkle the soil needed for the test. The watering operation was repeated three times, after the soil was soaked, and rest for three days. The soil moisture content was checked to ensure that the soil moisture content is wet, and ensure that the soil moisture content is about 18%. The soil was rotated by the 1GQN-125 rotary tiller, and the surface soil was loosened and beaten evenly. The soil after rotary tillage was compacted for three times by using the pressing roller to maintain the rated forward speed. Before the experiment, the soil in the soil bin was sprinkled, rotary ploughed, scraped and compacted, and the soil layers at different depths were sampled and preserved reasonably with a ring knife aluminum box. The soil moisture content and soil bulk density at different depths were measured by drying method, and the soil firmness was measured by SC900 digital soil compactness meter made by SPECTRUM Company of the United States. The five-point sampling method is used to measure the soil in the soil bin and take the mean value, the measured data are shown in Table 1.

Table 1

Soil condition

Soil depth [mm]	Moisture content [%]	Soil hardness [kPa]	Soil bulk density [g/cm^3]
100	19.4	468.8	1.56
200	18.5	682.8	1.54
350	18.2	1317.6	1.49
Average	18.7	823.1	1.53

The time-domain plot of vibration acceleration. Frequency range chart of vibration acceleration of each measuring point was obtained using the piezoelectric accelerometer, as shown in Figs. 7-8. It can be seen that the acceleration changes violently, there are many clutters, and the change law is not obvious, so it is processed by secondary integration in the dynamic signal test and analysis software system, and the displacement signal was obtained. Effective signal was intercepted and the average value was processed. Stable vibration displacement signal was obtained as shown in Fig. 9. Frequency spectrum was analyzed using TST5910 dynamic signal testing system. Final frequency domain signal of vibration displacement was obtained as shown in Fig. 10. Magnitude of the main vibration amplitude is statistically obtained, which is a relative quantity, not the actual magnitude of vibration displacement, however, it can be used as an indicator to analyze the signal of each test point. The de-averaging of the time domain signals can avoid the peak of the spectrum line at the Frequency 0.

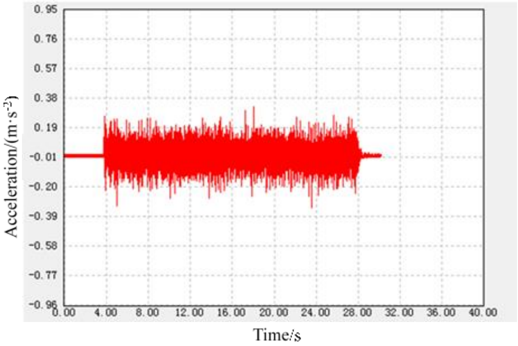


Fig. 7 - Time-domain plot of vibration acceleration

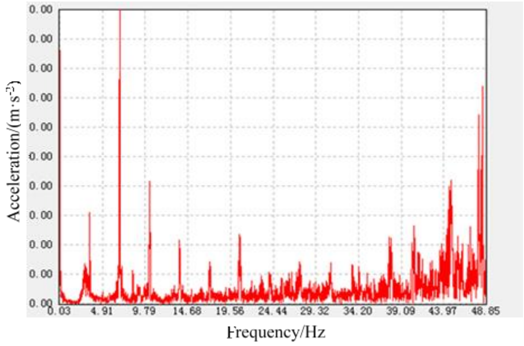


Fig. 8 - Frequency ranges chart of vibration

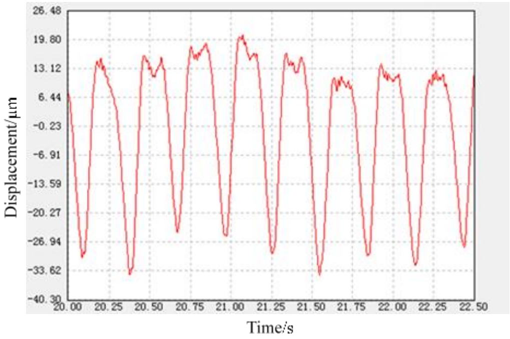
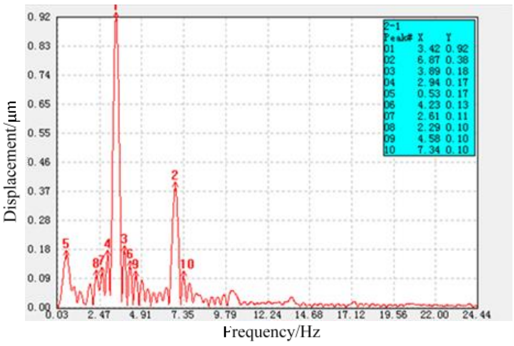


Fig. 9 - Time-domain plot of vibration acceleration



2-1

Peak#	X	Y
01	3.42	0.92
02	6.67	0.38
03	3.89	0.18
04	2.94	0.17
05	0.53	0.17
06	4.23	0.13
07	2.61	0.11
08	2.29	0.10
09	4.58	0.10
10	7.34	0.10

Fig. 10 - Frequency ranges chart of vibration

RESULTS

Different initial phase angle test

The initial phase angle of the fixed loosening shovel I was 0 °, and the other three shovels select the groups with less vibration according to the vibration acceleration reflected by the pre-experiment. Because the combination of different initial phase angles of the four groups of soil loosening components will affect the vibration characteristics of the frame, the soil bin tests with different initial phase angle combinations were carried out to find out the combination of the initial phase angle that caused the minimum vibration of the frame. The experimental phase angle combination is shown in Table 2.

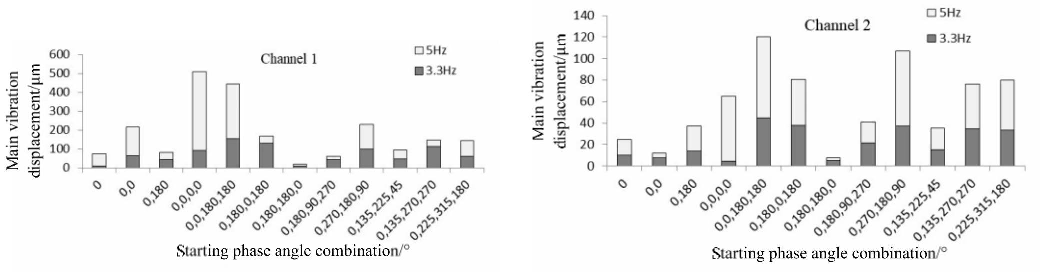
Table 2

Phase angle combination

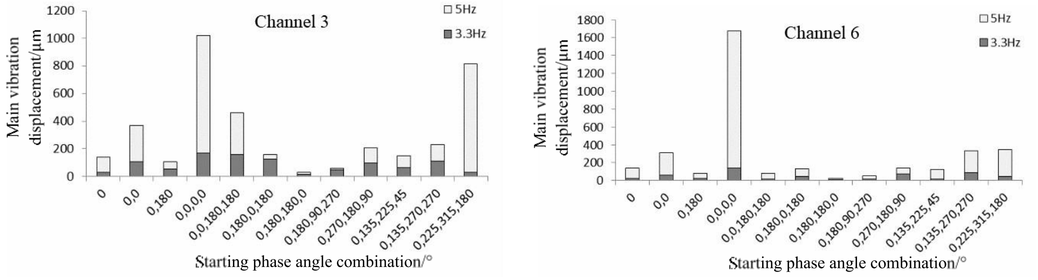
Number	Phase angle (°)			
	Break shovel Ⅰ	Break shovel Ⅱ	Break shovel Ⅲ	Break shovel Ⅳ
1	0	180	0	180
2	0	180	180	0
3	0	225	315	180
4	0	135	270	270
5	0	180	90	270
6	0	135	225	45
7	0	270	180	90
8	0	0	180	180
9	0	0	0	0
10	\	0	\	\
11	\	0	0	\
12	\	0	180	\

Vibration displacement characteristics

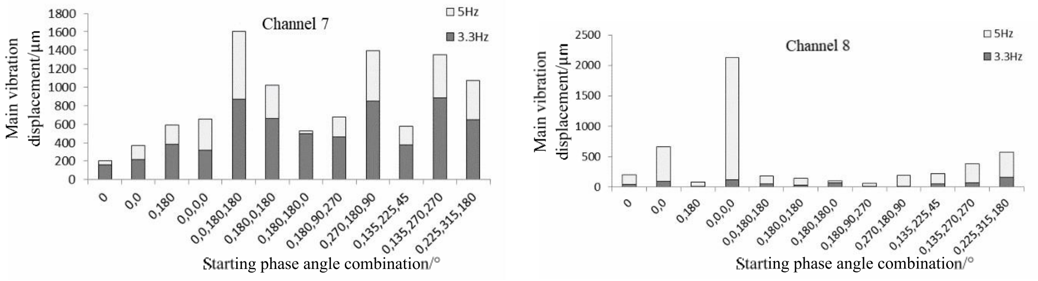
Before the soil loosening test, a no-load test was carried out by setting the traveling speed of the trolley to 0 with the soil shovel away from the soil. By analyzing the vibration data, it is found that the vibration Channel 4 (forward X_2 on the left side of the rear beam) and 5 (vertical Z_3 in the middle of the rear beam) were distorted due to vibration overload, which is not comparable. Fig. 11 shows the vibration data statistics (TST5910 spectrum analysis-real-time spectral peak) of Channel 1 (vertical Z_1 on the left side of the front beam), 2 (forward X_1 on the left side of the front beam), 3 (vertical Z_2 on the left side of the rear beam), 6 (forward Z_3 in the middle of the rear beam), 7 (Y_4 the lateral of the side beam), 8 (vertical Z_5 on the suspension bracket beam), 9 (forward Z_5 on the left side of the suspension bracket beam) and 10 (Y_5 on the side of the suspension bracket beam).



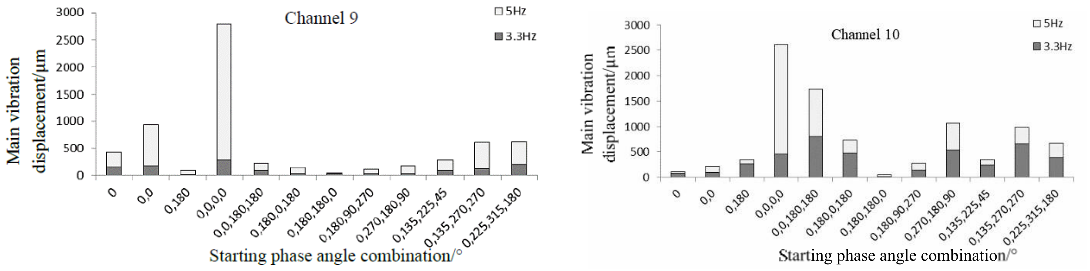
a. Channel 1 b. Channel 2



c. Channel 3 d. Channel 6



e. Channel 7 f. Channel 8



g. Channel 9 **h. Channel 10**

Fig. 11 - Vibration displacement at different positions

As shown in Fig. 11, the vibration displacement in the vertical direction of the rack is larger and the vibration displacement in the positions of channels 1 and 3 (left side of the front beam and left side of the rear beam) is the smallest when the initial phase angle combination is [0°, 180°, 180°, 0°] (symmetrical up and down staggered vibration), otherwise, the vibration displacements of channels 2 and 10 (the left forward direction of the front beam and the side of the suspension bracket frame) are also significantly minimum under that combined condition. In the forward direction, the vibration displacement of Channel 6 and 9 (middle of rear beam, suspension bracket) is smaller under the condition of the combination of initial phase angle [0°, 180°, 180°, 0°] (symmetrical up-down staggered vibration) and [0°, 180°, 90°, 270°] (uniform staggered vibration), otherwise, the vibration displacement of Channel (vertical suspension) is also quite small.

In theory, the lateral vibration displacement should be quite small, but due to the machining error, fit clearance and material deformation, the lateral displacement of staggered vibration is quite large, even larger than the unbalanced initial phase angle combination [0°, 0°, 0°, 0°] condition, as shown in Fig. 11 in Channel 7 (side beam).

Comparing the main vibration displacement of each channel of the four groups of shovel-vibration subsoiler we can see that the vibration displacement of each measuring point is quite small when the initial phase angle is [0°, 180°, 180°, 0°] (symmetrical up-down alternating vibration) and [0°, 180°, 90°, 270°] (uniform alternating vibration). Furthermore, when the initial phase angle combination is [0°, 180°, 180°, 0°], the vertical vibration displacement of the frame is smaller.

Traction characteristics

For the two vibration ways of vibration subsoiler, with the name of symmetrical up-and-down alternating vibration [0°, 180°, 180°, 0°] and uniform alternating vibration [0°, 180°, 90°, 270°] tested in the soil bin to loosen the soil, whose traction force tested in experiments is shown in Fig. 12 from which we can see the percentile values of traction force and the meaning value of symmetrical up-and-down alternating vibration are lower than those of uniform alternating vibration, which shows that the symmetrical up-and-down alternating vibration is more stable and the effect of reducing drag is better.

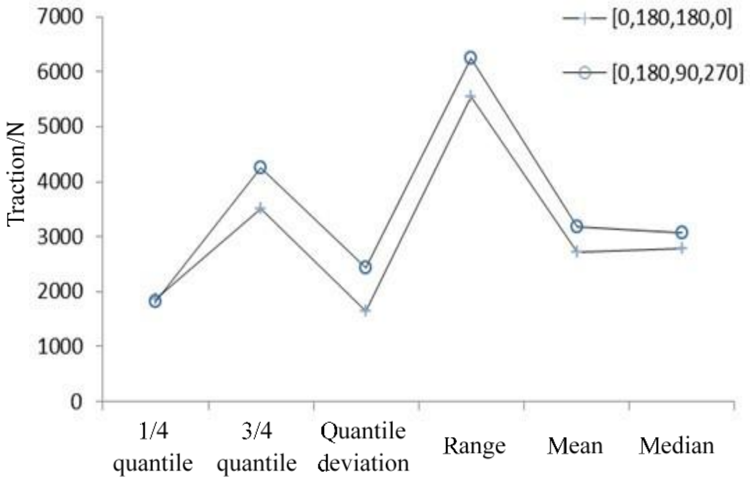


Fig. 12 - Effect of initial phase angle combination of traction

The influence caused by different amplitude/eccentricity ratio on vibration displacement

Method to adjust amplitude/eccentricity ratio

The adjustment of the connecting rod hitch location is shown in Fig. 13.

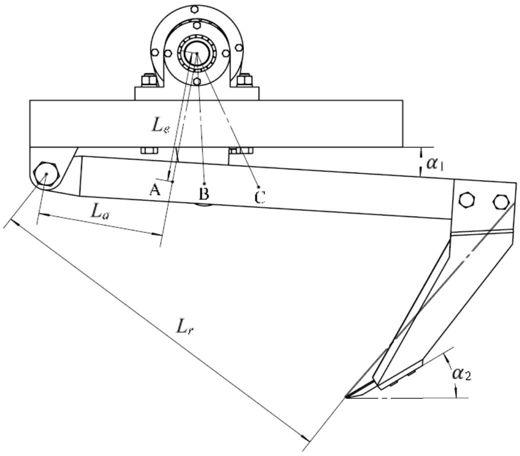


Fig. 13 - Adjustment of connecting rod hitch location

The law of the vibration radius L_r of the shovel tip, the force arm of the connecting rod La and the eccentricity e of the eccentric shaft in exciting parts and amplitude a can be summarized as Equation (1):

$$\frac{L_r}{L_a} = \frac{a}{e} \tag{1}$$

Where, L_r is vibration radius of shovel tip, mm; L_a is the force arm of the connecting rod, mm; a is amplitude, mm; e is eccentricity, mm.

Changing the hitch location between the connecting rod and pull rod (A, B, C in Fig. 14) can change the length of connecting rod arm L_a, and then cause the change of the amplitude. Because the vibration radius Lr of shovel tip is constant, the essence of adjusting connecting rod connection position is changing the length of connecting rod arm La, then cause the change of the amplitude/eccentricity ratio (*a/e*).

The penetration angle is an important parameter of the loosening operation. If we change it, the resistance of the vibrating soil loosening will be affected, causing the inconsistency of the test. In order to keep the penetration angle into soil unchanged, the length of the connecting rod should be adjusted while changing the position of the connecting rod. Therefore, the connecting rod designed in this paper includes the upper end and the lower end, and connects with different hole positions at the upper end or at the lower end of the connecting rod to get the different connecting rod length.

Vibration displacement characteristics

Under the condition of the different connection position, the amplitude/eccentricity ratio of vibration subsoiler is different. The vibration displacement amplitudes of each channel under the conditions of each connecting hole in the test were measured as shown in Fig. 14.

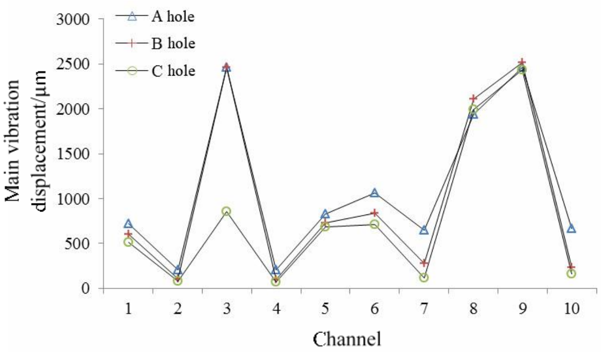


Fig. 14 - Effect of joint position on vibration displacement

For most channels, when connecting rod with B and C holes (amplitude/eccentricity ratio 2.5 and 2.0), the vibration displacement values are similar, and less than hole A (amplitude/eccentricity ratio 3.0), especially for the data of channels 2, 4, 5, and 10. In the vertical direction (Channel 3) of the rear beam, when the connecting rod is located in the C hole, the corresponding vibration displacement is obviously reduced, while the vibration influence is quite small. So, when the amplitude/eccentricity ratio is 2.0 and 2.5, the required traction force of the subsoiler was stable.

Traction characteristics

As shown in Fig. 15, we can see that when the connecting rod is connected with holes B and C, and there is a small difference in the average traction force. When the connecting rod is connected to the hole A of the pull rod, both the amplitude/eccentricity ratio and the amplitude are the largest, but the connecting rod force arm L_a is the smallest, increasing the force of the connecting rod. When the shovels are working with large amplitude, the shovels advance and retreat greatly, which makes the traction change violently and the operation unstable. It can be seen from Fig. 15, that it is manifested as a sharp increase in the traction difference and range. While doing an operation, to connect the B Hole, C hole, using connecting rod, the traction force change is smaller and the meaning operation is more stable.

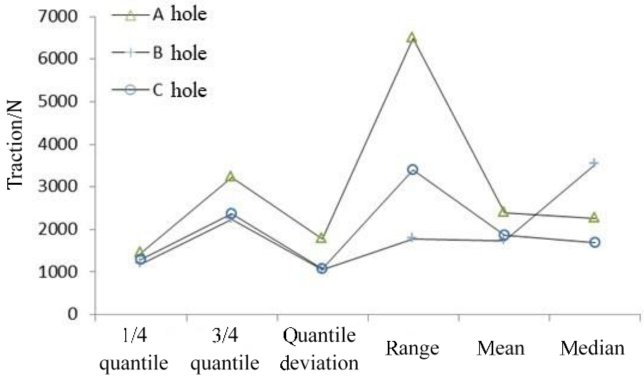


Fig. 15 - Effect of joint position on traction

Influence of different vibration frequency of vibration

Vibration displacement characteristics

The experiment of the combination of initial phase angle [0°, 180°, 180°, 0°] with different rotational speed (vibration frequency) was carried out, when the connecting rod is connected to the C holes. Taking the high frequency vibration into account, some of the measured channel data of the rack would distort, the Vertical Direction Z_5 (Channel 8), the forward direction X_5 (Channel 9) and the lateral direction Y_5 (Channel 10) of trolley suspension frame were measured and analyzed. As shown in Fig. 16, the vibration displacement of each channel is small, the increase of vibration frequency has little effect on the vibration displacement of the frame and trolley suspension, but when the vibration frequency reaches 9.2 Hz, the vibration noise of the structure is great. Therefore, the self-balance effect of symmetrical up-and-down alternating vibration is significant, and the negative effect of its vibration transmission is mainly shown on the great noise caused by the increase of vibration frequency, but the vibration displacement is quite small.

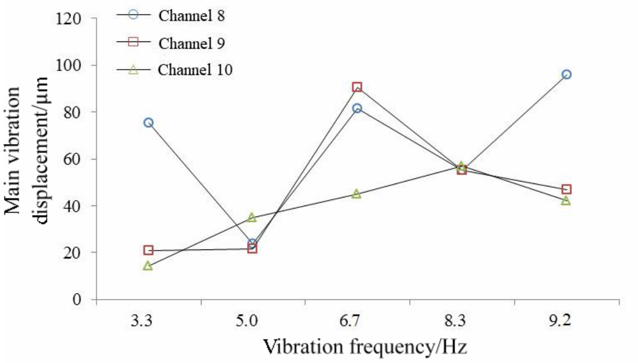


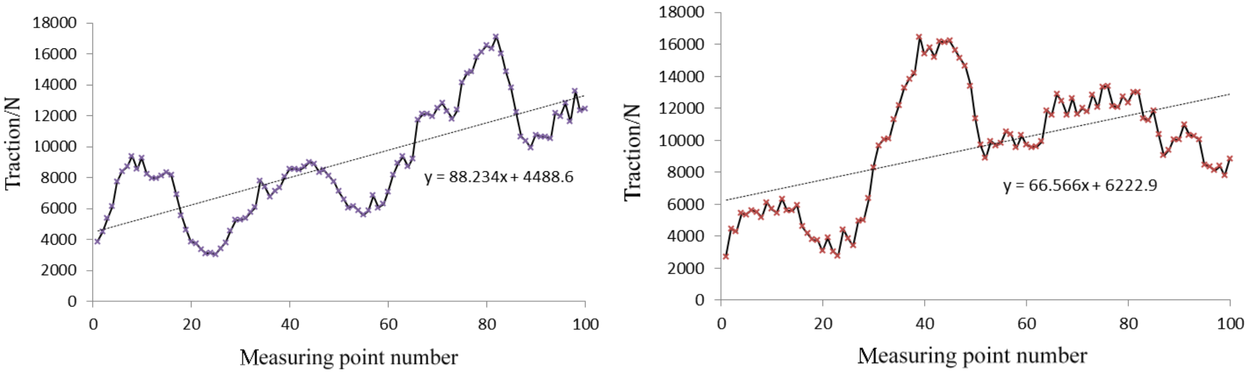
Fig. 16 - Effect of vibratory frequency of vibration displacement

Traction characteristics

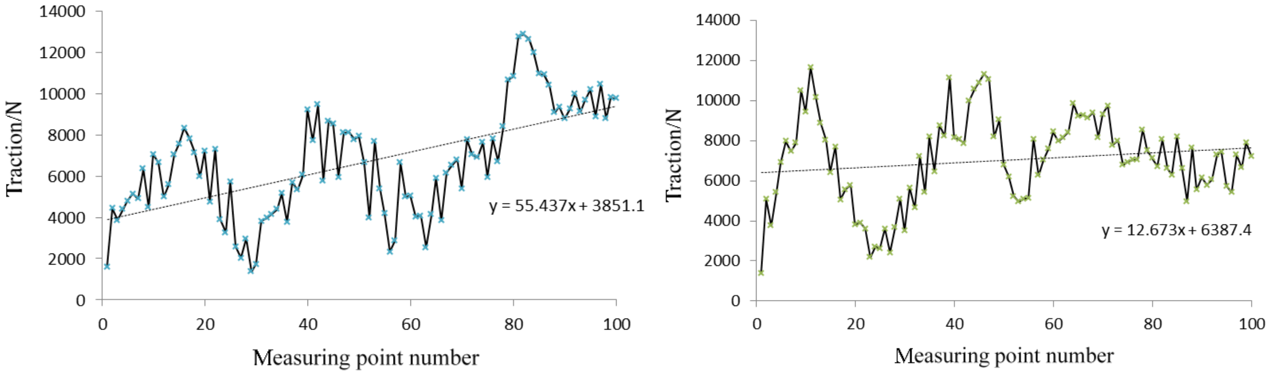
Soil loosening tests under non-vibration conditions show that subsoiler is easy to cause soil hilling, as shown in Fig. 17, which will lead to increased tillage resistance.

Fig. 17 - Non-vibrational soil loosening

Deep vibration loosening can reduce the soil hilling phenomenon. With the increase of vibration frequency, the soil hilling phenomenon was gradually weakened and the trend line slope of tillage resistance decreased. When the frequency of the shovels was 0, 5.0, 6.7 and 8.3 Hz, the slope of the traction trend line was 88.234, 66.566, 55.437 and 12.673 respectively, as shown in Fig. 18. It can be concluded that, with the increase of vibration frequency, the traction variance of a subsoiler became smaller and smaller, while the permeability of loose soil increased gradually.



a. *f*=0 Hz **b. *f*=5.0 Hz**



c. *f*=6.7 Hz **d. *f*=8.3 Hz**

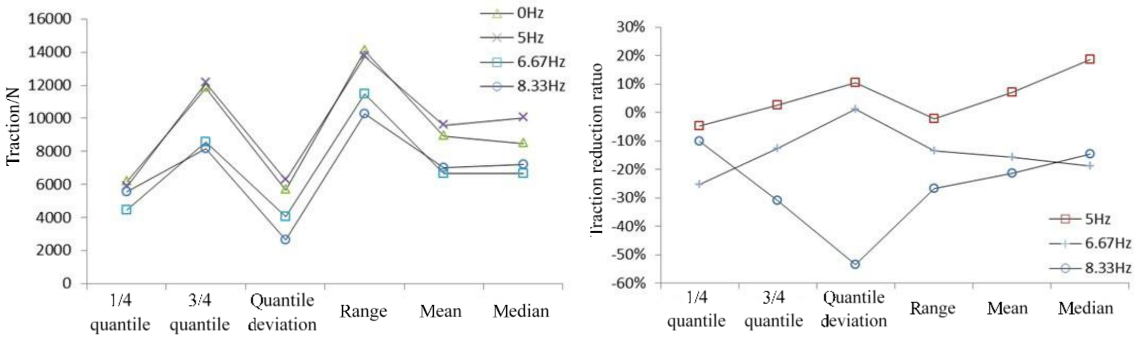
Fig. 18 - Variation tendency of traction

As shown in Fig. 19 and Table 3, the traction force of the subsoiler under different frequencies show that the mean value of the traction force decreased significantly as the vibration frequency increased. When the vibration frequency was 6.7 and 8.3 Hz, compared with the traction with non-vibration condition, the average traction force was decreased by 26% and 21% respectively. In addition, when the frequency of vibration loosening was 5.0, 6.7 and 8.3 Hz, the 1/4 percentile values of tractive force decreased by 5%, 25% and 10%, respectively and the tractive percentile difference decreased obviously as the vibration frequency increased, it shows that the variance of traction was reduced and the operation was stable. Therefore, vibration loosening soil using high frequency (*f*=6.7 and 8.3 Hz) was significant to get the effect of obvious drag reduction and small traction force variance, which is helpful to break the hard soil and improve the stability of soil loosening.

Table 3

Traction characteristic value statistics

Frequency	1/4 quantile	3/4 quantile	Quantile deviation	Range	Mean	Median
[Hz]	[N]	[N]	[N]	[N]	[N]	[N]
0	6143	11835	5268	13852	8735	8134
5	5835	12531	6116	13594	9463	9874
6.67	4594	8321	4137	11634	6429	6649
8.33	5516	7967	2863	10028	6897	7135



a. Traction **b. Traction reduction ratio**

Fig. 19- Effect of vibratory frequency on traction

CONCLUSIONS

In this paper, the acceleration signal was obtained by vibration acceleration test, and the vibration displacement characteristics were obtained by signal processing. According to the vibration displacement characteristics and traction characteristics, the initial eccentric phase angle combination, amplitude/eccentricity ratio and vibration frequency were selected in turn. The optimization of various parameters was integrated to reduce vibration. The whole research method can provide corresponding reference for the optimization of vibration agricultural machinery.

(1) Using the TST5910 dynamic signal testing system to get vibration displacement data by testing the vibration characteristics of the vibration subsoiler and collecting the vibration acceleration of the measuring point by the piezoelectric accelerometer with a second date treatment of integration, which has good applicability.

(2) Through the test of vibration characteristics and traction force, it can be concluded that the optimum initial phase angle combination of the four groups of shovel-vibration subsoiler was [0°, 180°, 180°, 0°], which caused the best effect of self-balance of symmetrical up-down alternating vibration. Under the condition of optimum initial phase angle combination, using the high frequency vibration and setting amplitude/eccentricity ratio 2.0 and 2.5 to loosen the soil (*f*=6.7 and 8.3 Hz), the effect of reducing drag is obvious and the influence of vibration is small. The self-balance vibration subsoiler worked stably after optimized, contributing to forming a virtual and real coexisting soil environment after tillage.

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