Vibration test and analysis of mini-tiller

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Abstract: Intense vibration happens at the handle of the mini-tillers that abundantly used in mountainous and hilly areas of southwest China. It is absolutely essential to probe into the vibration characteristics and factors why handle of the tiller vibrates violently. Therefore, the vibration acceleration signals of a mini-tiller's handle and engine cover were tested under the following four conditions: the engine being idle, racing at medium and high speeds, and the tiller working in the field with high engine speed. The signals were processed by means of the time domain eigenvalue analysis and the frequency spectrum analysis. The results showed that when the tiller was under static condition, with increase of the engine speed, the handle vibration decreased in the vertical direction, increased in the fore-and-aft direction and had marginal changes in the left-to-right direction. When the tiller worked at high engine speed, the handle vibrated most violently in the fore-and-aft direction, while the vibrations at the engine cover and handle decreased substantially in each direction, compared with the static conditions. Rotary blades cutting soil increased the damping of the whole machine so as to reduce the vibration at the handle and the engine cover, but the handle vibration was still violent. When the tiller worked, that soil absorbing energies of some frequencies led to the first order unbalanced inertia force of the engine becoming the main reason why handle vibrated intensely.

Keywords: mini-tiller, vibration test, time domain analysis, frequency domain analysis

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1 Introduction

The mini-tiller powered with gasoline or diesel engine of 2.2-6.3 kW and weighed 51-150 kg, can achieve tilling depth of 10-16 cm, width of 55-135 cm and efficiency of 220-540 m^2/h. When it works its roller fulfills three functions at the same time, that is, cultivating, driving and moving. The mini-tiller has the advantages of being light and convenient to field transfer, and therefore has become the main and indispensable agricultural machinery in southwest China[1].

However, its intense handle vibration does harm to the operator's health and reduces productivity. Ragni et al.[2] evaluated the vibration level at the handle for several small rotary tillers based on ISO5349, drawing the conclusion that in 10% of the exposed population, vascular disorders of the hand (Vibration White Finger) will appear after three years of continuous use of these machines, under usual working conditions.

Many researches have been done in order to reduce the vibration of agricultural machinery[3-13] or improve the operator's working conditions[14-21]. For mini-tiller and similar machinery, the handle is the only part which contacts directly with the operator and therefore its vibration transmits to the operator's hand. Yang et al.[22] did dynamic virtual prototype simulation with the GN31 type cultivator, analyzed the vibration mechanism of the machine, and proposed effective measures to reduce vibration of the handle frame. Tewari et al.[23] compared fatigue degree of the person operating walking tractor

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with standing and sitting posture, and experiments showed that the fatigue reduces sharply with appropriate sitting posture. Dewangan et al.[24] roundly analyzed the evaluation methods of arm injury for walking tractor operator, pointed out that the vibration energy absorption method is a better evaluation method. Tewari et al.[25] developed the damping device of walking tractor, and tests showed that the damping device reduced the vibration more than 50% when the engine ran at high speed. Kalra et al.[26] explored a low-cost system for measurement of coupling forces imposed by the hand on a handle under static and dynamic conditions, and tests show the linearity is very good, while considerable differences are evident in the sensitivity amongst different sensors. Ko et al.[27] designed new suspended handles to reduce the vibration level. Three different prototype handles with rubber mounts were designed and the materials were different, especially the distance of rubber mounts were varied. From the study, it was observed that not all the handles with rubber mounts were effective in reducing hand-arm vibration. The reduction of vibration depended on the handle material and distance installed between rubber mount and vibration transmissibility of handle-isolation system. Adewusi et al.[28] presented the vibration power absorption (VPA) of different hand-arm substructures in the bent-arm and extended arm postures excited by broadband random and power tool vibrations. However, so far there are few reports about the mini-tiller vibration. Therefore, the vibration acceleration signals at the handle and the engine cover were tested under the following four conditions, the engine was under idle, medium and high speed condition, respectively but the tiller was static, and the tiller worked in the field and its engine was under high speed condition, then the time domain eigenvalue analysis and frequency spectrum analysis were done.

2 Materials and methods

2.1 Materials

The test was conducted on the farm of Southwest University, Chongqing, China. The test area is located at 106.43589°E and 29.830728°N and its length and width are 20 m and 18 m, respectively. The model of the tiller for the test is 1Z105. It is the most popular type in southwest China. The tiller has been used for 40 h and its technique condition is good. Its key performance indexes, the soil and the sensors and data acquisition card were shown in Tables 1, 2 and 3, respectively. The analysis software matched with the data acquisition card is LabVIEW SignalExpress 2012 and the soil penetrometer is SC900 Soil Compaction Meter.

Table 1 Key performance indexes of mini-tiller

Item	Value
Model	1Z105
Manufacturing company	Chongqing Hesheng
Mass/kg	105
Wheelbase/cm	50
Tillage width/cm	75
Tillage depth/cm	12-15
Transmission type	Gear drive and two forward speeds
Rated speed of engine/r min^{-1}	3000
Rated power of engine/kW	3.5
Type of the blade	Machete
No. of blades	3×3

Table 2 Key performance indexes of soil

Soils indexes	Parameter value
Soil texture	Sandy loam
Moisture rate/%	19.91
Soil firmness in depth of 0-50 mm/MPa	0.138-0.586
Soil firmness in depth of 50-100 mm/MPa	0.207-0.448
Soil firmness in depth of 100-150 mm/MPa	0.242-0.380
Depth of average tillage/cm	12.5

Table 3 Key performance indexes of sensors and data acquisition card

Device name	Performance indexes	Parameter value	Manufacturer
The three-dimensional acceleration sensors type of 356A16	Range/g	±50	PCB company in United States
	Frequency/kHz	0.3-6	
	Sensitivity/mV g^{-1}	100	
	Transverse sensitivity/%	<5	
	Mass/g	7.4	
NI9234 data acquisition card	Dynamic range/dB	102	NI company in United States
	Input voltage/V	±5	
	Digital signal rate/kHz	51.2	

2.2 Methods

2.2.1 Vibration excitation source of mini-tiller

The mini-tiller can be regarded as a flexible system of multi-freedom-degrees, generating the elasticity and deformation under the action of vibration force[29]. When its vibration is considered, there are two different states. One is that its engine operates while the rollers are motionless and it is called static condition. At this time, the engine is the only vibration excitation source. Another is that both its engine and roller work, thus the vibration excitation sources include the engine and the roller, and the handle vibration is caused by the two coupling effects.

2.2.2 Test methods

Figure 1 showed the structure of mini-tiller's vibration test. NI 9234 data acquisition card collects the vibration acceleration signals at the handle and the engine cover through the three-dimensional acceleration sensors attached to the tiller and transmits them to LabVIEW SignalExpress analysis software, and the frequency domain characteristics of the signals can be obtained by filtering and fast Fourier transforming (FFT).

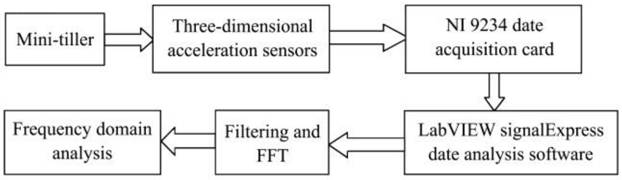

Figure 1 Structure of mini-tiller's vibration test

Four test conditions were chosen and they were shown in Table 4.

Table 4 Test plan

Test conditions	State of mini-tiller	State of engine speed	Condition of the field
I	Static (only engine operates)	Idling	Dry paddy field
II	Static (only engine operates)	Medium	
III	Static (only engine operates)	High	
IV	Working in the field (engine and blade rollers operate simultaneously)	High	

All the tests were done on November 18, 2014. The three-dimensional acceleration sensors were respectively posted on the engine cover and the handle, X, Y and Z directions of sensors correspond to the vertical, the for-and-aft and the left-to-right direction respectively (Figure 2). The mini-tiller was combined with sensors, data acquisition card and a laptop equipped with LabVIEW SignalExpress; the sampling frequency was set as 2 kHz; the slow forward speed was selected; the vibration acceleration signals at the engine cover and the handle were recorded under condition I, II, III and IV (Figure 3). The speeds of the engine under each condition were shown in Table 7.

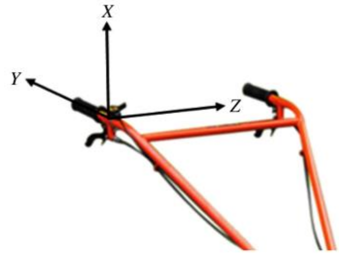

Figure 2 Corresponding relation of X, Y, Z directions

a. Static condition test b. Working condition test

Figure 3 Test process

3 Results and analysis

The vibration acceleration signals at the engine cover and the handle under four conditions were recorded. As an example, the time domain vibration wave at the handle in X direction under condition IV was showed as Figure 4.

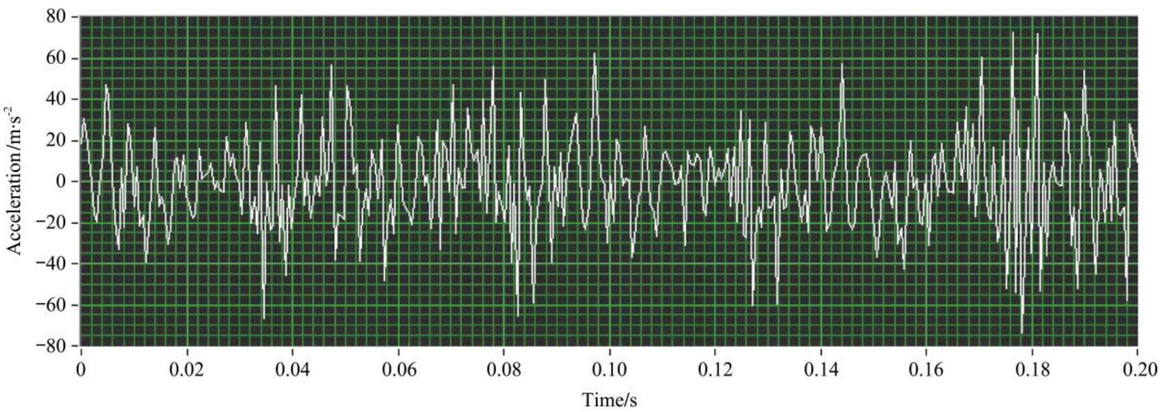

Figure 4 Vibration acceleration signals at the handle in X direction under condition IV

3.1 Time domain analysis

The vibration of mini-tiller belongs to random vibration and can be described by the statistical characteristic values. This study compared the vibration acceleration values through the root-mean-square (RMS) value.

The vibration acceleration signals at the engine cover and the handle under four conditions were tested, analyzed and processed, and the RMS values of time domain vibration signals in each direction were shown in Table 5. To compare the vibration strength at the engine cover and the handle under four conditions respectively, from Table 5 the RMS values varying with the change of conditions were shown in Figures 5 and 6.

Table 5 RMS values of time domain vibration signals at the engine cover and the handle in each direction

Measuring points	Direction	The RMS values for each condition/m s^{-2}			
		Condition I	Condition II	Condition III	Condition IV
Engine cover	*X*	3.39	5.51	8.46	3.90
	Y	2.26	3.02	2.79	2.87
	Z	3.78	6.17	6.78	4.02
Handle	*X*	17.92	17.56	10.77	5.91
	Y	7.76	8.83	9.13	8.14
	Z	6.66	5.12	6.02	5.17

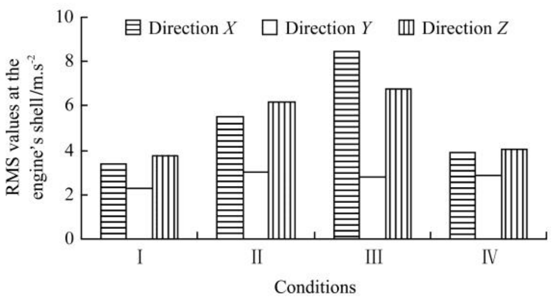

Figure 5 RMS values at the engine cover vary with the change of conditions in each direction

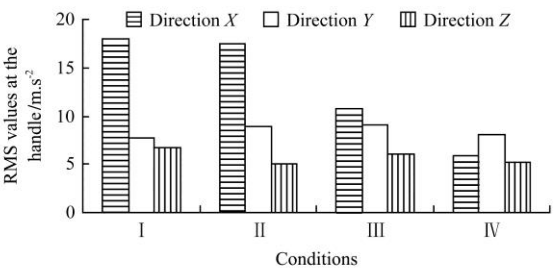

Figure 6 RMS values at the handle vary with the change of conditions in each direction

Figure 5 shows that under condition I, II and III (static conditions), with increase of the engine speed the engine cover vibration increased in *X* and *Z* directions and decreased sharply in *Y* direction. The values increased from minimum 3.39 m/s^2 to maximum 8.46 m/s^2, or increasing by 149.56% in *X* direction and from minimum 3.78 m/s^2 to maximum 6.78 m/s^2, or increasing by 79.37% in *Z* direction. When the tiller was under condition IV, compared with condition III, the engine cover vibration decreased sharply in *X* and *Z* directions, decreasing by 53.90% and 40.71%, while increased a small bit in *Y* direction.

Figure 6 shows that when the tiller was under condition I, II and III, the handle vibration decreased from maximum 17.92 m/s^2 to minimum 10.77 m/s^2 with increase of the engine speed in *X* direction, decreasing by 39.90%; the vibration increased from minimum 7.76 m/s^2 to maximum 10.77 m/s^2 in *Y* direction, increasing by 40.08%; the vibration decreased firstly and then increased in *Z* direction, while its change was marginal. When the tiller was under condition IV compared with condition III, the handle vibration decreased sharply in *X*, *Y* and *Z* directions, decreasing by 45.13%, 10.84% and 13.79% respectively. However, the handle vibration was still intense at this time. In fact, its corresponding value calculated by ISO5349[30] exceeded 5 m/s^2 when the tiller works four hours one day, the limit the Chinese national hygienic standard of GBZ-2.2-2007 stipulates.

3.2 Frequency domain analysis

When the combustion occurs in the engine cylinder, the pulse torque of the crankshaft changes periodically. The change results in engine vibrating periodically, and the vibration frequency is the combustion vibration frequency f_1 (Hz), calculated by:[31]

$$f_1 = \frac{2}{60c} ni \tag{1}$$

where, *n* is the speed of engine, r/min; *i* is the number of engine cylinder; *c* is the number of engine stroke.

The vibration frequency of inertia force f_2 (Hz) is caused by the quality of reciprocating motion and unbalanced rotation, calculated by[31]:

$$f_2 = \frac{Qn}{60} \tag{2}$$

where, *Q* is proportional coefficient (the first order unbalanced force *Q*=1, the second order unbalanced force *Q*=2).

In the test, the engine of the tiller is a vertical single-cylinder diesel engine of four strokes, and its frequency of first order unbalanced inertia force is as twice as that of the combustion vibration force. The usual working speed n of the engine is not more than 3000 r/min, and the vibration excitation frequency of engine is not more than 100 Hz from the above two equations. The normal working speed of the rotary blade rollers are not more than 300 r/min, and its vibration frequency is much smaller than that of the engine. Therefore, the vibration frequencies of the tiller are given priority to low (≤100 Hz)

The spectrogram of the handle was obtained through the FFT of time domain signals under each condition. The frequency scale of 0-200 Hz was selected as the analysis object. As an example, Figure 7 showed the handle spectrogram in X direction under condition IV. The frequencies and amplitude values at the handle in the first three orders in each direction under different conditions were shown in Table 6. Frequencies of the engine vibration were calculated from Equations (1) and (2), and shown in Table 7.

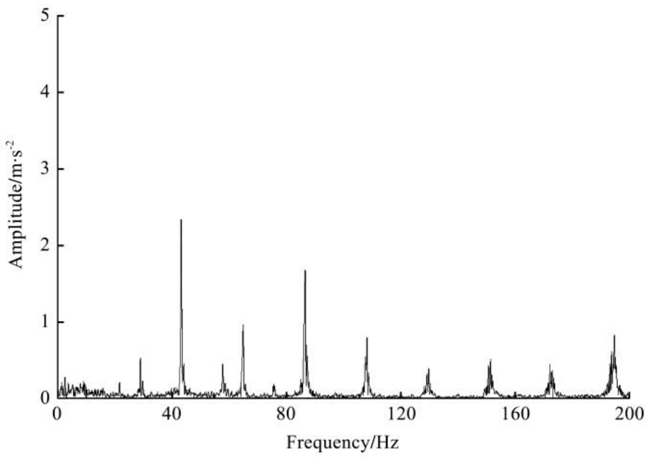

Figure 7 Handle spectrogram in X direction under condition IV

Table 6 Frequencies and amplitude values at the handle in the first three order in each direction under four conditions

Test condition	Order	Direction X		Direction Y		Direction Z	
		Vibration frequency/Hz	Amplitude/m s^{-2}	Vibration frequency/Hz	Amplitude/m s^{-2}	Vibration frequency/Hz	Amplitude/m s^{-2}
I	1	29.08	10.69	29.08	2.42	19.16	2.11
	2	19.16	3.51	19.16	1.15	29.08	1.31
	3	39.40	3.12	38.96	0.84	9.74	0.71
II	1	19.16	2.46	19.16	2.56	19.16	2.05
	2	29.08	1.83	29.08	1.34	29.08	1.43
	3	82.58	0.83	82.58	0.91	82.58	0.95
III	1	43.05	0.95	43.05	0.73	43.05	0.94
	2	107.44	0.43	86.10	0.38	86.10	0.35
	3	86.10	0.39	107.72	0.31	107.72	0.33
IV	1	43.05	1.42	43.05	2.86	43.05	0.95
	2	28.54	0.95	86.10	1.53	108.12	0.37
	3	21.46	0.59	64.61	0.80	86.10	0.31

Table 7 Speed of the engine and corresponding frequencies under each condition

Condition	Speed of engine/r min^{-1}	Frequency of combustion force/Hz	Frequency of first order inertia force/Hz	Frequency of second order inertia force/Hz
I	965	8.04	16.08	32.16
II	1945	16.21	32.42	64.84
III	2732	22.77	45.53	91.07
IV	2683	22.36	44.72	89.43

From Table 6, the following can be known.

When mini-tiller was under condition I, the frequency of 29.08 Hz produced maximum amplitude vibration in X and Y directions. And the amplitude in X direction reached the maximum in all directions in the test. When the tiller was under condition II, the similar amplitude vibration was produced in three directions by the frequency of 19.16 Hz. When the tiller was under condition III and IV, the frequency of 43.05 Hz produced maximum amplitude vibration in three directions.

It was indicated that the frequencies of 29.08, 19.16, 43.05 and 43.05 Hz in Table 6, corresponded to 32.16, 16.21, 45.53 and 44.72 Hz in Table 7 respectively, though there existed little errors between the two tables, which probably resulted from the error of speed measurement. Therefore, the following conclusions can be drawn.

When the tiller was under static condition while its engine was idle, the second unbalanced inertia force of the engine was the reason why the handle vibrated violently. When the tiller was under static condition while its engine was medium speed, the combustion excitation force of the engine caused handle vibrating violently. When the engine operated at high speed, the first unbalanced inertia force of the engine was the main reason why handle vibrated violently.

The engine operation and interaction between working parts and soil are two most important factors related to mini-tiller vibration. When mini-tiller tilled the soils, the handle vibration decreased compared to static conditions. The damping of soil decreased the mini-tiller vibration and affected the frequency structure at the handle. In fact, all the engine vibration frequencies will transmit to the handle. However, when the tiller worked, that soil absorbing energies of some frequencies leaded to the first unbalanced inertia force of the engine becoming the main reason why handle vibrates violently.

As the preliminary research, the vibration acceleration signals at the handle and the engine cover under four conditions (three static conditions and only one working condition) were tested, analyzed and processed in this study. In the future researches, more working conditions will be selected and the elements of more roller types, working speeds, soil textures and soil moisture levels should be contained.

4 Conclusions

When mini-tiller was under static conditions, the engine cover vibration increased with the increase of the engine speed, increasing from minimum 3.39 m/s^2 to maximum 8.46 m/s^2, increasing by 149.56%, and the engine cover vibrated most violently in the vertical direction; the handle vibration decreased in the vertical direction with the increase of the engine speed, increased in the fore-and-aft direction, and decreased firstly and then increased in the left-to-right direction while its change was marginal.

When the tiller worked under high speed conditions, the handle vibrated violently in the fore-and-aft direction. Compared with the static conditions, the engine cover and the handle vibration decreased sharply in three directions. It indicated that the vibration of mini-tiller was reduced because the blade rollers tilling soils increased the damping of the tiller, but the vibration was still very intense.

When the engine ran under idle conditions, the frequency of 29.08 Hz the second unbalanced inertia force of the engine producing caused handle vibrating violently; when the engine ran under medium speed condition, the frequency of 19.16 Hz the combustion exciting force of the engine producing was the reason why handle vibrates violently; when the engine ran at high speed, the frequency of 43.05 Hz the first order unbalanced inertia force the engine producing was the main reason which caused handle vibrating violently.

Therefore, to avoid the handle resonation, efforts should be made to the frequency of the first order unbalanced inertia force the engine produces and the natural frequency of the handle for assuring the two not near.

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