RESEARCH ON THE VIBRATION OF MINI TILLER
/
微耕机的振动研究

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ABSTRACT

The mini tiller is a type of agricultural equipment used for hilly and mountainous regions. The intense vibration it produces causes harm to the manipulator's body. Hence, it is imperative to analyse reported studies on the mini tiller, especially addressing the limitations of this machine. The mini tiller, brand 1z-105, was selected to be used as a prototype in several experiments using three different conditions. The data was analyzed in the time and frequency domains and the effects on the human body were explored. Finally, suggestion was made regarding the handling comfort of the mini tiller if it is articulated.

摘要

微耕机是丘陵山区重要的农业装备，然而其强烈的振动对操作者身体带来巨大的伤害。基于此，首先简要分析了微耕机的研究现状，尤其是使用中存在的问题。再以 1z-105 微耕机为研究对象，完成了其在三种工况下的振动实验。过对微耕机的振动信号进行了时域和频域分析，探讨了微耕机作业时对人体的影响。最后基于结果分析，给出了未来微耕机提高操作舒适性的建议，为微耕机的性能改进提供理论依据。

INTRODUCTION

China is a country with complex land formation. The statistics indicate that over 60% of the area is comprised of hilly and mountainous regions, and more than 40% of agricultural acreage is located in this terrain. It is difficult to implement modernization and mechanization for agriculture in hilly regions, resulting in the limitation of using large agricultural equipment. The mini tiller is driven by a gasoline or diesel internal combustion engine of 2~7.5 kW, weighs 50~150 kg, and has a tilling depth of 10~16 cm. Due to the advantages, such as being multifunctional, small in size and light weight, it is popular.

Although such characteristics are advantageous in hilly or mountainous terrain, the mini tiller has significant disadvantages, including severe vibration which cannot be endured. Studies suggest that the intense vibration can cause moving disorders, damage to various body organs including the ear, spine and gastrointestinal disorders, and neurological disease *(Ahmadian H., et al., 2012; Li, et al., 2016)*. Another disadvantage is operator fatigue caused by the operator walking behind the machine during tilling for 15~20 km *(Mehta C. R., et al., 1997)*. In Italy, 13% of injuries from all accidents are related to the use of power tillers *(Fabbri A., et al., 2017)*. With increasing urbanization, the older generation will be the operators of such equipment, and severe injuries, even death, are reported frequently. The handling comfort of mini tillers needs to be improved.

The biggest shortcoming of the mini tiller is the production of strong vibrations by the engine, rotary blade and uneven soil tilling. In addition, it is hard to find elastic components in the mini tiller resulting in the vibration amplitude to be difficult to buffer. During the tilling process, tires are replaced by the rotary blade, and almost all modules are assembled on a rigid rack. The harsh operating environment and the design faults, which are a result of lowering the cost, make the performance unacceptable for operators. Vibration is a complicated movement for the human body to react to, and some factors including vibration magnitude, frequency, duration time, input position, etc., are especially significant to the effects. It appears that some environmental elements, including light, heat and noise, are also relative to the effects of vibration *(British Standards 6481, 1987, ISO 2631/1, 1985).* There are multiple studies reported in the literature on the effects of vibration. The disease White Hand syndrome can be caused by vibration, and the mechanism of the illness has been reported *(Ragni L., et al., 1999)*. In order to determine optimal properties of the mini tiller, the vibrational mechanism of the tiller is analyzed and some measures for reducing vibration have been introduced *(Yang J., et al., 2005)*. The Finite Element Method (FEM) is an effective low cost method used to achieve an optimized structure of agriculture machinery *(Xu F., et al., 2008)*. The steering system must also be flexible in agricultural equipment *(Nafchi A. M., et al., 2011)*. The majority of the vibration is from the engine and the vibration effect of different fuels must be considered *(Heidary B., et al., 2013)*. Studies on the transmission of vibrations from the blade to the body are not easy to analyse. Therefore, it is crucial to establish a vibration model and reduce the vibration experienced by the operator *(Fabbri A., et al., 2017)*. Parts of the vibration is generated during the tilling process and the geometry of blade and the scoop angle characteristics of a handheld tiller's rotary blade has been explored *(Zhang Y. H., et al., 2016)*. Vibrational testing and a response analysis of the power tiller are essential *(Xu H. B., et al., 2016)*.

The structure of mini tillers requires the structural optimization of the handlebars using vibration modal analysis *(Niu P., et al., 2017)*. In reference [15], pre-stress means are used to analyse the vibration of the mini tiller, and the consistency between theoretical outcome and test data has been achieved *(Wang Z., et al., 2018)*.

Improving the handling comfort of the mini tiller is filled with challenges, due to several factors contributing to the performance, such as rotation speed of the engine, the geometry of rotary blade, the soil type, the depth and width of tilling *(Vaghela, et al., 2013, Fajardo A. L., et al., 2014, Matin M.A., et al., 2015)*. High value-added agriculture needs more advanced equipment with low pollution and satisfactory performance, especially in facility agriculture such as in the greenhouse. Therefore, tests for this study were finished in the two soils of the *greenhouse.*

MATERIALS AND METHODS

Compared to field experiments, the theoretical analysis of the mini tiller is easy and cost effective to conduct. However, not all the characteristics can be described precisely. For example, the soil model is hard to build, and some details of soil structure must be omitted to simplify the model.

The experimental location was situated at 29.81° N latitude and 106.42 ° E longitude, and field tests were completed on April 5, 2017. The mini tiller had worked for two years and its technique condition was good. The air temperature in the greenhouse was 21.5°C and the soil texture was a sandy loam. The parameters of mini tiller are listed in Table 1.

Table 1

Specification of the mini tiller

Mini tiller item	Parameter
Engine type	Four stroke direct injection
Related power	4.41 kW
Related rotation speed	3600 min/r
Cylinder number	1
Tilling depth	10-12 cm
Tilling width	75 cm
Transmission	2 forward and 1 reverse
Cooling system	Air cooling
Blade	Machete

The experimental scenario of mini tiller is recorded in Figure 1. The three-dimensional acceleration sensor was 356A16, which was produced by the PCB Company in the US. The frequency scope was 0.3~6 kHz, and measured range was -50~50 g. In addition, the sensitivity of the instrument in $x-$, $y-$ and $z-$ coordinate directions was 98.2, 101.0 and 98.5 mv/g, respectively. The acquisition card was NI 9234, which was made in NI Company in the US, the input voltage was -5~5 V and the rate of digital signal was 51.2 kHz. The vibration was transmitted from the rotary blade and engine to the body through the handlebar of the mini tiller, so the acceleration sensor was attached to the end of bar using the 502 glue. The coordinate directions of sensor and the whole measuring system are shown in Figure 1.

Fig. 1 - Sensor in the mini tiller and connection relation for different components

An experiment was undertaken in a greenhouse, as described below. Firstly, the acceleration sensor was situated outside of the handlebar, and uses a data cable to link the sensor, the acquisition card and USB port of the laptop. Secondly, vibration signals from the mini tiller with no load were collected using LabVIEW program when the tiller was operated. Thirdly, vibration signals were gathered while the tiller was running with a full load. During the process, the throttle was fixed in the open position and the gear ratio was unchanged. The experiments were repeated on two different grounds. Soil 1, had a moisture content of 13.5%, and average firmness of 0.41-0.63. The corresponding parameters in soil 2 were 9.4% and 0.58-0.75, respectively. The principle of vibration signal disposing is described in Figure 2.

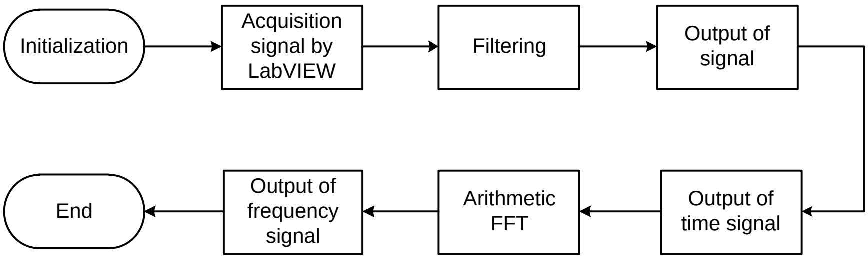


Fig. 2 - The principle of vibration signal disposing

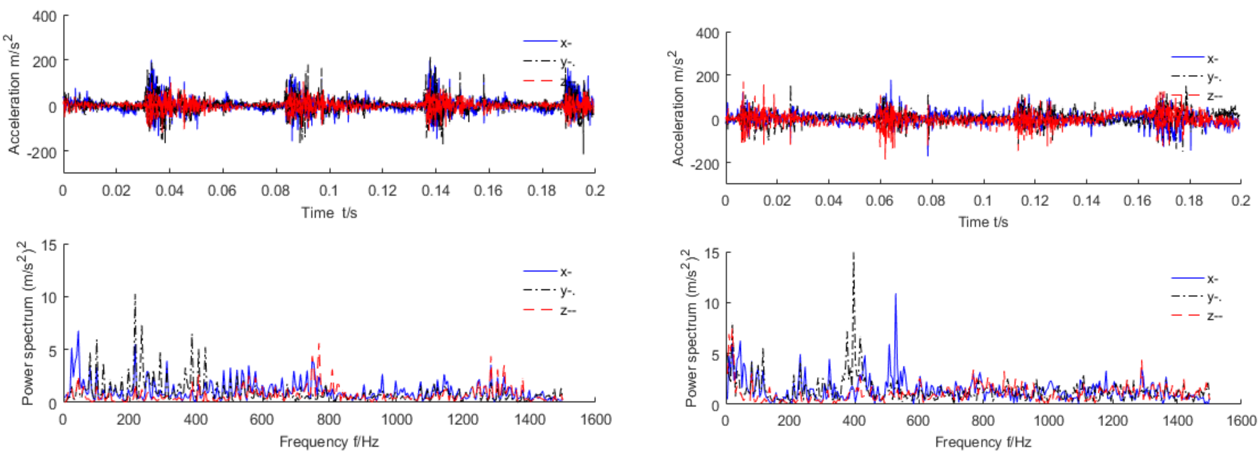
RESULTS

Results under different conditions are recorded and shown in Figure 3. The mini tiller working without a load and the acceleration signal is shown in Figure 3a.

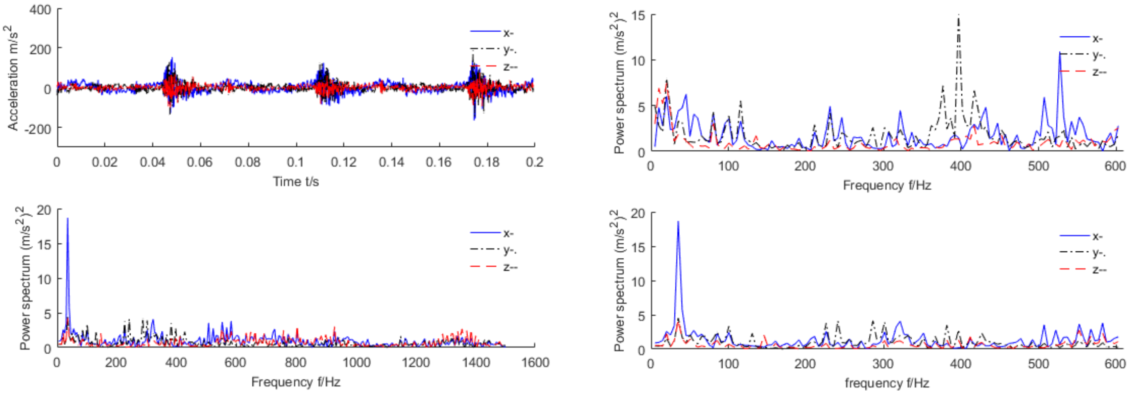
The mini tiller working under full load on soil that was less firm in texture is shown in Figure 3b.

In Figure 3c the experiment is repeated on a firmer textured soil.

The outcomes are expressed in a narrower frequency band in Figure 3d.



a) *b)*



c) d)

Fig. 3 - Acceleration signal of the mini tiller under different conditions

From Figure 3, it appears that the acceleration signal in the time domain occurs periodically. The primary reason for this could be the configuration of rotary blade which is symmetrical, reflected as the periodicity of curves. The variation in the curves could be attributed to the random firmness and moisture content of the soil. Furthermore, the variable power output of the engine is also reflected in the curves. While in the frequency domain, it is noted that the frequency spectrum is very distinct at the same frequency band. It is hard to find the same peak and trough in Figure 3, and individual signals do not represent characteristic vibrations during tilling. The application of statistics could be useful in describing the vibration process. The root mean square (RMS) value of weighted acceleration is used to analyse the vibration signal in the frequency domain, which can represent the vibrational energy, using the following equation:

$$a_{rms} = \sqrt{\left(\sum_{i=1}^{n} a_i^2\right) / n} \tag{1}$$

Where: a_i is the measured acceleration amplitude, [ms^{-2}];

n - the number of acquisitions;

a_{rms} -the vibration acceleration RMS value, [ms^{-2}].

Accordingly, the results can be seen in Figure 4.

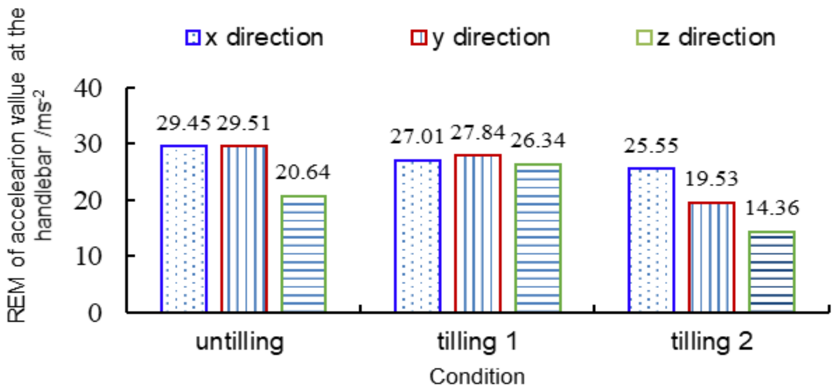


Fig. 4 - Vibration acceleration value in coordinate directions

In Figure 4, the acceleration at the end of the handlebar in the coordinate directions is different, which may be caused by the different stresses in each coordinate direction. The soil surface is uneven which result in the amount of tilling being varied, and the distribution of soil firmness is random. Therefore, the acceleration amplitude in each coordinate direction is unique. In no tilling mode acceleration in the $x-$ coordinate direction it was 43% greater than that in the $z-$ axis direction, while it was similar to the acceleration in the $y-$axis direction. Compared with tilling 1 and tilling 2 modes, the acceleration in $x-$ coordinate direction was 9% and 15% greater, respectively. Correspondingly, the acceleration in $y-$ coordinate direction was 6% and 51% greater, and acceleration in $z-$coordinate direction it was -22% and 10% greater, respectively. Overall, the acceleration in each axial direction was irregular, which was generated by the random values of the different forces exerted.

In the moving mode, the peak of vibration frequencies were 45 Hz, 216 Hz and 768 Hz, and the corresponding amplitudes were 6.8 ms^{-2}, 10 ms^{-2} and 5.6 ms^{-2}, respectively. However, the distribution and amplitude of the frequency in tilling mode 1 were significantly different to the values in the moving mode. The vibration frequency peak in coordinate directions under tilling mode 2 coincided at 35 Hz, which is dissimilar to other modes. In contrast to the moving and tilling mode 1, the acceleration in the $x-$ coordinate direction was 168% and 65% greater, while in the $y-$coordinate direction, the acceleration was 55% and 70% smaller, and in the $z-$coordinate direction it was 25% and 44% smaller. The human body is complicated in its reaction to vibration, resulting in different frequencies not being equally disruptive. Namely, different internal organs of the body can have different masses, damping and elasticity, so the resonance frequency within each is unique. For example, 4~8 Hz in the vertical direction and 1~2 Hz in the horizontal direction are more sensitive than other frequencies for most people. Hence, it is necessary to give the distribution of the frequency peaks (Table 2) and the vibration frequency of the mini tiller should be kept greater or smaller than the frequencies humans are sensitive to in order to ensure handling comfort.

Table 2

Human reactions to RMS weighted acceleration levels

Test	x-axis direction		y-axis direction		z-axis direction	
	Vibration frequency	Amplitude	Vibration frequency	Amplitude	Vibration frequency	Amplitude
	[Hz]	[ms^{-2}]	[Hz]	[ms^{-2}]	[Hz]	[ms^{-2}]
Moving	45	6.8	216	10	768	5.6
Tilling 1	527	11	397	15	20	7.5
Tilling 2	35	18.2	35	4.5	35	4.2

From the analysis above, it was noted that vibration frequency is diverse under different tilling conditions. Therefore, enhancing the handling comfort of the mini tiller is difficult. It is convenient to use the total acceleration value a_{rms} in any coordinate axis, because human reaction is a result of the whole vibration input in three coordinate directions. The equation 2 is used for calculating the total weighted acceleration value.

$$a_{sum} = \sqrt{1.4a_x^2 + 1.4a_y^2 + a_z^2} \tag{2}$$

Where:

a_x is the acceleration RMS value in $x-$coordinate axes, [ms^{-2}];

a_y -the acceleration RMS value in $y-$coordinate axes, [ms^{-2}];

a_z -the acceleration RMS value in $z-$coordinate axes, [ms^{-2}];

a_{sum} -the total weighted acceleration value, [ms^{-2}].

Using equation (2), the responding values were calculated as 51.8 ms^{-2}, 52.78 ms^{-2} and 38.41 ms^{-2}, respectively. It is accepted that the acceleration level can be used to evaluate the riding comfort of vehicles (Table 3). Comparing the tilling process results it is shown that the handling comfort of the mini tiller is unacceptable, and possibly the reason why operators of the mini tiller are frequently injured.

Table 3

Human reactions to RMS weighted acceleration levels

Weighted RMS acceleration	Description of human reactions
[ms^{-2}]	/
$<$0.315	Not uncomfortable
0.315-0.630	A little uncomfortable
0.5-1.0	Fairly uncomfortable
0.8-1.6	Uncomfortable
1.25-2.50	Very uncomfortable
$>$2	Extremely uncomfortable

Compared with studies reported in the literature *(Vaghela, et al., 2013, Bahareh H., et al., 2013, Li, et al., 2016)*, the RMS of test accelerations in this study were much greater. The distinction between different internal combustion engines was not obvious, so the most probable cause lies in the process of tilling itself, the key to enhance the handling comfort of the mini tiller. The stresses on the rotary blade of the mini tiller are shown in Figure 5.

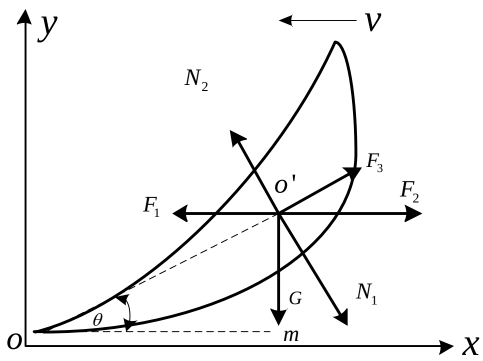


Fig. 5 - The stress analysis of rotary blade during tilling

The mechanism of the equilibrium of the blade can be described by equation 3 as :

$$\begin{cases} G + N_1\cos\theta - N_2\cos\theta + F_3\sin\theta = 0 \\ F_1 - F_3\cos\theta - F_2 - N_1\sin\theta + N_2\sin\theta = 0 \end{cases} \tag{3}$$

Where:

G is the gravity of blade, [ms^{-2}];

θ - the angle between the line $Oo^{'}$ and the line Om , [°];

N_1 -the clod pressure above the blade, [N];

N_2 -the clod pressure below the blade, [N];

F_1 -the force of blade roller, [N];

F_2 -the acceleration resistance, [N];

F_3 -the frictional force between the blade and soil, [N].

Furthermore, several forces can be described in more specific forms, which is convenient for calculating results. For example, $F_2 = \delta m\dfrac{dv}{dt}$, and $F_3 = \mu(N_1 - N_2) + \mu AS$, where δm signifies acceleration mass, μ shows friction coefficient between the blade and soil texture, S expresses the area of adhesive water envelop, and A represents the absorbing load caused by water film. The parameters in equation (3) can be measured and the results recorded under different conditions. Using equation (3), it can be concluded that different tilling depth results in different clod pressures on each coordinate direction, and the mechanical equilibrium also changes. A couple of dynamic parameters, including power output of the engine, firmness of the soil texture, different tilling depths, and different acceleration forces, cause a continuous couple and act on the rack of the mini tiller, creating vibration. If the changes of parameters are large, intense vibration can be produced.

From Figure 5, the rotary blade cuts the soil into a small slice or clod and throws it to the shield in each bite. If the firmness of soil is greater, then a smaller load may be finished in each bite, assuming the power output of the engine is unchanged. Significant variation from the composite force of the blade is generated due to the change of soil firmness and rotating fluctuation of the engine. The situation is aggravated by the single cylinder of the engine which has a lopsided reciprocating and rotary torque. The significant differences in experimental outcomes are due to the firmness of soil, and the relation between the firmness and acceleration is shown in Figure 4.

There is a paradox in Figure 4. The firmness in the first soil texture is smaller than that in the second soil texture, while the acceleration of the handlebar is smaller in the two soils. In addition, the acceleration at the end of the handlebar in the moving mode is greater than that of the acceleration in the tilling mode. These results agree with that reported by Li, et al., 2016. During the process of tilling, more vibrational energy is absorbed by the soil than that transmitted to the handlebar. If the tilling depth is increased, the acceleration is reduced. It is not economical to decrease the acceleration by enlarging the tilling depth, as this will cause higher fuel consumption by the engine and disperse more soil. Whether heightening the tilling depth is feasible should be considered in another study.

CONCLUSIONS

The tilling process is complicated under changing conditions, with further studies, including theoretical analysis and field experiments, needed to understand it.

- The vibration frequency for the mini tiller is wide, and it is hard to keep the frequency within a range to result in satisfactory handling comfort under different terrain and working conditions. It is feasible to design an active system which matches diverse terrains.
- Test results show that the manipulator’s body is hurt by the evident vibration during the mini tiller working. In the hilly and mountainous regions, how to transform vibration energy which is produced by the rotary blade and the single cylinder engine into other energy form is more urgent.
- The physical design of the mini tiller should be improved greatly. It is unreasonable to use a rigid structure for the mini tiller. In addition, some elastic components should be included into the assembly of the mini tiller to buffer the vibrational energy.

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