HANDLING COMFORT ANALYSIS OF ELECTRIC MINI-TILLER UNDER DIFFERENT CONDITIONS
/
电动微耕机不同工况下的操作舒适性分析

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ABSTRACT

The electric mini-tiller can produce extra vibration during tilling, shortening the span life of components and undermining manipulator's body. Therefore, sensors are set in the electric motor and armrest, and field experiments under different conditions have been accomplished. Test data show that some of the vibration frequency bands of electric mini-tiller are sensitive to the human, imposing great harm on people's health. So redesigning the electric one to lessen or cut off the vibration transmission is an urgent engineering problem.

摘要

电动微耕机在作业过程中会产生较为明显的振动，既缩短了零部件的寿命，也给操纵者的健康带了巨大的伤害。在微耕机的电动机和扶手处设置了传感器，进行了不同工况下的田间实验。数据表明微耕机部分振动频率接近人体的敏感频段，因而对人体的影响较大。因此，如何对微耕机的结构进行全新设计，进一步减小和切断电动机和刀具的振动传递是亟待解决的工程问题。

INTRODUCTION

The mini-tiller is powered by a gasoline or diesel engine of 1.0-7.5 kW and weighs 50-150 kg. It can achieve a tilling depth of 10-16 cm and efficiency of 220-540 m^2/h *(Chen J. et al, 2014)*. In the mountainous regions, the use of large and middle sized mechanical equipment is restricted, so such tillers are popular.

Although the progress of technology can improve mini-tillers, the problems are still significant. Firstly, intense vibration is common for most agriculture equipment. In the case of the mini-tiller, nearly all the assembly is connected in a rigid rack, which creates unacceptable vibration during the tilling process. Vibrations caused by engines and rotary blades, will transfer to the handlebar which is directly in contact with the operator's body, causing body organs disorders and neurological disease *(Range L. et al,1999; Tewari V. K. et al, 2009)*. Secondly, high fuel consumption means that it is difficult to meet the severe environmental requirements of less pollution, especially in high value-added equipment in agriculture. Thirdly, being short of protecting measures, the rotary blades are exposed and can easily injure the manipulator who is fatigued and absent-minded after walking on the furrow for a distance of approximately 15 to 20 km *(Mehta C. R. et al, 1997)*, especially in mountainous and hilly regions. If mini-tillers cannot offer satisfactory properties including handling comfort and safety, then severe accidents will occur.

There are many reports in the literature of studies trying to improve the mini-tiller. In order to reduce the vibration level, biodiesel and biodiesel-diesel have been tried to replace traditional fuel for engines *(Heidary B., et al, 2013; Taghizadeh-Alisaraei A. et al, 2012)*. Vibration is a complicated action process involving several factors, including firmness of the soil, tilling speed, the geography of the blade, moisture content of the soil, material type, depth of tilling, etc. In these papers the relationship between vibration and contributing factors is explored *(Niu P. et al, 2017; Zhang Y. H. et al, 2016)*. Statistics indicates that most agricultural equipment do not contain elastic components, in particular tilling instruments. Hence, assemblies installed in a flexible way may improve the handling comfort, as reported in the literature *(Hao K. Y. et al, 2011; Caffaro F. et al, 2016)*. In addition, some new methods are used to settle vibration reduction *(Fabbri A., et al, 2017; Cutini M., et al, 2016)*.

Some factors, including light, temperature, moisture, should be considered to analyse the vibration effect *(Deboli R. et al, 2017)*. Furthermore, it is beneficial to investigate some accidents to enhance the performance of tillers *(Mattetti M. et al., 2017)*.

Compared with the traditional mini-tiller, the electric one has vast advantages on environmental friendliness, lower noise and controlling convenience. Unluckily, few papers focused on the dynamic character have been published. Considering distinct difference of driving condition between electric vehicles and new type of mini-tillers, the features of thermal and span life for lithium battery are still unknown and should have been analysed, although such mechanisms have been researched in the domain of electric vehicles.

MATERIALS AND METHODS

The prototype used in this study is the electric mini-tiller 1WG0.75-70DD-ZC, which is developed by Hesheng Co., Ltd., Chongqing. The firmness of soil is a significant factor to test outcomes, which has been measured several times and then the average value was obtained. The prototype of the tiller is shown in Figure 1, and the coordinate direction is also signified at the same time. Besides, the parameters of this tiller are listed in Table 1. It must be pointed out that the capacity of battery and the power of electric motor are both smaller than those computing outcome, verifying the feasibility of prototype.

Fig. 1 - Electric elementary prototype and battery box

Table 1

The parameters of electric mini-tiller

Properties of mini-tiller	**parameters**
Rated power [kW]	0.75
Dimension（L×W×H[mm]	1750×700×920
Pure weight [kg]	<65
Tilling width [mm]	70
Tilling depth [mm]	10-16
Working speed [m/s]	0.1-0.3
Roller rotational speed [r/mm]	150(h),130(m),110(l)
Efficiency [hm^2/h·m]	≥0.04

Supplementary instruction is listed here. Collecting data program is compiled by LabVIEW software, and the three-dimensional acceleration sensor is 356A16, produced by the PCB Company in the US. The frequency scope is 0.3~6 kHz and measured range is -50~50g. In addition, the sensitivity of the instrument in x-, y- and z- coordinate directions is 98.2, 101.0 and 98.5 mV/g, respectively. The acquisition card is NI 9234, made in NI Company in the US, the input voltage is -5~5V and the rate of digital signal is 51.2 kHz.

The test location was situated at 29.3° N latitude and 106.3° E longitude, and the experimental date was on March 19, 2017. The air temperature was 17.5^{o}C, and the soil texture was sandy loam. The soil was covered with grass and the moisture was 30.5%. In addition, the average firmness was 0.26-0.31mm/MPa.

Commonly a vibration signal is expressed as a time domain and frequency domain. The advantage of time domain is that the relationship between time and vibration magnitude is distinct, while the influencing frequency elements are vacant. Instead, it is easy to determine specific frequency spectra, but time signals are vague. Therefore, two methods to describe the vibration process will be used, which are signified by the formula below:

$$\begin{cases} S(f)=\int_{-\infty}^{\infty} s(t)e^{-j2\pi ft}dt \\ s(t)=\int_{-\infty}^{\infty} S(f)e^{j2\pi ft}df \end{cases} \tag{1}$$

Where:

$s(t)$ is time signal，and t is time, [s];

$S(f)$ is frequency spectrum, and f is frequency, [Hz].

In a strict sense, the output signal of a mini-tiller is a non-stationary random signal, and two formulas cannot be used directly. Simplifying study course, it is common to assume that the vibration signal within infinitesimal time is stationary in engineering field, so the formula can then be applied. Furthermore, the precision of the calculations is dependent on the length of time the signal collected, and 5100 vibration accelerations are gathered for each time point in this study.

The tilling process of the mini-tiller is difficult to be described, but can be depicted as follows based on how the vibration is generated and transmitted in Figure 2. Part of the vibration is generated by the electric motor, and the armrest is the only part of the mini-tiller touching human body. Transducers have been installed on the cover of the motor and the end of each handlebar using 502 glue.

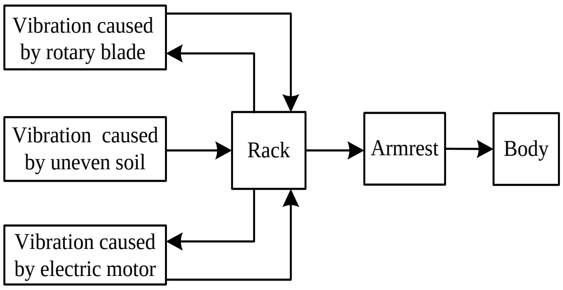


Fig. 2 - The process of producing and transmitting vibrations

Theoretical analysis and field experiments can be used to determine the properties of the electric mini-tiller. In order to investigate the range of performance of the tiller, different operational conditions, including reverse gear, essential in minimizing the turning radius of the mini-tiller, are designed.

RESULTS

Figure 3 shows that vibration signals are similar over a time span of less than four gears. However, in the frequency domain, there are more frequency peaks and troughs under low and middle gears than in other gears. In each gear, the acceleration vibration peak in tri-axle directions is unique. Besides, the faster the electric motor runs, the more wave peaks are generated.

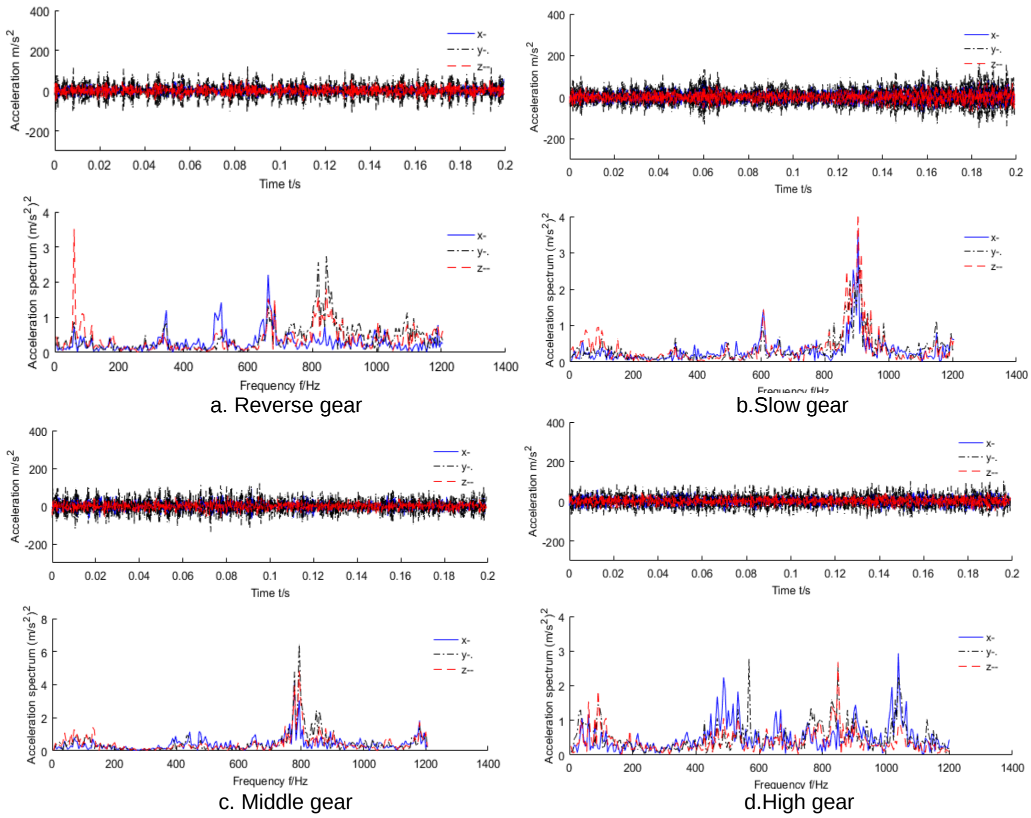
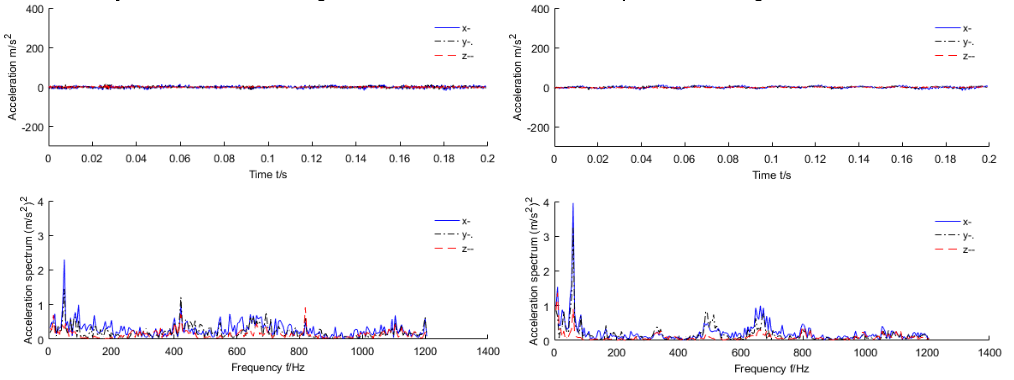
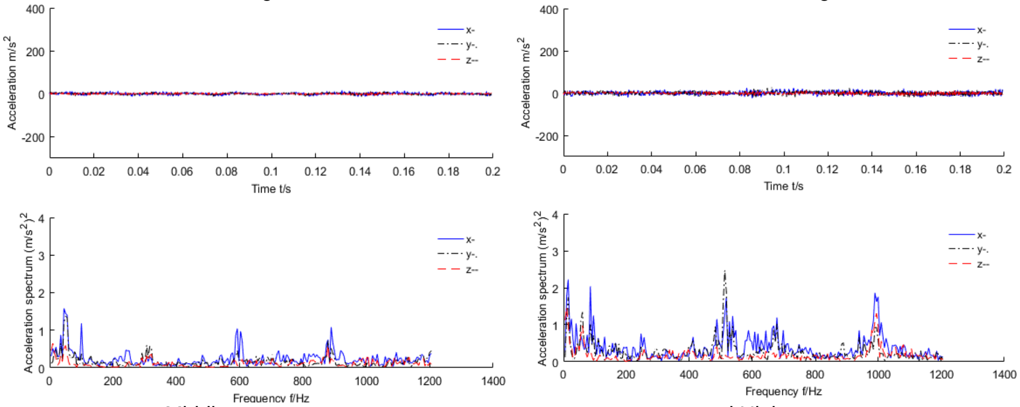


Fig. 3 - Vibration signal of electric motor during movement

In the same way, the vibration signal of armrest can be disposed in Figure 4.



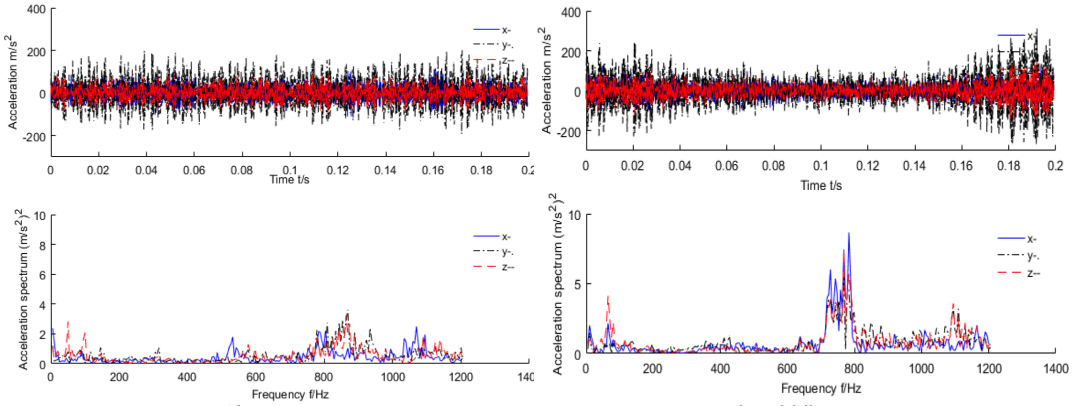
a. Reverse gear b.Slow gear



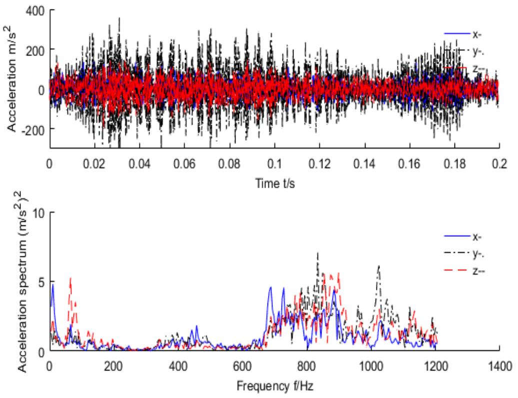
c. Middle gear d.High gear

Fig. 4 - Vibration signal of armrest during movement

From Figure 4, it is easy to discern the vibration amplitude in the armrest is significantly weaker than that of the covering of motor, being absorbed by the soil. Moreover, the variation trend of acceleration is similar to that in Figure 3. Identically, vibration signals can be expressed in Figure 5 and Figure 6 during working.

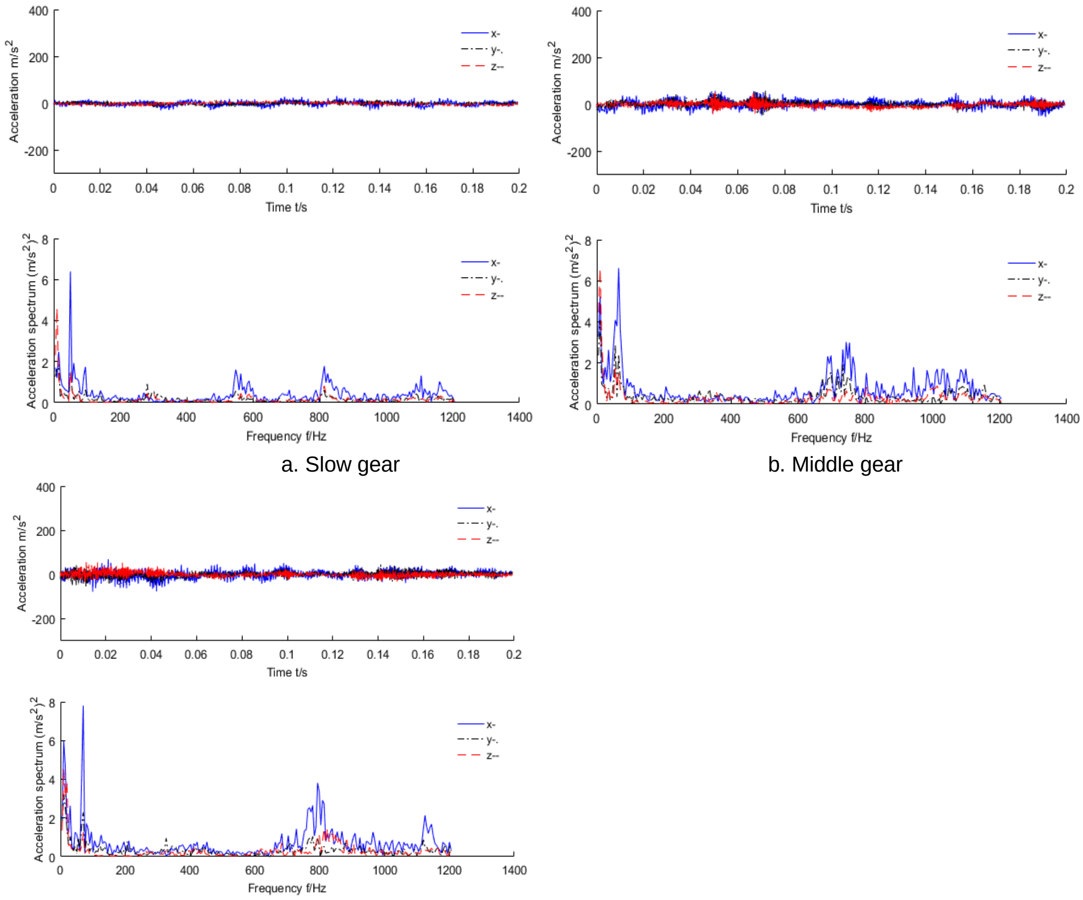


a. Slow gear b. Middle gear



c. High gear

Fig. 5 - Vibration signal of electric motor during tilling



a. Slow gear b. Middle gear

c. High gear

Fig. 6 - Vibration signal of armrest during tilling

Obviously, the vibration acceleration is much greater in Figure 5 than that in Figure 4; the same conclusion is also drawn from Figure 4 and Figure 6. During movement, the weight of mini-tiller is supported by the blades, resulting in a lower tilling depth. While tilling the working depth is greater than 10 mm, which means large force must be output to cut the clod into pieces, bringing about vibration intensity being measured either in time domain or frequency domain. When the mini-tiller is walking in the reverse gear, the less cutting force is needed and the vibration acceleration can be neglected, so such case has not been analyzed in Figure 5 and Figure 6. In addition, there is a distinct vibration peak of x-coordination direction in Figure 6, which is different from that in Figure 4, and by such phenomenon can be explained that the shape of rotary blade plays a crucial role *(Liang X.C. et al, 2018)*. This is easy to be demonstrated when the rotary blade is replaced by the new rotary blade with the different shape. Briefly, in Figure 5 and Figure 6, the intensity of vibration is increased in time and frequency domains, which would lead to the handling comfort of the mini-tiller to deteriorate quickly. During the process of tilling, most time is spent in tilling mode and the time spent moving is very short. Consequently, it is rational to ignore the mini-tiller walking in the reverse gear during tilling.

The reaction of the human body to the vibration is determined by the average acceleration, although every vibration frequency can give rise to different effect, so it is necessary to compute the root mean square (RMS) acceleration and evaluate the handling comfort of the electric mini-tiller. Formula (2) is used to calculate RMS acceleration, and results are shown in Figure 7.

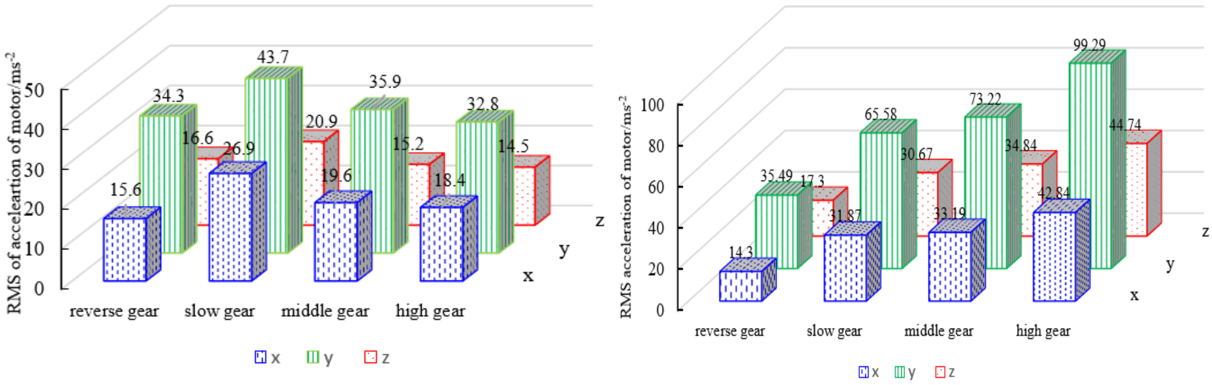
$$a_{rms} = \sqrt{\left(\sum_{i=1}^{n} a_i^2\right) / n} \tag{2}$$

Where:

a_i is an arbitrary acceleration, [ms^{-2}];

n is the number of collected vibration signal;

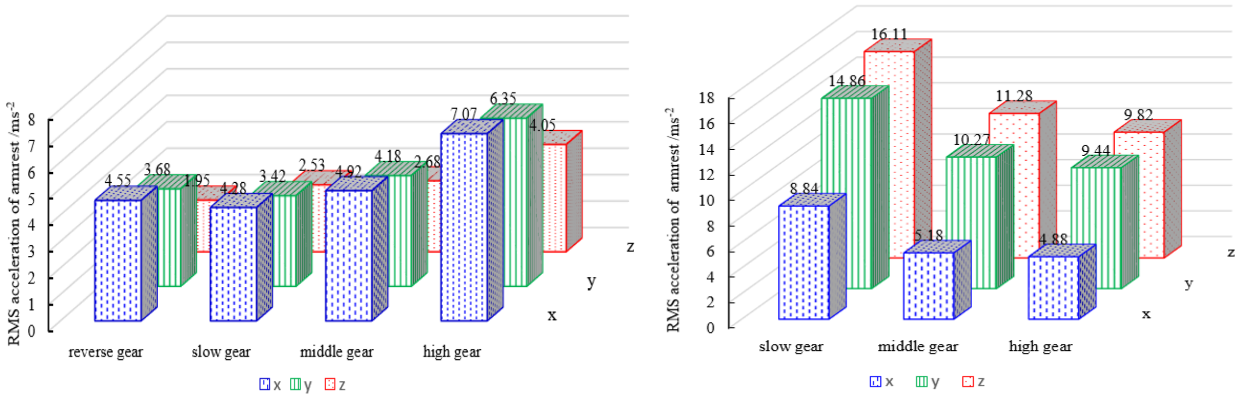
a_{rms} is the RMS acceleration, [ms^{-2}].



a. Moving mode b. Tilling mode

Fig. 7 - RMS acceleration of electric motor under different modes and gears

The acceleration in the moving mode is smaller than that in tilling mode, and acceleration in y- axis is much greater than the value in other axis directions, which could be caused by the geometry of the rotary blades, but needs to be further verified by experiment. Meanwhile, the variation tendency of RMS acceleration, shown in Figure 7a, is initially increasing and then decreasing. While in Figure 7b, it is uniformly increasing for three coordinate directions.



a. Moving mode b. Tilling mode

Fig. 8 - RMS acceleration of armrest under different modes and gears

Figure 8 shows a similar outcome, and thus the acceleration of vibration in the moving mode is smaller than that in the tilling mode, which may be explained that the rotary blade in moving mode cuts the soil at a shallower level. The significant difference about the variation tendency of RMS acceleration is inverse. Besides, RMS acceleration in x- coordinate direction is the greatest for all axis directions in Figure 8a, while it is the smallest for all axis directions in Figure 8b. However, acceleration in the high gear has the least vibration in Figure 8b. This paradox may be explained by the higher the electric motor runs, the less each bite accomplishes, so the acceleration is decreased slightly. Moreover, not all of the vibrational energy of the electric motor is transmitted to the handlebars. Though the reaction to vibration is different for each person, when the vibration acceleration is larger than 2ms^{-2}, the handling comfort is hard to sustain for over half an hour for most of people. In a word, the handling comfort of electric mini-tiller is not wanted, in particular for an intelligent agriculture era.

It is not always possible to describe the reaction to vibration with three different accelerations. In a common scenario, the acceleration in an axis direction is large, while in the other directions is small. In order to depict the vibration level, a total weighted acceleration is calculated based on the ISO2631-1:1997(E)

$$a_V = [(1.4a_{xw})^2 + (1.4a_{yw})^2 + a_{zw}^2]^{0.5} \tag{3}$$

Where:

a_V is the total weighted acceleration, [ms^{-2}];
a_{xw} is the acceleration in x- coordinate direction, [ms^{-2}];
a_{yw} is the acceleration in y- coordinate direction, [ms^{-2}];
a_{zw} is the acceleration in z- coordinate direction, [ms^{-2}].

For this study, almost all accelerations in Figures 7 and Figure 8 are greater than 2ms^{-2}, so the weighted accelerations must be bigger than 2 ms^{-2}, and thus the results are similar to the outcome computed by the formula (2) as well.

It is noted that a frequency band of 1~2Hz in the horizontal direction and 4~8Hz in the vertical direction are very uncomfortable to the most of human. Therefore, a distribution of vibration frequency has also been analyzed, and is shown in Table 2 and Table 3.

Table 2

Frequency distribution of armrest in each axis direction under moving and tilling modes

Item		a_x		a_y		a_z	
		f [**Hz**]	A [**ms^{-2}**]	f [**Hz**]	A [**ms^{-2}**]	f [**Hz**]	A [**ms^{-2}**]
Moving	r	60	3.96	60	3.25	10	1.37
	s	45	1.58	50	1.37	10	0.65
	m	50	2.3	50	1.46	818	0.92
	h	15	2.22	512	2.47	10	1.48
Tilling	s	50	6.39	15	1.7	10	4.6
	m	65	6.61	10	4.1	10	6.58
	h	70	7.8	10	3.23	10	4.5

Table 3

Frequency distribution of motor in each axis direction under moving and tilling modes

Item		a_x		a_y		a_z	
		f[**Hz**]	A[**ms^{-2}**]	f[**Hz**]	A[**ms^{-2}**]	f[**Hz**]	A[**ms^{-2}**]
Moving	r	666	2.2	844	2.7	60	3.5
	s	904	3.6	909	2.6	904	4.1
	m	778	4.1	793	6.4	793	4.8
	h	1038	2.9	567	2.8	849	2.7
Tilling	r	10	3.5	795	2.6	10	1.7
	s	1069	2.5	868	3.6	863	3.2
	m	783	8.7	768	5.6	768	7.4
	h	10	4.8	833	7.1	898	5.6

Symbols in Tables 2 and Table 3 such as r, s, m and h represent reverse gear, low gear, middle gear and high gear, respectively. Table 2 shows that all except two maxima accelerations in x-, y- and z-coordinate directions are smaller than 100Hz, and the peak distribution is not regular. It is necessary to acknowledge that there are some differences between the coordinate system used in this study and the coordinate system in the ISO criterion. Namely, a_x in this study is equivalent to a_z in ISO norm, etc. There are eight peaks at 10Hz, with 75% distributed in the z- coordinate direction, which is close to the sensitive frequency of the human body. Furthermore, over 50% of vibrational amplitudes are greater than 2ms^{-2}, nearly three times greater than the ISO standard, which will disturb the operator's body and tilling quality.

In Table 3, most frequency peaks are larger than 600Hz, and the maximum acceleration is 8.7ms^{-2}, which is four times the ISO norm. Observed from Figure 7, Figure 8, Table 2 and Table 3, the vibrational amplitude of the electric motor is greater than the values in the armrest. Two conclusions can be drawn. Firstly, the working environment of the electric motor is unsatisfactory. Secondly, not all of the vibrational energy of the electric motor is transmitted to the armrest. Although these peaks are not within the sensitive frequency bands of the human body, additional vibration amplitudes harm the service life of the components of the mini-tiller. Therefore, to minimize the vibrational energy of the motor is the key to improving the performance of the electric mini-tiller.

CONCLUSIONS

- The structure of the electric mini-tiller is not superior because no elastic components are used in its assembly, causing vibrations to be transmitted throughout the machine. Therefore, redesigning of the structure for a new tiller rather than partly modify a conventional mini-tiller, is probably the best option.
- It is not always possible to enhance the properties of the mini-tiller through the optimization of the structure. The terrain is diverse in mountainous and hilly regions, and certain aspects of the mini-tiller are not suitable for all terrains. Designing a suspension system in the tiller could be more feasible.

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