DEVELOPMENT AND TEST OF FREQUENCY SUBSECTION REGULATION SYSTEM FOR COMBINE HARVESTER HEADER CUTTER
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联合收获机割台切割器频率分段调控方法及试验

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ABSTRACT

Aiming at the problems that the cutter frequency of combine harvester is difficult to be adjusted adaptively with the forward speed, and that the missed cut or repeated cut may cause the harvesting loss to increase and the operation effect to fluctuate greatly, the system is designed to regulate the cutter frequency of combine harvester by sections. By constructing the cutter trajectory equation, the influence of the relationship between the forward speed of the harvester and the cutting frequency on the cutting area is analysed, and the optimum cutting frequency range at different operating speeds is determined. The results show that the error between the actual cutting frequency and the desired frequency of the cutter is less than 0.8Hz, and the maximum relative error is less than 8.6%; the average steady-state adjustment time of the system is 1.3s when the input cutting frequency of the device changes abruptly. The research class provides technical support for the improvement of the combine harvester handling system and the increase of the machine automation level.

摘要

针对目前联合收获机割台切割器频率在收获过程中通常保持不变，容易产生秸秆的重割或漏割现象，造成谷物收割损失增大、作业性能不稳定等问题，设计了联合收获机割台切割器频率分段调控装置，该装置主要由信号采集及调理模块、按键模块、控制模块和显示模块等组成。对切割图进行理论分析，确定了不同动刀片刃部高度与机器作业速度条件下切割频率范围。调控装置根据实时监测的联合收获机作业速度和切割频率，运用调控算法实现切割器频率的分段调控。测试结果表明，装置调整切割频率偏差保持在±0.8Hz 以内，最大相对误差为-8.6%。在装置输入切割频率阶跃信号情况下，系统平均稳定调节时间为 1.3s；田间试验表明，使用该切割器频率分段调控装置后，未出现漏割穗现象，且短小茎秆数量明显减少，重复切割的情况得到改善。

INTRODUCTION

The cutter cuts the straw through the movement of the cutter, which is one of the main working parts of the grain combine harvester. In the process of harvester operation, the forward speed needs to be adjusted according to the grain yield, density and moisture content. However, because the traditional combine harvester generally adopts mechanical transmission, the frequency of the cutter is constant, and it is difficult to adjust it adaptively with the forward speed, resulting in a large number of missed cutting or repeated cutting, which increases the loss of grain harvesting, and the short stalks will enter the cleaning system with the cut crops, increase the cleaning load of the machine, increase the cutter wear, affect the service life of the machine (*Chaab et al., 2020; Hirai et al., 2004; Song et al., 2012; Chuan-Udom, 2010*). *Guarnieri et al.*, (*2007*), established a lumped mass mathematical model of reciprocating single blade harvester rod with crank slider mechanism, and numerically analysed the motion equation. *Kwag* and *Chung,* (*1994*), studied the basic characteristics of the torque of the cutter rod drive shaft when the traditional standard single cutter form is replaced by double cutters. The optimal cutting frequency at different forward speeds is typically made based on the cutting pattern (*Copur et al., 2017*). *Xu et al.,* (*2014*), *Chen et al.,* (*2011*) and *He*, (*2012*), tested and analysed the vibration of combine header.

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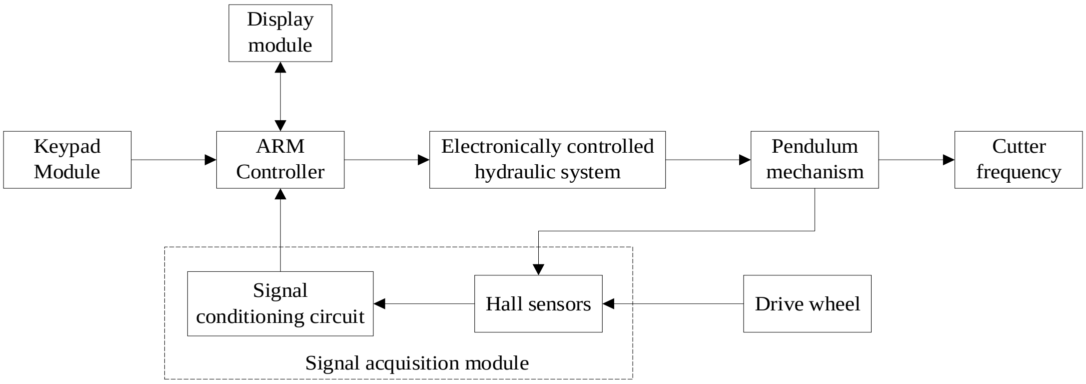
Chai (*2013*), *Xia et al.* (*2007*) and *Xiang et al.*, (*2015*), analysed the cutting diagram theoretically. *Guan et al.* (*2019*) proposed bidirectional electric drive side knife for rape combine harvester and a cutting speed adaptive control system, compared to the fixed speed cutting, header loss was reduced by 14.05% and side knife loss was reduced by 34.76% (*Copur et al., 2017*). However, there are few reports on the application of frequency control of machine cutter.

In this paper, aiming at the problem that the frequency of combine header cutter is difficult to adjust adaptively with the forward speed, the frequency segment control device of combine harvester cutter is designed. By constructing the cutter trajectory equation, the influence of the relationship between forward speed and cutting frequency on the cutting area is analysed, and the optimal cutting frequency range under different operating speeds is determined. The segmented regulation is beneficial to reduce the loss of grain harvesting, reduce the power consumption of the machine, reduce the labour load of the operator, and improve the intelligent level of the machine.

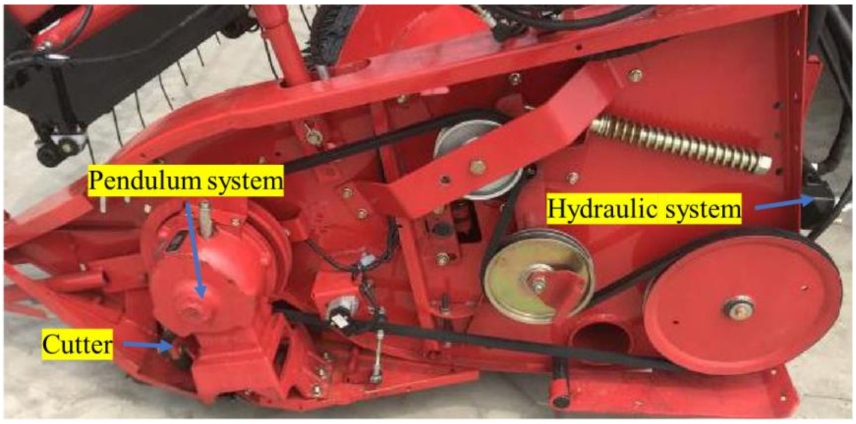
MATERIAL AND METHODS

OVERALL STRUCTURE OF CONTROL SYSTEM

As shown in Fig. 1a, the frequency segment control system of the cutter mainly includes signal acquisition and conditioning module, cutting frequency control module and cutter drive actuator (as shown in Fig. 1b). Hall sensor monitors the speed of the cutter drive swing ring and the speed of the harvester drive wheel to obtain the frequency of the cutter and the forward speed of the harvester. ARM embedded controller as the core of the control system, receives the filtered and reshaped sensor signal, calculates the frequency value and working speed of the cutter, outputs the control signal, and controls the electro-hydraulic proportional valve to adjust the cutting frequency. The composition of the cutter drive actuator is shown in Fig. 1, mainly including hydraulic system, pulley, swing ring box and cutter. The main parameters of cutter include: the stroke displacement of cutter is 76.2mm, the height of moving blade is 502mm, 542mm, and the width of bottom edge of moving knife is 76.2mm.



a. Frequency subsection regulation system



b. Cutter drive actuators

Fig. 1 - Structure of frequency subsection regulation system

CUTTING AREA ANALYSIS MODEL

The absolute motion of cutter is the combination of reciprocating cutting motion and forward motion of harvester, and its motion trajectory can be regarded as simple harmonic motion (*Guarnieri et al., 2007; Pang et al. 2019*). The cutting diagram is shown in Fig. 2. For the crop in area I, the passive blade is pushed to the edge of the adjacent fixed blade and cut.

After cutting, the stubble of the crop in area II is repeatedly touched by another cutting edge, resulting in repeated cutting. The crops in Area III are not touched when the blade moves to the right. They are only pushed by the front axle and adjacent blades. However, they cannot be cut off because they are not close to the blade edge of the fixed blade. They need to be cut off in bundles by the moving cutter when they return. Due to the large cutting resistance of bunch cutting, it is possible to break the stem and miss cutting, which will affect the harvesting effect. Therefore, the miss cutting area and re-cutting area should be minimized in the process of harvesting.

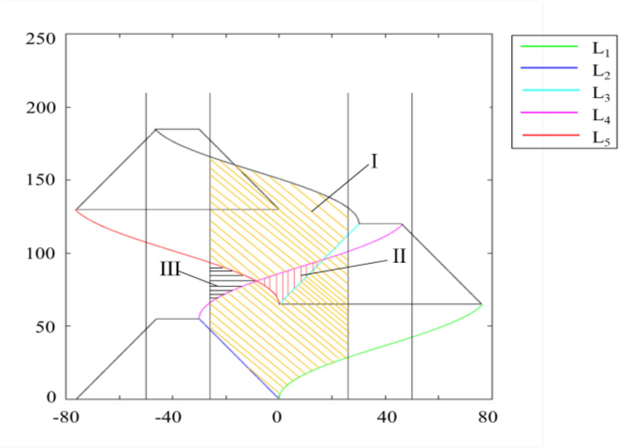


Fig. 2 - Reciprocating cutter cutting diagram

As shown in Fig. 3, the motion path of the swing ring driving mechanism is shown:

$$x = -L\sin\alpha\cos\omega t \times \frac{1}{\cos\alpha\sqrt{1+\tan^2\alpha\cos^2\omega t}} \tag{1}$$

$$L = \frac{r}{\sin\alpha} \tag{2}$$

L is the length of swing rod (mm); r - half stroke displacement of cutter (mm);
ω - angular velocity of swing ring driving shaft (rad/s); α - swing angle (°).

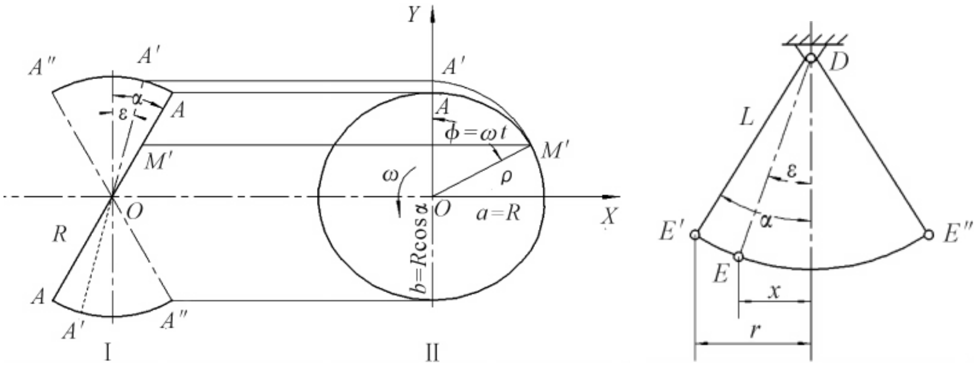


Fig. 3 - Schematic diagram of pendulum movement

According to the machine speed, the motion equation of cutter in longitudinal direction is obtained as follows:

$$y = v_m t \tag{3}$$

The curve equation of moving tool path can be obtained by combining (1), (2) and (3):

$$x = -L\sin\alpha cos\frac{\omega y}{v_m}\frac{1}{\cos\alpha\sqrt{1+\tan^2\alpha\cos^2\frac{\omega y}{v_m}}} \tag{4}$$

where:

X is the transverse displacement of cutter (mm);
y - the longitudinal displacement of cutter (mm);
v_m – the machine operation speed (mm/s).

Because the blade is translational, the motion trajectory of each point on the blade is the same. In the same coordinate system, the equation of each point of the moving blade can be obtained by translating formula (3). Similarly, the trajectory equation of the moving knife in return motion can be obtained by turning and translating formula (3).

The equations of L1, L2, L3, L4 and L5 were established:

$$\begin{aligned}
&L_1: x = -L\sin\alpha cos\frac{\omega y}{v_m}\frac{1}{\cos\alpha\sqrt{1+\tan^2\alpha\cos^2\frac{\omega y}{v_m}}} + L\sin\alpha\\
&L_2: x = -0.55y\\
&L_3: x = 0.55\left(y-H\right)\\
&L_4: x = -L\sin\alpha cos\frac{\omega\left(y-h\right)}{v_m}\frac{1}{\cos\alpha\sqrt{1+\tan^2\alpha\cos^2\frac{\omega\left(y-h\right)}{v_m}}} + L\sin\alpha - \frac{a-b}{2}\\
&L_5: x = L\sin\alpha cos\frac{\omega\left(y-H\right)}{v_m}\frac{1}{\cos\alpha\sqrt{1+\tan^2\alpha\cos^2\frac{\omega\left(y-H\right)}{v_m}}} - L\sin\alpha
\end{aligned} \tag{5}$$

where*:*

h - the height of moving blade (mm);
a - the width of the moving edge (mm);
b – the front axle width of moving cutter (mm);
H - the cutter advance (mm).

Cutter advance refers to the forward distance of the machine within the time of cutter completing one stroke. The calculation formula is as follows:

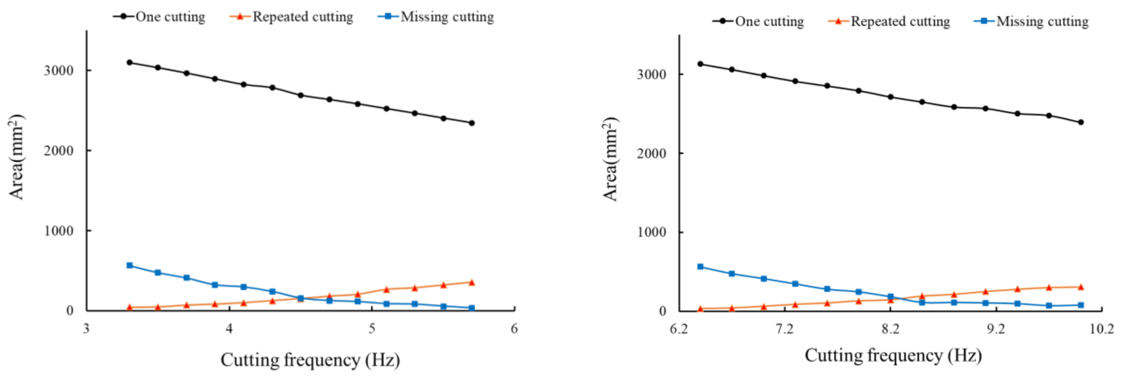
$$H = v_m\frac{\pi}{\omega} \tag{6}$$

ANALYSIS OF INFLUENCING FACTORS OF CUTTING AREA

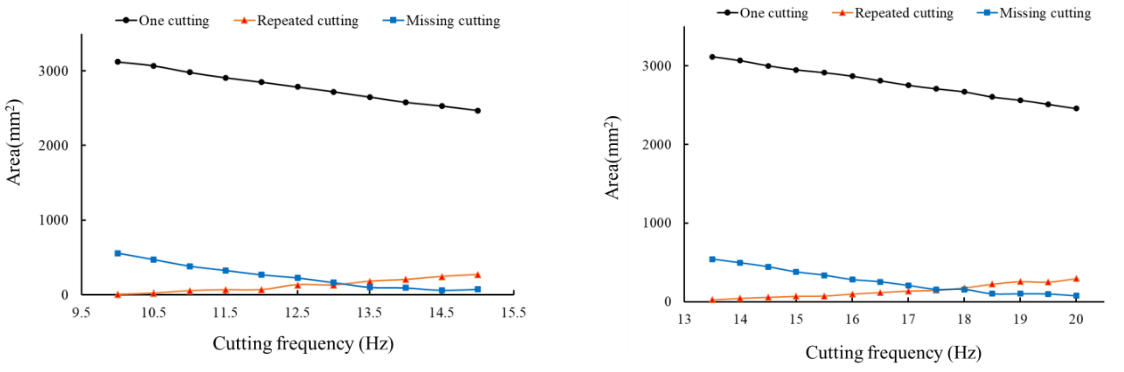
According to the cutter motion trajectory modelling, the parameters that affect the area of the three areas in the cutting diagram are machine operation speed, angular velocity of swing ring driving shaft, moving blade height, swing ring angle, swing rod length, bottom edge width and front axle width. The swing rod length can be calculated by cutter travel displacement and swing ring angle. According to the national standard of reciprocating cutter and cutter parameters, the range of parameters is determined. The displacement of cutter stroke is 76.2mm, the height of moving blade is 50.2mm and 54.2mm, the width of moving blade bottom is 76.2mm, and the inclination angle of swing ring is generally 15°~16°. In this paper, the angle of inclination is 10°, 15° and 20°. The results were analysed. In the above parameters, in order to facilitate the subsequent expression, the angular velocity of the swing ring driving shaft is converted into the cutting frequency value in the program, and because the width of the bottom edge of the moving blade and the width of the front axle of the moving blade have no significant influence on the cutting area, this paper mainly analyses the influence of the machine operation speed, the cutter frequency and the swing ring inclination angle on the cutting area.

In order to further analyse the influence of the relationship between harvester forward speed V and cutting frequency h on each cutting area, numerical simulation analysis was carried out. Figure 4 shows the relationship between the cutting frequency and the area of each cutting area under different forward speeds.

According to the figure, the area of each cutting area changes significantly with the cutting speed and cutting frequency. The area of re-cutting area increases with the increase of cutter frequency, the area of missed cutting area decreases with the increase of cutter frequency, and the area of primary cutting area also decreases. In order to get a suitable range of cutter frequency at a certain machine speed, the relationship between the areas of these three characteristic areas should be comprehensively considered: (1) The area of missed cutting area should be as small as possible; (2) Under the same parameters, the area of primary cutting area should be as large as possible; (3) In order to maintain the cutting quality of the cutter, the area of the missed cutting area should be smaller than that of the re-cutting area.



v=0.5 m/s *v=1 m/s*



v=1.5 m/s *v=2 m/s*

Fig. 4 - The curve of the area of each area of the cutting graph with the cutting frequency under different machine operating speeds

Under the condition of the same cutting area s, the comprehensive evaluation formula is designed according to the above conditions:

$$\begin{cases} B = \dfrac{S_2 + S_3}{S_1} \\ S_2 > S_3 \end{cases} \tag{7}$$

where: S_1 - area of primary cutting area (mm);
S_2 - re cutting area (mm);
S_3 - area of missed cutting area (mm).

According to the area data of each area in the cutting map and the above evaluation formula, when the crop density is basically the same and there is no lodging, when the working speed is 0.5 m/s, the frequency of the cutter is 4.3~5.0 Hz. Similarly, when the operating speed is 1.0 m/s, it is 8.8~9.5 Hz; when the operating speed is 1.5 m/s, it is 13.3~14.2 Hz; when the operating speed is 2.0 m/s, it is 17.8~18.8 Hz.

Because the frequency of the combine doesn't need to change in real time with the change of the working speed of the machine, and the cutting operation is required to be fast and efficient, this paper adjusts the cutting frequency according to the working speed of the machine. When the working speed of the machine is 0~1.0 m/s, the cutting frequency is 8.5~9.2Hz. When the working speed of the machine is 1.0~1.5m/s, the cutting frequency is 13.0~13.9Hz. When the working speed of the machine is 1.5~2.0 m/s, the cutting frequency is 17.5~18.5Hz. When the working speed of the machine is greater than 2.0m/s, the cutting frequency value is 18.8~23.7Hz, of which 23.7Hz is the maximum cutting frequency value provided by the combine harvester.

When the machine is working, due to the different density of crops in the field, the frequency value of the cutter can be adjusted. When the grain density is large, in order to reduce the number of missed cut grains, the frequency of the cutter should be increased appropriately to reduce the area of the blank area; When the grain density is small, in order to reduce the area of re-cutting area and the cutting power consumption of the machine, the frequency value of the cutter can be appropriately reduced. The cutting frequency range under different working speeds is shown in Table 1.

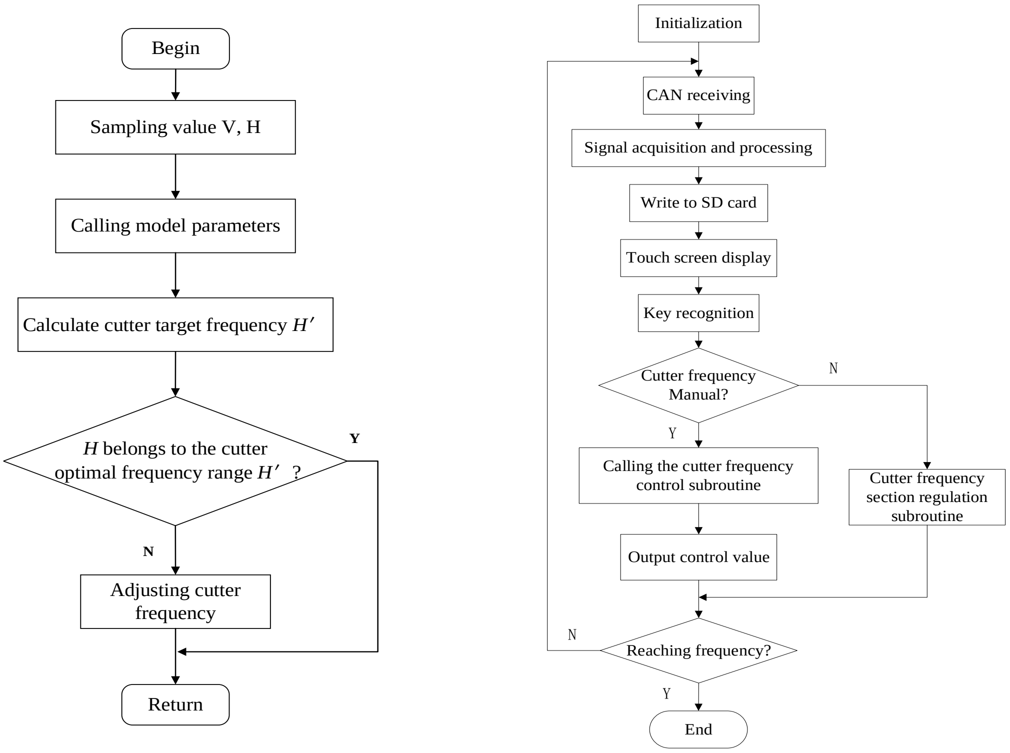
Table 1

Frequency range of cutter under certain operating speed

Machine operating speed (m/s)	**Cutter frequency (Hz)**
0~1.0	8.0~8.5
1.0~1.5	12.2~13.0
1.5~2.0	16.4~17.0
>2.0	17.3~23.7

DESIGN OF SEGMENTED FREQUENCY CONTROL ALGORITHM FOR CUTTER

The segmented regulation process of cutter frequency is shown in Fig. 5a. The optimal cutting frequency of the cutter is obtained by harvesting forward speed. The actual value of current cutter frequency is compared and adjusted. The flow chart of control program is shown in Fig. 5b.



a. Flow chart of frequency regulation of cutter

b. Flow chart of main program of cutter frequency segmentation control device

Fig. 5 - System programming

After the system started and initialized, the basic data of the harvester is obtained from the CAN bus. The working speed is indirectly obtained by measuring the speed of the driving wheel. The speed of the swing ring spindle is collected by the speed sensor, and processed by filtering and shaping. Then the signal is input into the arm controller to calculate the current speed of the swing ring mechanism spindle and the speed of the driving wheel. It is converted into the actual cutter frequency and operation speed, written into the SD card and displayed on the touch screen. The manual and automatic mode can be switched by key recognition. In the automatic mode, the frequency subsection control subroutine of the cutter is called, and the cutting frequency control value is calculated according to the input value of the control algorithm. By outputting PWM control signal, the electro-hydraulic proportional valve is controlled, and then the speed of the hydraulic motor is controlled to realize the frequency subsection control of the cutter. When the automatic mode program of the control device is wrong or manual operation is necessary, the device can be in manual control mode by manual automatic switching module to realize the manual intervention of the cutting frequency of the cutter.

RESULTS

TEST AND ANALYSIS

As shown in Fig. 6, the actual object of the segmented frequency control system of the cutter is integrated into GK100 wheel type full feeding combine to carry out field test.

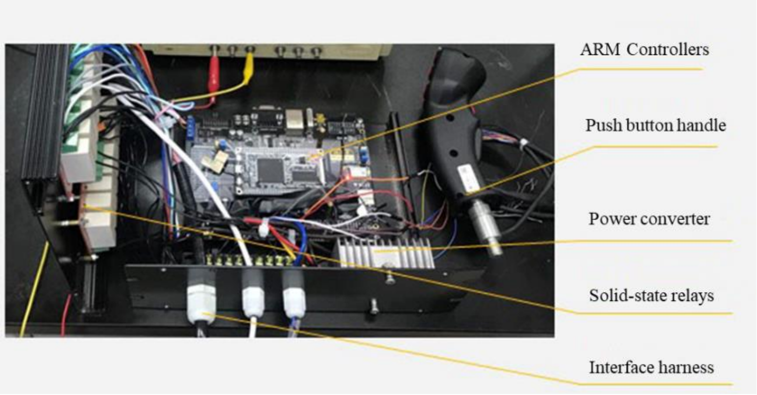


Fig. 6 - Hardware diagram of the control device

The frequency control value of cutter is sent to the controller by computer and the target value is taken as the target value, and the data displayed on the display screen is taken as the measurement value. Use stopwatch to record the time required for the cutter frequency to change from the beginning to the relative stability, which is used as the system adjustment time data, and record the relevant data. The cutting frequency control accuracy and adjustment time test data are shown in Table 2.

Table 2

Control accuracy and adjustment time test data table

Serial number	Target value (Hz)	Measurements (Hz)	Relative error (%)	Adjust the time (s)
1	3.8	3.5	-8.6	1.2
2	5.2	5.6	7.1	1.4
3	6.4	6.7	4.5	1.1
4	8.1	8.6	5.8	1.5
5	11.2	10.7	-4.7	1.2
6	14.9	14.1	-5.7	1.2

According to table 2, the deviation of cutting frequency of device adjustment is kept within ±0.8Hz, and the maximum relative error is -8.6%. Due to the nonlinearity of hydraulic system, there is error in data fitting between the speed of hydraulic motor and input signal of electro-hydraulic proportional valve, which may be the main reason for the change of relative error. When the cutting frequency step signal is input, the average stable adjustment time of the system is about 1.3s, which meets the design requirements.

In November 2019, the frequency segment control device of cutter was installed on GK100 wheel type full feeding combine harvester, and the field test of device installation was carried out in Changyinsha farm, Zhangjiagang City, Jiangsu Province. The harvested rice variety was "Changyou 998", with natural height of 120 cm, ear length of 19.6 cm and yield of 716kg / 667m^2.

Taking the harvester to maintain a relatively stable speed through the 20 meters calibration area as a group of test samples, 10 groups were set up in the test, of which the first four groups did not turn on the frequency segment control system of the cutter as a comparative test, and the last six groups turned on the control system as a functional verification test. In this paper, the control effect test of the cutter is based on whether there are missing ears and the number of short stalks in a certain range of the ground after harvest.

In the field function test, because of the high grain density in the field, the grain density level is set to 1. The basic parameters are set in the arm controller program in advance, and then the harvester passes through the 20 meters calibration area at different operating speeds. The time of each passing through the calibration area is recorded with a stopwatch, and the average operating speed is calculated as the test data. The cutting frequency data is obtained from the SD card of the control device. Five data are randomly selected, and the average value is taken as the test data of the cutting frequency. The materials produced by the cleaning system of the harvester are manually caught with oilcloth to keep the ground in the state after cutting by the cutter, which is convenient for counting the number of short stalks and missing grains. 30 cm in each group × The number of short stalks in the 30cm box was counted for 5 times, and the average value was taken as the test data, as shown in Figure 7. In the process of 10 groups of tests, there was no phenomenon of missing cut grain, so the missing cut grain data was not shown in the test data table. The comparison test data is shown in Table 3, and the function verification test data is shown in Table 4.

a. Field test site *b. Stem quantity statistics*

Fig. 7 - Control effect test

Table 3

Comparison test data table

Serial number	Average operating speed (m/s)	Cutting frequency value (Hz)	Number of short stalks
1	0.4	14.7	28
2	0.67	15.1	23
3	0.81	15.0	20
4	1.06	14.7	17

Table 4

Functional verification test data table

Serial number	Average operating speed (m/s)	Cutting frequency range (Hz)	Number of short stalks
1	0.54	8.0~8.5	13
2	0.71	8.0~8.5	9
3	0.87	8.0~8.5	6
4	0.91	8.0~8.5	7
5	1.02	12.2~13.0	12
6	1.10	12.2~13.0	10

It can be seen from table 2 and table 3 that when the frequency segmented control system of the cutter is not turned on, the machine harvests at a higher cutting frequency, the number of short stalks is at a higher value, and the re-cutting phenomenon is serious, resulting in a waste of cutting power. With the increase of machine operation speed, the number of short stalks shows a downward trend, which is in line with the theoretical analysis. After turning on the segmented control system of cutting frequency, the number of short stalks decreased significantly under the condition of approximate working speed, and there was no phenomenon of missing cutting rice ears in the process of harvesting, which indicated that the segmented control system of cutting frequency of the cutter had significantly improved the cutting effect.

CONCLUSIONS

(1) In view of the problems of inconvenient control and poor cutting effect, the paper compiles the analysis program of reciprocating cutter working characteristics based on MATLAB, analyses the factors affecting the area of cutting drawing, determines the cutting frequency and machine working speed as the main influencing factors. The range of cutting frequency under different machine operating speed conditions is determined by using comprehensive evaluation formula. The frequency segment control algorithm of the cutter is designed to realize the segmented control of the frequency of the cutter.

(2) The test results show that the adjustment cutting frequency deviation of the control device is kept within 0.8 Hz, and the maximum relative error is -8.6%. Under the condition of input cutting frequency step signal, the average stable adjustment time of the system is about 1.3s.

(3) After the frequency segment control system of cutter is opened, the number of short and small stalks decreases obviously under the condition of approximate operating speed, and there is no leakage in the process of harvesting. There cutting and missing cutting are improved during the cutting process.

When the machine type and harvested grain are changed, the number of short stalks and missing panicles may be changed, but the number of short stalks and missing panicles will be reduced and the cutting effect will be improved compared with that when the frequency segment control device of the cutter is not turned on. More comparative experiments are needed to analyse the specific situation.

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