Design and test of two-wheeled walking hemp harvester

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Abstract: Aiming at the planting characteristics of hemp in southern hilly regions, a two-wheeled walking hemp harvester suitable for harvesting hemp in southern hilly regions is studied and designed. The harvester mainly consists of a header frame, single-moving cutter, cutter mechanical transmission, stalk lifter and reel, stalk divider, stalk horizontal conveyor, wheeled chassis, motor, gearbox, etc. To improve the cutting performance of the two-wheeled walking hemp harvester, response surface tests of three levels are conducted for three factors influencing the operation quality, including the cutting speed, blade length, and forward speed, on the constructed hemp cutting test bench. Moreover, test results are analyzed with the response surface method, and multi-objective optimization is carried out for the regression mathematical model with Design-Expert software. Results show that when the cutting speed is 1.2 m/s, the blade length is 120 mm, forward speed is 0.6 m/s, the cutting efficiency is 38.92 stalks/s, the cutting power is 776.37 W and the failure rate is 6.24%. Trial production of sample machine and field trial are finished according to the optimized parameters and structural design scheme, and the test results reveal that the cutting rate can reach 92.5%, the rate of transmission can reach 86.7%, the productivity is 0.18 hm^2/h, and all performance indexes can meet the design requirements. This research can provide references for resolving the mechanical harvesting of hemp.

Keywords: hemp, harvester, structural design, parameter optimization, productivity
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1 Introduction

Currently, there are more than 30 countries across the world planting hemp, mainly in Asia, Europe and North America. China is one of the largest hemp planting countries in the world[1], and hemp is mainly planted in Yunnan, Guizhou, Heilongjiang, Liaoning, Anhui and Shandong. In recent years, the planting area of hemp in China increases by years. According to the national industrial development planning, the domestic planting area of hemp is estimated to be 667 000 hm^2 by 2020, and about one million tons of hemp fiber and five million tons of wood pulp[2] would be produced per year on average. But, the difficulty of mechanical harvest has always been seriously restricting the fast development of the hemp industry, mainly because of the wide plantation of hemp in China, considerable proportion of hilly areas, small square fields for small-scale farming, complex landform, and particularity of geographic position, which are unfavorable for the moving of harvesting machinery. Furthermore, the hemp has many particular characteristics, like long and flexible bast fiber, stalks of uneven thickness and length, which may wear and tear the cutter, and winds round the cutter or block the cutter.

Regarding large hemp harvester, Europe shows a high mechanized harvesting level, while Russia and the Czech Republic have studied the hemp harvester and developed large hemp harvester[3-6], but it is quite expensive and unsuitable for the planting mode in China's hilly areas, and it is difficult to be widely promoted in China.

The hemp harvester developed by Nanjing Research Institute for Agricultural Mechanization Ministry of Agriculture and Rural Affairs and Jiamusi Donghua Harvest Machinery Manufacturing Co.; Ltd. can meet some of the requirements on the harvesting of hemp in flat area[7,8]. There is no small hemp harvester, and only high-stalk crop harvesters, like swather, reed harvester and small binder, are applied for the harvest[9-12]. As a result, the harvesting technology lags behind, and it has various problems, such as miss cutting, low efficiency, poor cutting quality, etc. hardly satisfying the actual demands of hemp farmers.

Therefore, this paper launches the study and development of small hemp harvester duly by combining the present planting state of hemp in China, based on the digestion and assimilation of domestic and foreign advanced technology of hemp harvester. The improvement of harvesting efficiency and reduction of labor costs is of great realistic significance for the development of the hemp industry. Small hemp harvester is characterized by a compact structure, flexible operation, transfer convenience, low price, etc. thus being able to adapt to the small-farmer and

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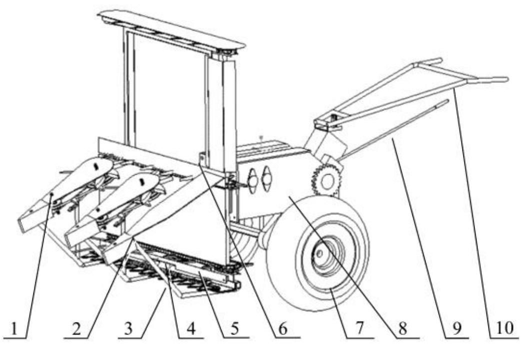
widely-distributed hemp planting mode, and conform to the demands of era development and the market.

2 Overall structure and working principles

2.1 Overall structure and main technical indexes

Aiming at the hemp planting mode in southern hilly regions and meeting the design principles of harvester, a small (two-wheeled walking) hemp harvester is studied and designed. It mainly consists of a header frame, single-moving cutter, cutter mechanical transmission, stalk lifter and reel, stalk divider, stalk horizontal conveyor, wheeled chassis, motor, gearbox, etc. It controls the steady walking and diversion of the harvester through the hand rod at the end of the machine, installs the control rod on the gearbox to regulate the forward and backward speed of the harvester. The overall structure is shown in Figure 1, while the main performance indexes and technical parameters are shown in Table 1.



1. Stalk lifter and reel 2. Stalk divider 3. Reciprocating single moving-knife cutter 4. Cutter mechanical transmission 5. Stalk horizontal conveyor 6. Header frame 7. Wheeled chassis 8. Gearbox 9. Control rod 10. Hand rod

Figure 1 Schematic diagram of entire design

Table 1 Main performance indexes and technical parameters

Parameters	Value
Overall dimension/mm	1900×1200×1200
Matched power/kw	4.0
Cutting width/mm	1000
Operating speed/m s^{-1}	0.4-0.8
Work efficiency/hm^2 h^{-1}	0.14-0.28
Total weight/kg	150

2.2 Working principles

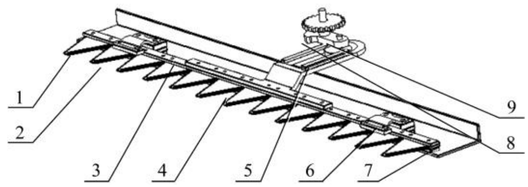
During the field operation, the power is from the gasoline engine, which is transmitted to the single-moving cutter, stalk horizontal conveyor and walking device through the drive system, to drive all working devices to finish the harvesting of hemp. Stalk divider will divide the hemp to be cut and lead it to the header while the harvester moves forward; the rotation of the stalk lifter and reel star wheel forces the stalk to be cut straightly into the cutter; the cutter mechanical transmission will drive the knife on the reciprocating single moving-knife cutter to take reciprocating motion, and cut off the stalk in the cutter horizontally; in the stalk horizontal conveyor, after the conveyor chain with finger-type teeth conveys the cut stalk to one side of the harvester and the stalk arrives the stalk discharge mouth, the stalk will be paved under the action of gravity and inertia force, and that’s the entire process of stalk divide, stalk lift, cutting, conveying and paving. According to the specific planting density, the forward speed of the harvester can be controlled by the control rod, and according to the cutting height, it can meet the cutting requirement by controlling the header height through the hand rod.

3 Design of key parts

3.1 Reciprocating single moving-knife cutter

Cutter is an important part of the hemp harvester, and its structure and performance will directly influence the stalk harvesting quality and working efficiency. The design of the cutter shall meet various technical requirements, like simple structure, strong adaptability, neat cutting, no miss cutting, low power consumption and little vibration[13,14].

At present, there are mainly three types of cutter. One is the reciprocating cutter, whose cutter will make reciprocating movement, and it can be further divided as reciprocating single moving-knife cutter and reciprocating double moving knife cutter according to the number of moving knives. Second, the disc cutter, which makes rotational motion, featuring steady operation and little vibration, but the knife has a short life span; third, the flail cutter, whose knife will rotate within the plane parallel to the forward direction, and it displays a strong cutting power, suitable for the high-speed operation[15]. Considering the hemp planting mode and material characteristics in southern hilly regions, and meeting the design requirements of a simple and compact structure, reciprocating single knife cutter is employed. The reciprocating single moving knife cutter mainly cuts off the hemp stalk horizontally, and it is mainly composed by the cutter bar, moving knife, fixed knife, knife pressure device, cutter bar base and crank Shute, etc. as shown in Figure 2; the knife and cutter bar are riveted, while the knife pressure device is fixed to the cutter bar by bolts, since it can prevent the life of cutter during operation or large gap. The moving knife is connected to the upper cutter bar, and the crank chute is fixed to the middle of the cutter bar through riveting, so that the crank chute and crank can cooperate in the transmission, and drive the reciprocating movement of the upper cutter bar. A clump weight is installed in the symmetrical direction of the slider, to balance the inertia force during the operation of the cutter, and reduce the vibration of the cutter and frame.



1. Moving knife 2. Fixed knife 3. Upper cutter bar 4. Lower cutter bar 5. Crank chute 6. Knife pressure device 7. Cutter bar base 8. Clump weight 9. Crank

Figure 2 Schematic diagram of reciprocating cutter

3.1.1 Knife clamping condition

This cutting device adopts the moving knife and fixed knife which are of the same shape, and structural parameters of the knife have great impacts on the reliability and power of the cutting device[16]. When deciding the width of knife, the cutting angle α is an important factor deciding the length of knife and impacting the clamping stability and cutting resistance. Research shows that the increase of cutting angle may reduce the cutting resistance, but the too large cutting angle would influence the clamping stability. Therefore, it mainly discusses the cutting angle on condition that the knife clamps the stalk. When the knife clamps the stalk, the stress analysis is shown in Figure 3.

At the contact points A and B of the knife and stalk, there is positive pressure N_1 and N_2 and force of friction F_1 and F_2. The cutting angle of the knife is α, and the resultant force of the positive pressure and force of friction is indicated by R_1 and R_2. The condition in which the knife clamps the stalk is: the resultant force acting on the two contact points, namely R_1 and R_2 are in a straight line.

$$\tan\varphi = \frac{F}{N} \quad (1)$$

which, φ is the frictional angle between knife and stalk, (°).

In ΔOAB,

$$\theta + 2\varphi = \pi \quad (2)$$

In quadrangle $OACB$, $\angle OAC = \angle OBC = \pi/2$

Namely $$\theta + 2\alpha = \pi \quad (3)$$

which, α is the cutting angle of the knife, (°).

By combining the above two equations,

$$\alpha = \varphi \quad (4)$$

To sum up, the clamping condition of stalk is:

$$\alpha \le \varphi \quad (5)$$

Namely, the cutting angle of the knife is smaller than the frictional angle of the stock. When the knife length is 120 mm and the cutting angle α is 23°, the tested frictional angle between the carbon steel and stalk is 29°. Therefore, the selected knife meets the clamping condition.

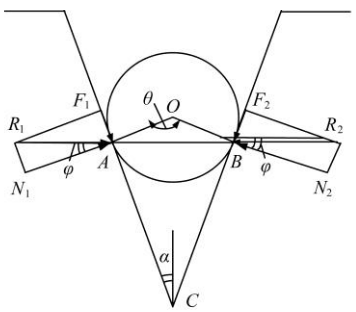
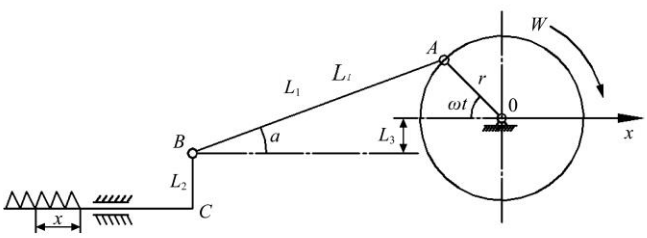


Figure 3 Force analysis of clamped stalk

3.1.2 Motion analysis of the cutting knife

To make the cutting knife do reciprocating motion, all kinds of transmission mechanisms can be adopted, which mainly consists of three types according to the working principle: crank pitman mechanism, suspending loop mechanism and planetary gear mechanism. According to the design requirements of compact structure and high transmission efficiency of the two-wheeled walking hemp harvester, crank pitman transmission mechanism is adopted, as shown in Figure 4.



Note: x is the cutter displacement; L_1 is the pitman length; ωt is the crank rotation angle

Figure 4 Crank pitman mechanism

With the crank center O as the original point, the vector equation of point C on the cutting knife can be obtained according to Figure 4:

$$\vec{OA} + \vec{AB} + \vec{BC} = \vec{OC}$$

$$\begin{cases} x_c = r\cos\omega t + L_1\cos a \\ y_c = L_2 + L_3 = L_2 + L_1\sin a - r\sin\omega t \end{cases} \quad (6)$$

By taking the derivative of the time according to Equation (6), the speed of the cutting knife can be worked out:

$$\begin{cases} v_{x_c} = \dfrac{dx_c}{d_t} = -r\omega\sin\omega t - L_1\sin a \\ v_{y_c} = \dfrac{dy_c}{d_t} = L_1\cos a - r\omega\cos\omega t = 0 \end{cases} \quad (7)$$

By taking the derivative of the time according to equation (7), the accelerated speed of the cutting knife can be obtained:

$$a_{x_c} = \frac{dv_{x_c}}{d_t} = -r\omega^2\cos\omega t - L_1\cos a \quad (8)$$

which, x_c is the cutter displacement, mm; v_{x_c} is the cutter speed, mm/s; a_{x_c} is the accelerated speed of the cutter, mm/s^2; r is the crank radius, mm; ω is the angular speed of crank, rad/s; t is the motion duration, s; L_1 is the pitman length, mm; a is the pitman rotation angle, (°); L_2 is the length of pitman arm, mm.

3.1.3 Relationship between the cutting speed and forward speed

During the harvesting process, the motion trial of the cutter is composed of the reciprocating motion and linear motion of the harvester at a constant speed. The feed pitch is the forward distance of the harvester during the period when the cutter finishes a stroke (the crank rotates in half a circle), and it can be used to indicate the relationship between the cutting speed and forward speed.

$$H = v_m\frac{\pi}{\omega} = \frac{30v_m}{n} \quad (9)$$

which, v_m is the forward speed of the machine, m/s; ω is the angular speed of crank, rad/s; n is the rotational speed of crank, r/min.

The motion trail equation of the cutting knife is:

$$\begin{cases} x = v_m t \\ y = r\cos\omega t \end{cases} \quad (10)$$

By removing t, and then:

$$y = r\cos(\omega x / v_m) = r\cos(\pi x / H) \quad (11)$$

Cutting pattern of the cutter, as shown in Figure 5. When the cutter finishes a stroke from left to right, the machine will move forward by a feed pitch. Cutting areas covered by the right edge of the cutter include *A*, *B*, *C* and *D*. And then, the cutter continues to finish a stroke from right to left, and the machine will move forward by a feed pitch again. Cutting areas covered by the left edge of the cutter include *E*, *F*, *G* and *H*. Cutting areas between knives consist of three areas, namely the primary cutting area, re-cutting area and blank area. According to the analysis, if the re-cutting area is too large, the re-cutting would lead to the waste of power; if the blank area is too large, some stalks may be pushed over and lead to the miss cutting. Therefore, the two areas should be reduced as much as possible to improve the cutting performance. It can be seen from the cutting pattern that when the feed pitch increases, the blank area will increase, while the re-cutting area will decrease, or vice versa[17,18].

The cutter does reciprocating motion driven by the crank block mechanism. The speed is a sine function of time. In normal conditions, the average speed of the cutter is regarded as the cutting speed, and the average speed is[19]:

$$v_p = \frac{ns}{30} = \frac{nr}{15} \quad (12)$$

which, n is the rotational speed of crank, r/min; s is the knife stroke, m; r is the crank radius, m.

According to the planting mode and density of hemp, the initial forward speed of the cutter is 0.4-0.8 m/s, to reduce the miss cutting and power waste, the cutting speed is 1.0-1.4 m/s, and the crank rotational speed is 394-551 r/min.

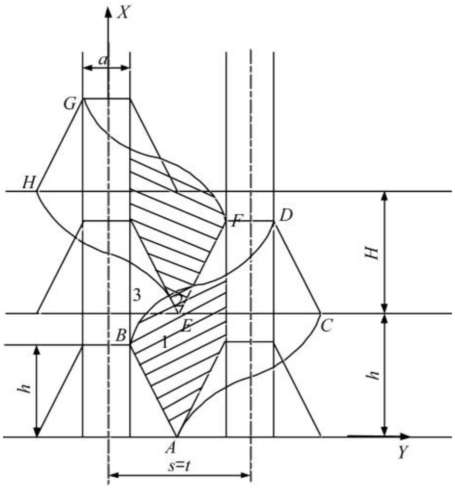
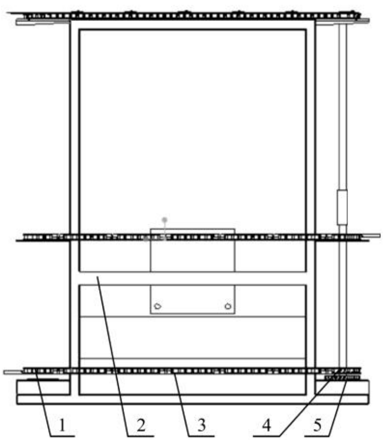


Figure 5 Cutting pattern of the cutter

3.2 Stalk horizontal conveyor

Stalk horizontal conveyor is an important part of the cutter, which can convey and pave the stalks of hemp steadily and smoothly to one side of the cutter, and prevent the stalks from tilting, overturning and blocking during the conveying process.

Stalk horizontal conveyor consists of the header frame, upper, middle and lower conveyor chain with finger-type teeth, active sprocket, driven sprocket and drive sprocket, as shown in Figure 6. The upper and middle driven and active sprockets are installed on the sprocket base of the mounting plate. The mounting plate is welded on the frame, while the driven sprocket and sprocket of the cutter gearing mainly transmit the power through the chain drive. The active sprocket rotates to implement the synchronous rotation of three active sprockets.



1. Driven sprocket 2. Header frame 3. Conveyor chain with finger-type teeth 4. Active sprocket 5. Driven sprocket

Figure 6 Schematic diagram of the stalk horizontal conveyor

3.2.2 Horizontal conveying condition

The cut stalks of hemp enter the stalk horizontal conveyor driven by the star wheel in reel, and are transmitted horizontally by the conveyor chain with finger-type teeth. Meanwhile, it needs to analyze the conveying condition to prevent the overturn of stalks during the conveying process. The force of stalks in the conveying process is shown in Figure 7, and the condition of horizontal conveying is:

$$F_1+F_2+F_3 \geq f_1+f_2+f_3+f_4 \tag{13}$$

which, F_1, F_2, F_3 are the acting forces of reel on the stalk; f_1 is the frictional resistance between the cutter and the stalk; f_2 is the frictional resistance between the lower damper and the stalk; f_3 is the frictional resistance between the upper damper and the stalk; f_4 is the implication force between stalks.

To finish the conveying smoothly and prevent the overturn of stalks, the sum of moment within the plane of action is zero, with C as the central point.

$$\begin{cases} \sum M_1 = F_1\times l_1 + F_2\times l_3 + F_3\times l_5 - f_2\times l_2 - (f_3+f_4)\times l_4 = 0 \\ \sum M_2 = (P_2-P_1)\times l_4 + (P_4-P_3)\times l_2 = 0 \end{cases} \tag{14}$$

which, P_1 is the extrusion force of stalks; P_2 is the braced force of the upper damper; P_3 is the pressure of compressed spring on the stalk; P_4 is the braced force of the lower damper; l_1, l_2, l_3, l_4, l_5 are the vertical dimension from the points of action F_1, f_2, F_2, f_2f_3, F_3 to the cutter.

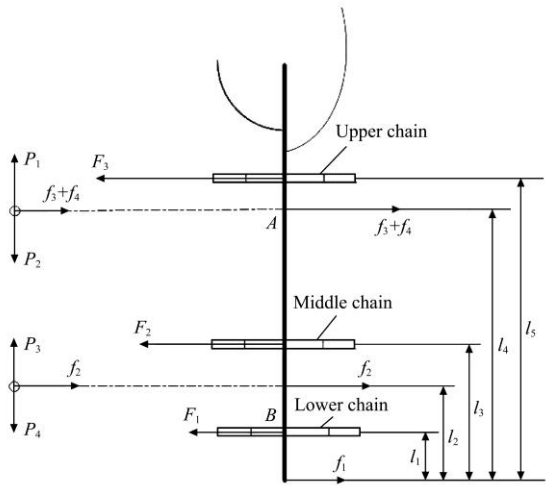


Figure 7 Force analysis of stalk on the conveying chain

It is tested that the height of hemp stalks is about 3000-5000 mm, and the height of the lower branch is 3450 mm. According to the previous design experience and the handbook[20], it is preliminarily determined that the lower conveying chain is about 70 mm from the cutter, the middle conveying chain is about 400 mm from the lower conveying chain, the upper conveying chain is about 630 mm from the middle conveying chain, and the total height of the header is 1200 mm.

3.2.2 Relationship between the conveying speed and forward speed

The cut stalks enter the stalk horizontal conveyor in upright state due to the action of the compressed spring, star wheel in reel, and conveying chain. During the conveying process, stalks may be piled and cause blocking, so the conveying speed shall match the forward speed. In the stalk horizontal conveyer, the adjacent finger-type teeth, conveying chain and star wheel in reel form the conveying space, as shown in Figure 8. The conveying space mainly contains the cut stalks and conveys them, represented by S_0, which can be worked out approximately according to the geometrical relationship[21]:

$$S_0 = \left\{ b + d\sin\left[\tau - \arcsin\left(\frac{d\sin\tau}{D}\right)\right]\right\}\cdot\frac{(D+d)}{4} + l_c\cdot b \tag{15}$$

which, b is the gap between fingers; d is the inner diameter of the star wheel in reel; τ is the included angle between the tangent line of the external gear and radial direction; D is the outer diameter of the external gear of the star wheel in reel; l_c is the finger length.

The quantity of stalks conveyed by the stalk horizontal conveyor is related to the conveying speed, and gap of fingers[22,25]. The total area of stalks conveyed consists of several conveying spaces. Suppose the accumulation density of stalks inside the conveying space is even, the quantity of stalks conveyed in t period is:

$$Q_1 = k_1 S_0 \frac{V_s t}{b} \tag{16}$$

which, Q_1 is the quantity of stalks for conveying; k_1 is the density of accumulation in the conveying space; b is the gap between fingers.

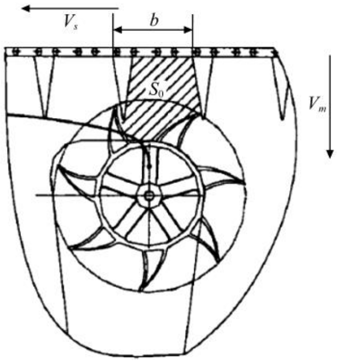


Figure 8 Schematic diagram of conveying space

The quantity of cut stalks is related to the cutting width, forward speed and planting density. Suppose the stalk planting density is even, the quantity of cut stalks in t period shall be:

$$Q_2 = k_2 B V_m t \tag{17}$$

which, Q_2 is the quantity of cut stalks; k_2 is the planting density; B is the cutting width.

To guarantee the smooth conveying of stalks, the quantity of stalks conveyed should be greater than the quantity of cut stalks in order to prevent blocking, namely:

$$Q_1 > Q_2 \tag{18}$$

Then, the conveying speed and forward speed shall meet the following conditions:

$$\frac{V_s}{V_m} > \frac{k_2 B b}{k_1 S_0} \tag{19}$$

According to the equation, the ratio between the conveying speed and forward speed is related to cutting width, gap between fingers, conveying space, planting density and accumulation density, etc. The accumulation density stands for the filling of conveying space by stalks, and it is related to the planting density and stalk size. When the actually designed cutting width is 1000 mm, the gap between fingers is 167 mm, the preliminarily determined speed ratio is V_s/V_m>1.5, and the forward speed is 0.4-0.8 m/s, the conveying speed is 0.6-1.2 m/s, and the stalk horizontal conveyor can meet the conveying requirements.

3.2.3 Structural analysis of the header frame

To learn whether the header frame of two-wheeled walking hemp harvester meets the design requirements, ANSYS Workbench is applied to carry out the static analysis and modal analysis of the header frame.

The frame material is Q235, the elasticity modulus is 2.1×10^5 MPa, the Poisson's ratio is 0.3, the density is 7.85×10^{-9} kg/mm^3, and the yield strength is 235 MPa. The posterior connecting plate of the frame is fixed onto the harvester through bolts, and fixed constraint is exerted on the connecting plate. The mounting plate of the driven sprocket bears the gravity of the sprocket, about 20 N, while the mounting plate of the active sprocket bears the gravity of the sprocket, about 20 N. The middle mounting plate bears the total gravity of the sprocket and transmission shaft, about 40 N. The lower mounting plate bears the gravity of two sprockets and transmission shaft, about 60 N. The area of the bearing part is the surface area of the sprocket base. The square pipe below the frame is connected to the stalk divider and reel, stalk lifter through bolts, which would generate a clockwise torque. The torque is 36 N·m, 36 N·m and 12 N·m respectively. The bevel gear box is connected to the T-shaped plate through bolts, and generates a clockwise torque on the T-shaped plate, about 22 N·m. The frame constraint and load are shown in Figure 9.

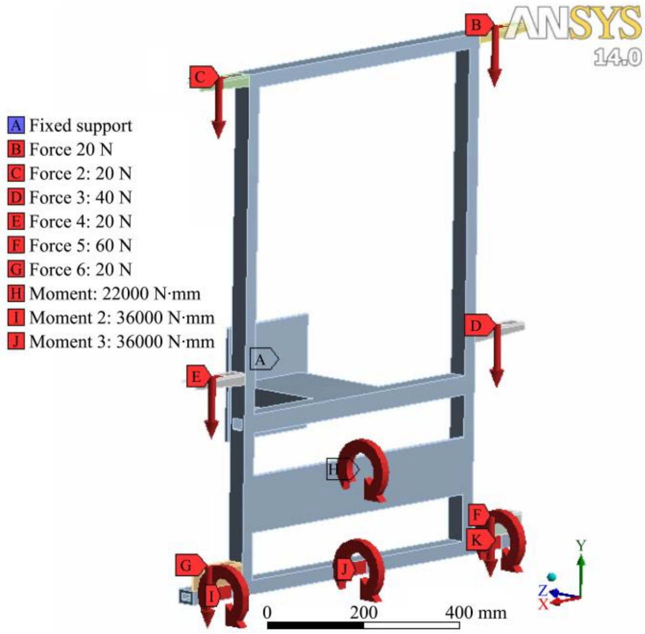


Figure 9 Frame constraint and load diagram

Stress nephogram and displacement nephogram of the frame are shown in Figures 10 and 11. According to the stress nephogram, the stress value of the frame is low, and the area with great stress value locates on T-shaped plate. The load of bevel gear box concentrates in this area, and the stress in other areas is smaller than 6 MPa. The greatest stress occurs on the mounting plate of the active sprocket, about 55 MPa. The mass of sprocket and transmission shaft generate concentrated load here, and the greatest stress is smaller than the allowable stress of the constructional steel, suggesting that the frame meets the strength requirement. According to the displacement nephogram, the deflection of frame is small, and the maximum deflection is 0.62 mm, above the square pipe. The deflection of vertical square pipe increases from the middle to both sides. The upper and lower square pipe is the mounting position of stalk horizontal conveyor. Moreover, small deflection would not influence the operation, showing that the frame just meets the stiffness requirement.

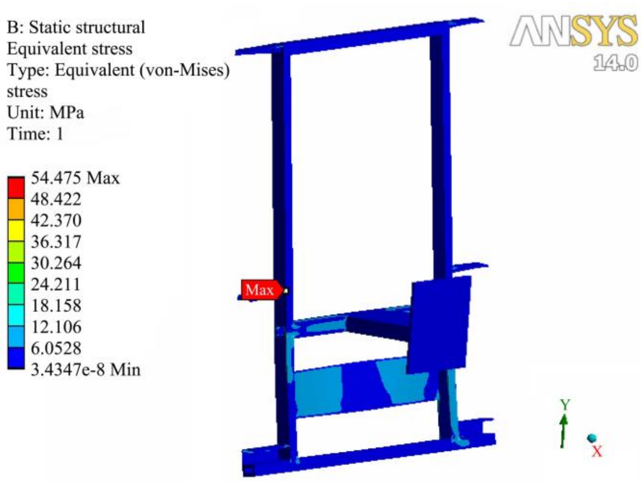


Figure 10 Stress nephogram of the frame

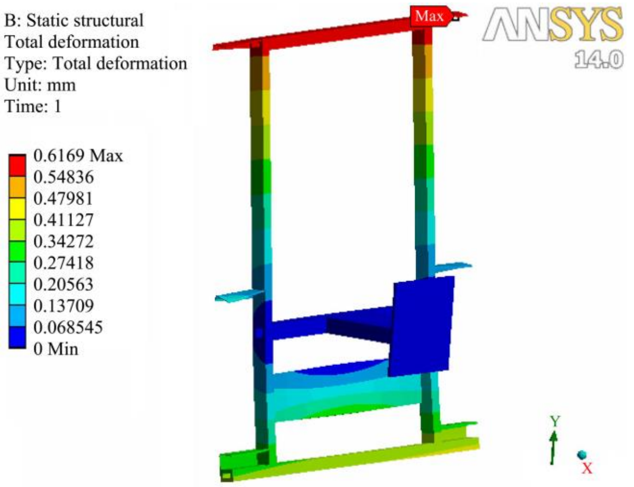
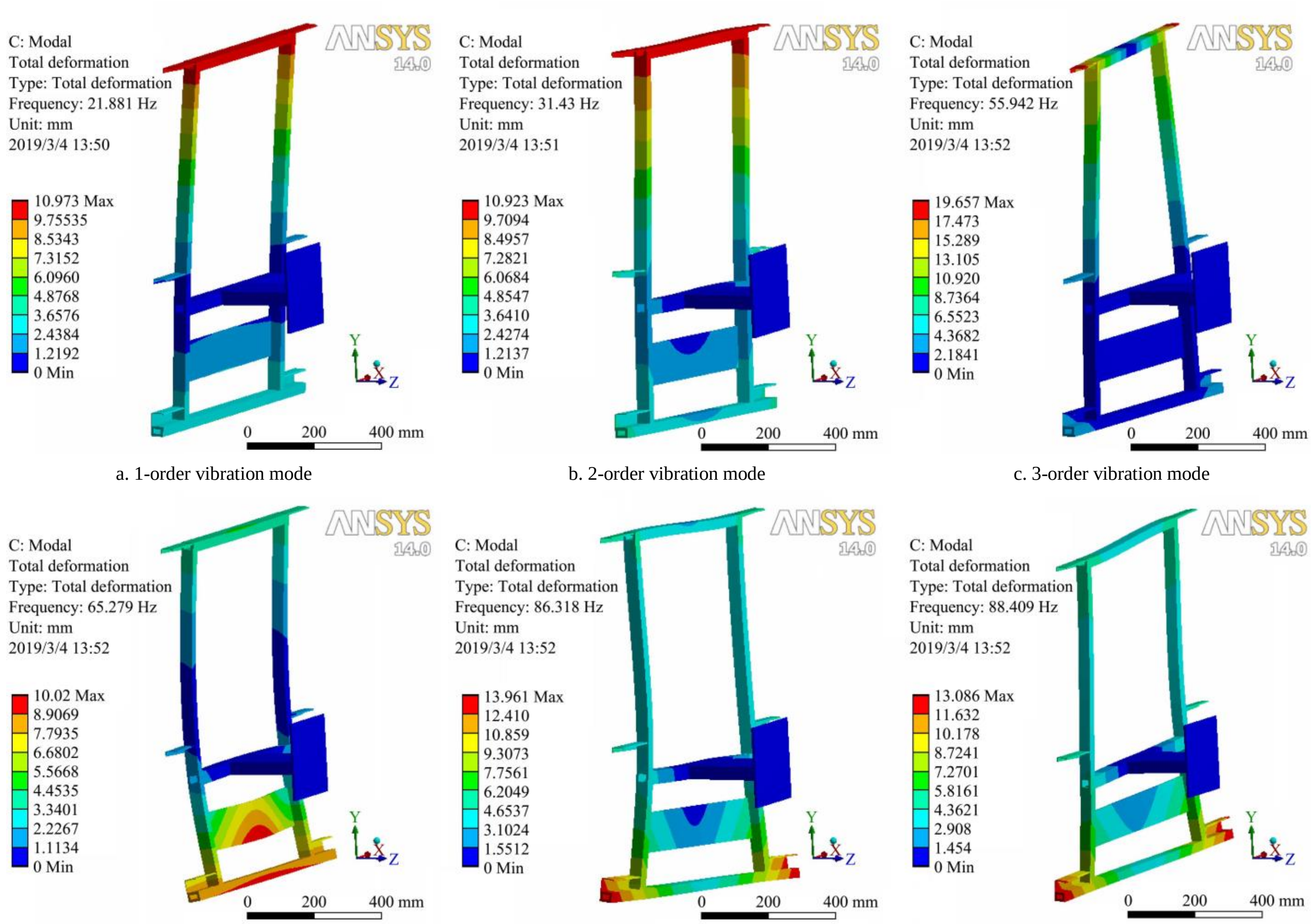


Figure 11 Displacement nephogram of frame

When the header works, the frame would generate vibration due to the excitation of the dynamic load. When the natural frequency of the frame coincides with the excitation frequency, resonance phenomenon will occur, and the frame will be destroyed and deform. Therefore, modal analysis shall be carried out for the frame, to guarantee the safety and reliability of header. During the modal analysis, the construction of the finite element model is the same as the load, restriction imposing and static analysis. The first 6-order natural frequency of the frame is analyzed and calculated, as shown in Table 2, and the vibration mode of each order is shown in Figure 12.

Table 2 First 6-order natural frequency of the frame

Order	Natural frequency/Hz
1	21.881
2	31.430
3	55.954
4	65.279
5	86.318
6	88.409



a. 1-order vibration mode
b. 2-order vibration mode
c. 3-order vibration mode
d. 4-order vibration mode
e. 5-order vibration mode
f. 6-order vibration mode

Figure 12 First 6-order vibration mode of the frame

According to Figure 12, little longitudinal bending deflection takes place above the vertical square pipe in the first-order vibration mode; the two-order vibration mode shows little deflection; torsional deflection takes place in the frame in the 3-order vibration mode; great longitudinal bending deflection takes place in the middle of the vertical square pipe in the 4-order vibration mode; horizontal bending deflection takes place in the vertical square pipe in the 5-order vibration mode, and bending and torsional deflection takes place in 6-order vibration mode. According to the analysis, deflection of the vibration mode of each order mostly occurs in the vertical square pipe or upper square pipe of the frame, and the deflection is small in other areas. Besides, the vibration mode is smooth and steady in structure. While working, the excitation source of the frame vibration is mainly the rotation of crank axis, whose revolving speed is 472 r/min, excitation frequency is 7.87 Hz, far lower than the first-order natural frequency 21.881 Hz. As a result, resonance phenomenon would not occur.

4 Test and parameter optimization of cutting mechanism

4.1 Test materials

The test material, Anhui Hemp No.1, is taken from Liu'an Hemp Test Station, China Agriculture Research System for Bast and Leaf Fiber Crops. The test samples are well-grown hemp stalks, put in the freezer of the lab for fresh preservation. The planting mode of the hemp test station is learnt through measurement and statistics. Specifically, the line spacing is 200 mm, the row spacing is 100 mm, and the moisture content is 71.62%.

4.2 Test factors and evaluation index

Main factors impacting the cutting performance of the hemp harvester include the thickness of stalk, cutting speed, knife length, forward speed, moisture content and header structure. This test mainly selects the cutting speed, knife length and forward speed. If the cutting speed is too high, it would lead to high power consumption, but if it is too low, the cutting failure would increase. According to the harvest, the cutting speed is designed and calculated to be 1.0-1.4 m/s. If the knife is too long, it would lead to the increase of re-cutting rate, which is a waste of power, but if it is too short, it may increase the blank rate, and lead to the incomplete cutting. As a result, the knife length is designed to be 80-120 mm. If the forward speed is too high, it would also increase the cutting failure, but if it is too low, it may influence the harvesting efficiency, thus being unable to meet the harvesting requirement. The forward speed is designed to be 0.4-0.8 m/s.

Main evaluation indexes of the cutting device include the cutting efficiency, cutting power and cutting quality. Specifically, the cutting efficiency mainly is analyzed and evaluated according to the quantity of stalks cut within a unit period; the cutting power is mainly analyzed and evaluated by measuring the real-time test, and the cutting quality is analyzed and evaluated by the failure rate of stalk cutting. The failure rate is obtained by calculating the ratio of uncut stalks and total stalks in the test, and the calculation equation is:

$$Y_3 = \frac{N_1}{N} \times 100\% \tag{20}$$

where, Y_3 is the failure rate; N_1 is the quantity of stalks that are not cut successfully; N is the total quantity of stalk.

This test adopts three evaluation indexes, the cutting efficiency, cutting power and failure rate, and according to the test results, a comprehensive analysis is conducted to obtain the parameter combination with the best cutting performance.

4.3 Test design and result analysis

The cutting of hemp stalks is quite complicated. Test factors are in a non-linear relationship with evaluation indexes. This paper builds a mathematical model between three factors (cutting speed, knife length and forward speed) and three evaluation indexes (cutting efficiency, cutting power and failure rate) using the response surface test method, fits the functional relationship between evaluation indexes and factors, analyzes the relationship among factors and changing rule of their interactions, and figure out the optimal parameter combination and optimal response value.

4.3.1 Design of test plan

The test adopts the three-factor and three-level orthogonal test plan (Table 3), and selects the cutting speed X_1, knife length X_2 and forward speed X_3 as test factors, for the response surface test research. Quadratic polynomial regression analysis is conducted for the test data using Design-Expert software, to fit the regression model equations respectively for the cutting efficiency Y_1, cutting power Y_2 and failure rate Y_3, so as to analyze the influence of factors on the evaluation indexes and effect law of their interactions.

Table 3 Test factor and level

Factor	Test level		
	–1	0	–1
Cutting speed/m s^{-1}	1.0	1.2	1.4
Knife length/mm	80	100	120
Forward speed/m s^{-1}	0.4	0.6	0.8

4.3.2 Test results

The test mainly designs the three-factor three-level test plan using the Box-Behnken of *Design-Expert*. The response surface test plan and results are shown in Table 4. There are 17 groups of tests, and the test is repeated five times at the central point.

Table 4 Test plan and response value results

No.	Factor level			Response value		
	Cutting speed /m s^{-1}	Knife length /mm	Forward speed /m s^{-1}	Cutting efficiency /stalk s^{-1}	Cutting power /W	Failure rate /%
1	–1	0	1	29	753.90	8.33
2	1	1	0	40	935.71	4.17
3	0	–1	–1	30	723.14	12.5
4	0	–1	1	38	644.25	29.17
5	0	1	1	42	635.38	20.83
6	0	0	0	39	727.75	6.94
7	1	0	–1	28	978.07	4.17
8	–1	–1	0	33	643.24	20.83
9	1	–1	0	39	865.14	8.33
10	0	0	0	37	753.46	11.11
11	0	0	0	38	781.34	8.33
12	0	0	0	39	802.05	9.72
13	1	0	1	43	772.27	12.50
14	–1	1	0	34	675.84	19.44
15	–1	0	1	34	664.61	44.44
16	0	1	–1	31	812.35	5.56
17	0	0	0	38	765.41	5.56

4.3.3 Regression model building and significance testing

According to the data of the test, multiple regression fitting analysis is conducted using Design-Expert software. Furthermore, mathematical regression models are built for the cutting performance indexes (cutting efficiency Y_1, cutting power Y_2 and failure rate Y_3 and cutting speed X_1, knife length X_2 and forward speed X_3 of the hemp cutting device.

$$Y_1=38.20+2.50X_1+0.88X_2+4.88X_3+0.000X_1X_2+2.50X_1X_3+0.75X_2X_3–1.73X_1^2+0.025X_2^2–2.97X_3^2 \tag{21}$$

$$Y_2=766.00+101.70X_1+22.94X_2-68.87X_3+9.49X_1X_2–29.13X_1X_3–24.52X_2X_3+51.21X_1^2–37.23X_2^2–25.00X_3^2 \tag{22}$$

$$Y_3=8.33–7.98X_1–2.60X_2+9.55X_3-0.69X_1X_2–6.95X_1X_3–0.35X_2X_3+2.60X_1^2+2.26X_2^2+6.43X_3^2 \tag{23}$$

The above equation is further analyzed. Meanwhile, significance testing is conducted for the regression coefficient, and results are shown in Table 5.

According to the analysis results in Table 5, the response surface model P of the cutting efficiency Y_1, cutting power Y_2 and failure rate Y_3 is 0.0001, 0.0004 and 0.0002 respectively, which is smaller than 0.01, meaning that the significance of three models conforms to the requirement. The lack of fit of three indexes is 0.3329, 0.3907 and 0.1749 respectively, greater than 0.05, meaning that the three models are of high fitting degree, also meeting the requirement. The determination coefficient R^2 of three models is 0.9818, 0.9601 and 0.9669 respectively, suggesting a high degree of fitting. Besides, the response surface analysis results are of high reliability. Therefore, this model can predict and analyze the changes in the cutting performance of the cutter.

Table 5 Regression equation analysis of variance results

Source of variation	Cutting efficiency Y_1				Cutting power Y_2				Failure rate Y_3			
	Sum of squares	*DOF*	*F*	Significance level *P*	Sum of squares	*DOF*	*F*	Significance level *P*	Sum of squares	*DOF*	*F*	Significance level *P*
Model	325.95	9	41.90	<0.0001**	1.496E+005	9	18.70	0.0004**	1731.33	9	22.71	0.0002**
X_1	50	1	57.85	0.0001**	82743.12	1	93.07	<0.0001**	509.92	1	60.19	0.0001**
X_2	6.13	1	7.09	0.0324*	4209.49	1	4.73	0.0660	54.24	1	6.40	0.0392*
X_3	190.12	1	219.98	<0.0001**	37943.24	1	42.68	0.0003**	729.24	1	86.08	<0.0001**
X_1X_2	0.000	1	0.000	1.0000	360.43	1	0.41	0.5446	1.92	1	0.23	0.6487
X_1X_3	25.00	1	28.93	0.0010**	3393.65	1	3.82	0.0917	192.93	1	22.77	0.0020**
X_2X_3	2.25	1	2.60	0.1507	2404.92	1	2.71	0.1440	0.49	1	0.058	0.8168
X_1^2	12.53	1	14.50	0.0067**	11040.44	1	12.42	0.0097**	28.52	1	3.37	0.1092
X_2^2	2.63E-0.03	1	3.045E-003	0.9575	5834.84	1	6.56	0.0375*	21.46	1	2.53	0.1555
X_3^2	37.27	1	43.12	0.0003**	2630.74	1	2.96	0.1291	173.83	1	20.52	0.0027**
Residual	6.05	7			6223.36	7			59.30	7		
Lack of fit	3.25	3	1.55	0.3329	3067.78	3	1.30	0.3907	40.04	3	2.77	0.1749
Error	2.80	4			3155.58	4			19.27	4		
Total	332.00	16			1.558E+005	16			1790.63	16		

Note: $p<0.01$ (Extremely significant, **); $p<0.05$ (Significant, *).

The above stated significance analysis shows that X_1, X_3, X_1X_3, X_1^2 and X_3^2 in the cutting efficiency Y_1 response model would impact the model very significantly, X_2 also has a significant impact on this model; X_1, X_3 and X_1^2 of the cutting power Y_2 response model would impact the model very significantly, and X_2^2 has a significant impact on the model; X_1, X_3, X_1X_3 and X_3^2 of the failure rate Y_3 response model would impact the model very significantly, and X_2 has a significant impact on this model. Items that have an insignificant impact on the regression model are removed from this above mentioned model, guaranteeing model $p<0.01$ and lack of fit $p>0.05$, and the simplified regression model is shown as follows:

$$Y_1=38.20+2.50X_1+0.88X_2+4.88X_3+2.50X_1X_3-1.73X_1^2-2.97X_3^2 \quad (24)$$

$$Y_2=766.00+101.70X_1-68.87X_3+51.21X_1^2-37.23X_2^2 \quad (25)$$

$$Y_3=8.33-7.98X_1-2.60X_2+9.55X_3-6.95X_1X_3+6.43X_3^2 \quad (26)$$

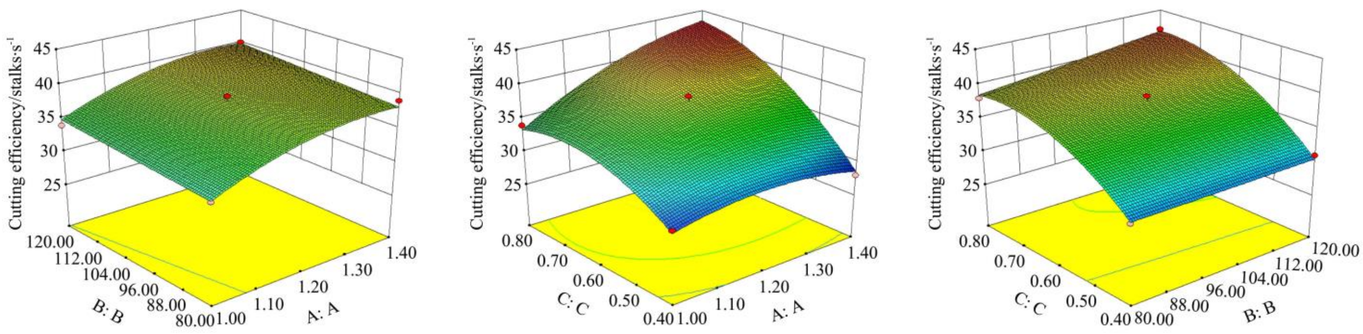
The analysis shows that the impact of three factors on the cutting efficiency is $X_3>X_1>X_2$; on the cutting power: $X_1>X_3>X_2$; on the failure rate: $X_3>X_1>X_2$.

4.3.4 Influence of interactive factors on the evaluation index

A certain factor is fixed at the middle level to analyze the interactive effect of two other factors on the evaluation index. The impact of three factors (cutting speed, knife length and forward speed) on the evaluation index is analyzed by making response surface and contour map.

(1) Analysis of the effect law of interactive factors on the cutting efficiency

The response surface curve of the impact of interactive factors (cutting speed, knife length and forward speed) on the cutting efficiency is shown in Figure 13.



a. $C = f(X_1, X_2, 0)$ b. $C = f(X_1, 0, X_3)$ c. $C = f(0, X_2, X_3)$

Figure 13 Influence of interactive factors on the cutting efficiency

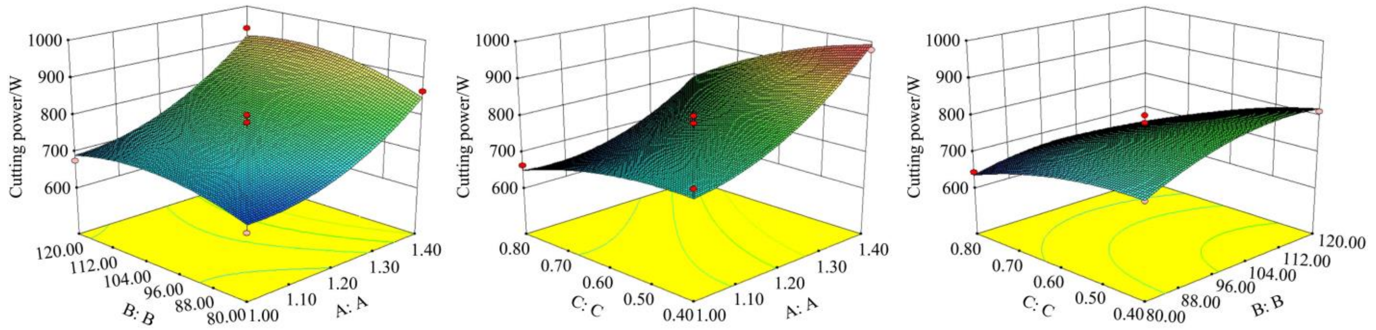
(2) Analysis of the effect law of interactive factors on the cutting power

The response surface curve of the impact of interactive factors (cutting speed, knife length and forward speed) on the cutting power is shown in Figure 14.

In Figure 14 a, forward speed is in the middle level, namely X_3=0.6 m/s, the interactive effect of cutting speed and knife length on the cutting power is shown, and it is clear that the interactive effect of the two factors is not significant. In case of the same knife length, the cutting power increases with the cutting speed; in case of the same cutting speed, the cutting efficiency increases slowly with the knife length. The impact of knife length on the cutting efficiency is far smaller than that of the cutting speed on efficiency. In Figure 14b, the knife length is in the middle level, namely X_2=100 mm, the interactive effect of cutting speed and forward speed on the cutting efficiency is shown, and it is clear that the interactive effect of the two factors is not significant, the trend in which the cutting power increases with the cutting speed at a relatively low forward speed is more obvious than that at a high forward speed. On the contrary, the trend in which the cutting power decreases with the increase of the forward speed at a relatively high cutting speed is more obvious than that at a relatively low cutting speed. Both the cutting speed and forward speed have very significant impacts on the cutting power. In Figure 14c, the cutting speed is in the middle level, namely X_1= 1.2 m/s, the interactive effect of knife length and forward speed on the cutting power is shown, and it is clear that the interactive effect of the two factors is not significant. In case of the same knife length, the cutting power decreases with the increase of the forward speed; when the forward speed is relatively low, the cutting power increases with the increase of knife length, while the forward speed is relatively high, the cutting power decreases with the increase of the knife length, and the impact of knife length on the cutting power is not as significant as the impact of forward speed on the cutting power.

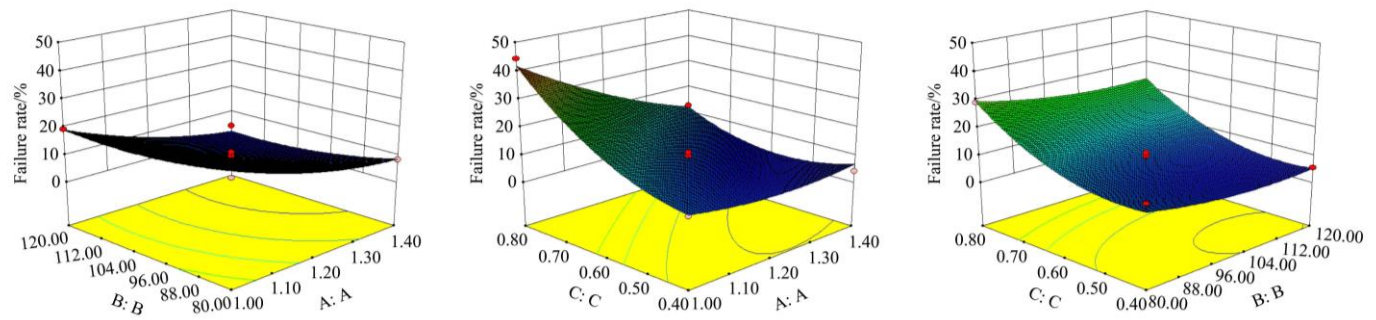
(3) Analysis of the effect law of interactive factors on the failure rate

The response surface curve of the impact of interactive factors (cutting speed, knife length and forward speed) on the failure rate is shown in Figure 15.



a. $C = f(X_1, X_2, 0)$ b. $C = f(X_1, 0, X_3)$ c. $C = f(0, X_2, X_3)$

Figure 14 Influence of interactive factors on the cutting power



a. $C = f(X_1, X_2, 0)$ b. $C = f(X_1, 0, X_3)$ c. $C = f(0, X_2, X_3)$

Figure 15 Influence of interactive factors on the failure rate

In Figure 15a, forward speed is in the middle level, namely X_3=0.6 m/s, the interactive effect of cutting speed and knife length on the failure rate is shown, and it is clear that the interactive effect of the two factors is not significant. In case of the same knife length, the failure rate decreases quickly with the increase of cutting speed; in case of the same cutting speed, the failure rate decreases with the increase of knife length. The impact of knife length on the failure rate is far smaller than that of the cutting speed on the failure rate. In Figure 15b, the knife length is in the middle level, namely X_2=100 mm, the interactive effect of cutting speed and forward speed on the failure rate is shown, and it is clear that the interactive effect of the two factors is not significant. When the cutting speed is at a relatively low level, the failure rate increases with the forward speed; when the cutting speed is at a relatively high level, the failure rate decreases first and increases later with the increase of the cutting speed. When the forward speed is at a relatively high level, the failure rate decreases with the increases of the cutting speed, and the impact of the cutting speed and forward speed on the failure rate is quite significant. In Figure 15c, the cutting speed is in the middle level, namely X_1= 1.2 m/s, the interactive effect of knife length and forward speed on the failure rate is shown, and it is clear that the interactive effect of the two factors is not significant. In case of the same knife length, the failure rate increases with the forward speed; in case of the same forward speed, the failure rate decreases with the increase of knife length, and the impact of knife length on the failure rate is not as significant as the impact of forward speed on the failure rate.

To improve the cutting performance of the cutter, test parameters are optimized using *Design-Expert* on condition that all factors meet the test range. According to the actual production design requirement and referring to other related standards, the cutting efficiency shall be greater than 30 stalks/s, the cutting power is smaller than 800 W the failure rate is smaller than 10%, and the constraint condition is:

$$\begin{cases} Y_1 \geq 30 \\ Y_2 \leq 800 \\ Y_3 \leq 10\% \\ 1.0 \leq X_1 \leq 1.4 \\ 80 \leq X_2 \leq 120 \\ 0.4 \leq X_3 \leq 0.8 \end{cases} \quad (27)$$

The optimal parameters of all factors are obtained: cutting speed 1.2 m/s, knife length 120 mm, forward speed 0.6 m/s, cutting efficiency 38.92 stalks/s, cutting power 776.37 W and failure rate 6.24%.

4.4 Test verification

The response surface test does not include the above optimized optimal parameter combination. In order to test the reliability of the response surface model and optimization results, the above optimal combination is adopted repeating the verification test five times on the hemp stalk cutting test bench (Figure 16). The mean value is taken to test the results, namely cutting efficiency 38 stalks/s, cutting power 768.52 W, failure rate 6.31%. According to the comparative analysis, the theoretical optimal value of Y_1, Y_2 and Y_3 is quite close to the verification value. Therefore, the above model is reliable, and optimal structure parameters also meet the requirements. This optimal parameter combination is recommended for the structure design, namely cutting speed 1.2 m/s, knife length 120 mm, and forward speed 0.6 m/s.

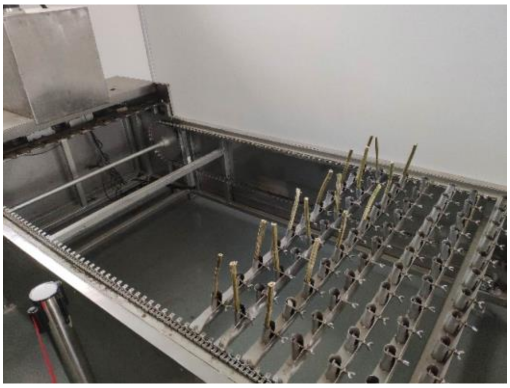


Figure 16 Hemp stalk cutting test bench

5 Field test and result analysis

5.1 Test condition

The test was conducted in the test base in Xishuangbanna Academy of Agricultural Sciences, Yunnan Province from September 1 to 15, 2018, as shown in Figure 17. By measuring the hemp planting mode and geometric dimensioning of stalks with tape and vernier caliper, it is learnt that the average spacing of hemp stalks is about 20 mm, the stalk spacing is about 100 mm, the root diameter is 10-25 mm, and the height is 2000-4000 mm. Specifically, the knife length is 120 mm, the forward speed is 0.6 m/s, the cutting speed is 1.2 m/s, and the harvesting of hemp is finished.

Figure 17 Field testing of small hemp harvester

Currently, there are no standards related to the test method and the working quality of hemp harvester in China. This paper mainly refers to GB/T10395.1-2009 *Agricultural and Forestry Machinery Safety Part 1: General Requirements*, GB/T5262-2008 *Measuring Methods for Agricultural Machinery Testing Conditions General Rules* and GB/T5667-2008 *Productive Testing Methods for Agricultural Machinery*, performance indexes like the cutting rate and conveying rate are tested[26-28]. The cutting rate is obtained by calculating the ratio of the quantity of stalks cut and total quantity of stalks in the test, and the conveying rate is obtained by calculating the ratio of the quantity of blocking stalks and quantity of stalks in the stalk horizontal conveyor. The calculation equation of productivity is:

$$Q = 0.1kBv_m \tag{28}$$

which, k is the productivity coefficient; B is the cutting width, m; v_m is the operating speed of the harvester, km/h.

5.2 Test results and analysis

Test results of performance indexes like the cutting rate, conveying rate and productivity are shown in Table 6.

Table 6 Test results of the performance

Test parameters	Unit	Test results
Forward speed	m/s	0.6
Cutting speed	m/s	1.2
Knife length	mm	120
Cutting rate	%	92.5
Conveying rate	%	86.7
Productivity	hm^2/h	0.18

The field test shows that the sample harvester is stable in performance and reliable in operation during the cutting process, and test results can meet the design requirements. It can fulfill the harvesting of hemp in Yunnan, and the intensity and manufacturing process of the sample harvester can also meet the harvesting requirement. In the meantime, the sample harvester, characterized by simple operation and high working efficiency, will improve the mechanical harvesting level of hemp in Yunnan.

6 Conclusions

(1) Key parts of two-wheeled walking hemp harvester are designed and optimized, including the reciprocating single moving-knife cutter and stalk horizontal conveyor. Static analysis and modal analysis of the header frame is conducted using the finite element analysis software, to verify whether the frame structure meets the operating requirements.

(2) Test bench experiment is carried out with the cutting speed, knife length and forward speed as the test factors and cutting efficiency, cutting power and failure rate as the evaluation indexes by applying the response surface method. Moreover, a multi-factor mathematical model is built to analyze the influence law of related factors and their interactions on the performance indexes. The optimal parameter combination of multiple objective parameter optimization is: cutting speed 1.2 m/s, knife length 120 mm, forward speed 0.6 m/s, and at this moment, the cutting efficiency is 38.92 stalks/s, cutting power 776.37 W, and failure rate 6.24%.

(3) According to the parameter optimization and structural design plan, the sample machine trial production and the field test are carried out. Test results are: cutting rate 92.5%, conveying rate 86.7%, and productivity 0.18 hm^2/h, and the sample machine meets the design requirements.

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