Design and optimization of the parameters of the key components for reed harvester

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Abstract: In the present, most of domestic reed harvesters are still in the research and prototype stage, and there is not yet a model with mature technology, strong versatility and mass production. Some modified reed harvesters used in some places can partially solve the reed harvesting problem, but there are problems such as small cutting width, unstable harvesting quality and low operational efficiency that need further improvement. In the study, a reed harvester was designed to integrate with the cutting and conveying. The key components of reed harvester were analyzed to determine the working parameters of the upper stalk-guiding device, the reciprocating double-acting cutter and the three-layer chain conveyor. Then, a quadratic orthogonal rotation combination test was designed to process the data by Design-Expert, where the failure rate, cutting efficiency and conveying rate were taken as the response indexes. An analysis was also made to explore the effects of forward speed, cutting speed, and chain conveying speed on the response index of the reed harvester. A regression mathematical model was established for the response indexes. The response surface method was then selected to implement the multi-objective optimization of the regression model. The results demonstrated that an optimal combination of operation parameters was achieved as follows: the forward speed was 0.85 m/s, the cutting speed was 1.40 m/s, and the chain conveying speed was 1.33 m/s, where the failure rate was 4.17%, the cutting efficiency was 44.21 plants/s, and the conveying rate was 93.60%. The optimized parameters were verified in the field on the reed harvester. In the field test, failure rate, cutting efficiency, and conveying rate were 4.38%, 43.82 plants/s, and 92.55%, respectively. The relative errors with the optimized values were 9.8%, 5.0%, and 1.1%, respectively. The results of the study provide a theoretical basis for the control of operating parameters and improved design of reed harvesting implements.

Keywords: reed, harvester, operation parameters, multi-objective optimization, response surface
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1 Introduction

Reeds are perennial aquatic tall grasses that grow near irrigation ditches, saline areas and marshes, and are widely distributed in many places of Asia, South Europe, the Middle East and North America, featuring waterlogging tolerance, salinity tolerance, high temperature resistance and high yield[1,2]. Meanwhile, reeds, of great ecological value, play a vital role in inhibiting the growth of algae, promoting siltation, preventing corrosion, improving water quality, preventing floods, fixing dikes, regulating the climate, and maintaining biodiversity, etc[3,4]. Reeds are ideal industrial raw materials for papermaking, composites and biochar, since the roots, stems, leaves and stalks of reeds are rich in cellulose, lignin, and other natural polymers[5-8].

Foreign reed harvesters have been developed earlier and are relatively mature[9], for instance, the MRS reed harvester designed by INMA (Romania) can cut, compress and bundle up reed stalks in deep water[10]; the tracked reed harvester produced by De Vries Cornjum (Netherlands) can complete the cutting, vertical bundling and piling of reed stalks at one time[11]. Currently, there is not yet a model with mature technology, strong versatility and mass production, and most are still in the prototype research stage. In some places, modified reed harvesters are used to harvest the reeds, but there are still such problems as small cutting width, unstable cutting quality and low operating efficiency[12-15].

Aiming at the existing problems of reed harvesters, a tracked reed harvester was developed through the structural optimization and design of the stalk guiding device, cutting device and conveying device, and other key components. In addition, with the failure rate, cutting efficiency and conveying rate as the test indexes, the relationship between the related motion parameters of the cutting and conveying parts and test indexes were researched in the field test, aiming to guide the filed operation of reed harvesters and provide references for the design of reed harvesters.

2 General structure and operating principle

A reed harvester is composed of a cab system 1, an upper stalk-guiding device 2, a reciprocating double-acting cutter 5, a three-layer chain conveyor 3, a lower stalk-splitting and stalk-holding device 4, and a chassis system 6, as shown in Figure

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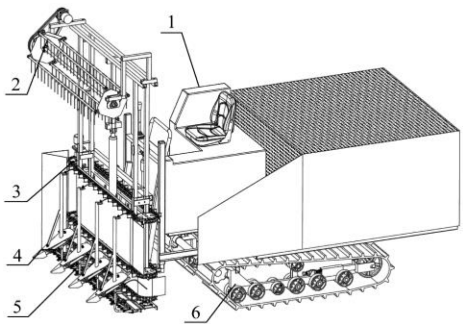
1. Its operating principle is as follows: the height of the header and the upper stalk-guiding device 2 is adjusted by the hydraulic cylinder to meet the design requirements on the stubble height. The upper stalk-guiding device is almost as high as the middle and upper part of the stalk. As the harvester moves forward, reed stalks within the working width are plucked up and guided into the reciprocating double-acting cutter 5 under the joint action of the lower stalk-splitting and stalk-holding device 4 and the upper stalk-guiding device 2. And then, the cut reed stalks are laterally clamped and conveyed to the laying side by a three-layer chain conveyor 3, thus completing the mechanized reed harvesting. The main parameters are listed in Table 1.



1. Cab system 2. Upper stalk-guiding device 3. Three-layer chain conveyor 4. Lower stalk-splitting and stalk-holding device 5. Reciprocating double-acting cutter 6. Chassis system

Figure 1 General structure schematic of reed harvester

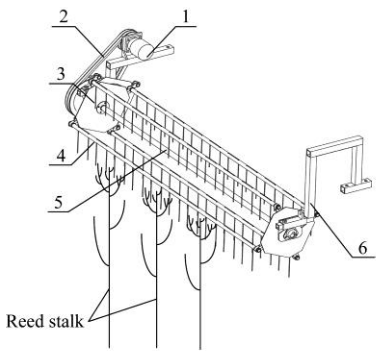
Table 1 Structure and working parameters of reed harvester

Parameters	Values
Overall dimensions size (length×width×height) /mm×mm×mm	5400×1800×3700
Chassis power/kw	74.5
Cutting width/mm	1600
Forward speed/m·s^{-1}	0.45-1.00
Harvesting efficiency/hm^2·h^{-1}	0.25-0.40
Machine weight/kg	2500

3 Design of key components

3.1 Design of upper stalk-guiding device

The upper stalk-guiding device mainly guides reed stalks into the reciprocating double-acting cutter and the three-layer chain conveyor, and holds the fallen reed stalks, for the convenience of forced clamping and lateral conveying by the three-layer chain, can greatly improve the conveying rate Its structure is shown in Figure 2.



1. Motor 2. Belt 3. Eccentric width plate 4. U-shaped pick teeth 5. Drive shaft 6. Frame

Figure 2 Structure schematic of upper stalk-guiding device

While operating, the motion of the reel is synthesized by the circular motion around the drive shaft of the reel and the forward motion of the reed harvester[16]. A necessary condition for the effective operation of the reel is that the ratio of the circumferential speed v_b of the reel and forward speed v_m of the harvester (stalk-guiding speed ratio) λ>1. At this moment, the movement track of the reel is trochoid[17,18], as shown in Figure 3. Let the projection point O on the ground of the reel shaft O_0 be the coordinate origin, the x-direction be the forward direction of the harvester, and the y-direction be the upward direction of the axis, so the equation of its movement track is:

$$\begin{cases} x = v_m t + R\cos\omega t \\ y = (H+h) - R\sin\omega t \end{cases} \tag{1}$$

where, R is the radius of the reel, m; v_m is the forward speed of the reed harvester, m/s; ω is the angular speed of the reel, rad/s; h is the height of the cutter from the ground, mm; H is the installation height of the reel shaft, mm.

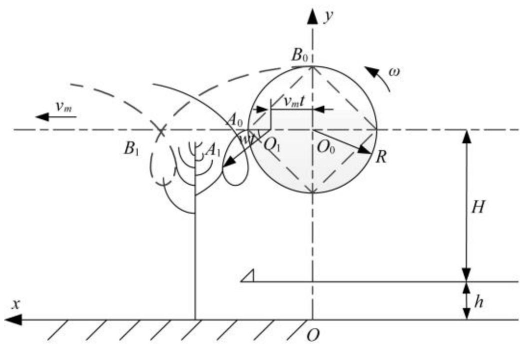


Figure 3 Movement track of reel

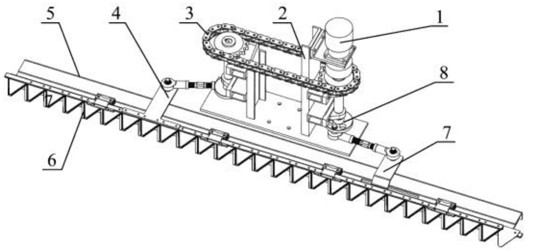
The test shows that the increase of λ within a certain range could enhance the stalk-guiding capacity, but it could not be too large, since it may cause the U-shaped picking teeth to strike the reed stalk tip too much and result in tangling and damage easily. In the early field testing of the reed harvester, when the circumferential speed of the reel v_b was over 1.8 m/s, it was unfavorable for stalk guiding. Based on the forward speed v_m of the harvester, λ was set to be 1.6, the diameter of the reel was D= 400 mm, the installation height of the reel was H=3600 mm, the height of the cutter from the ground was h=100 mm; while operating, the rotation rate of the reel shall not be greater than 85.9 r/min.

3.2 Design of reciprocating double-acting cutter

Cutter is one of the key components of the reed harvester, which cooperates with the forced clamping and conveying device to complete the cutting of the reed roots. The cutting quality directly affects the subsequent conveying effect and decides the operating quality of the reed harvester. Currently, there are mainly three types of cutter, including reciprocating cutter, which makes reciprocating motion, and can be further divided into reciprocating single blade cutter and reciprocating double blade cutter according to the number of moving blade; cutting disc, which makes rotary motion, featuring small vibration and stable operation, but a short service life; free-swinging knife rotary cutter, which rotates in a plane parallel to the forward direction of the harvester, displays a strong cutting capacity, and is suitable for high-speed operation[19-21]. To prevent the reed stalk from winding around the rotating shaft of the cutting disc and to reduce the inertia of the single-action cutter after cutting, a reciprocating double-acting cutter was adopted for the reed harvester, which can effectively improve the cutting quality and cutting efficiency, and its structure is shown in Figure 4.

The reciprocating double-acting cutter mainly completes the clamping and cutting of stalks between the upper and lower cutters.

The blade structural parameters have a significant impact on the power consumption and reliability of the cutter. When deciding the width of the blade, the cutting angle α is an important factor that decides the length of blade and influences the clamping stability and cutting resistance[22,23]. Research shows that larger cutting angle may reduce the cutting resistance, but affect the clamping stability. The cutting angle is now analyzed with the premise that the blade clamps the reed stalks. When the blade clamps the reed stalks, the force analysis is shown in Figure 5.



1. Motor 2. Frame 3. Drive chain 4. Lower knife link arm 5. Cutter mounting plate 6. Blade 7. Upper knife link arm 8. Eccentric wheel

Figure 4 Structure schematic of reciprocating double-acting cutter

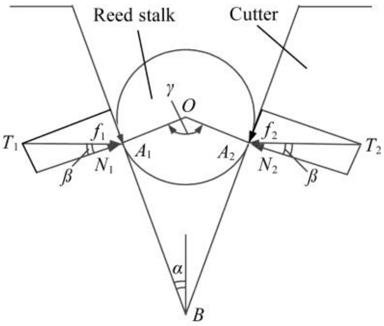


Figure 5 Force analysis of clamped reed stalk

There are frictional forces f_1 and f_2 and positive pressure N_1 and N_2 at the contact points A_1 and A_2 between the blade and reed stalk, and the cutting angle of the blade is α. The combined forces of friction and positive pressure are expressed as T_1 and T_2 respectively. The condition for reed stalks to be clamped without sliding out is that the combined force T_1 and T_2 acting on the two contact points is in the same line.

From the triangle OA_1A_2 in Figure 5.

$$\gamma + 2\beta = \pi \tag{2}$$

where, γ is the angle between positive pressure N_1 and N_2, (°), β is the friction angle of the blade against the reed stalk, (°).

In the quadrilateral OA_1BA_2, $\angle OA_1B=\angle OA_2B=\pi/2$, that is where, α is the cutting angle of the blade, (°).

$$\gamma+2\alpha=\pi \tag{3}$$

By combining the above two equations, it can be obtained that

$$\alpha=\beta \tag{4}$$

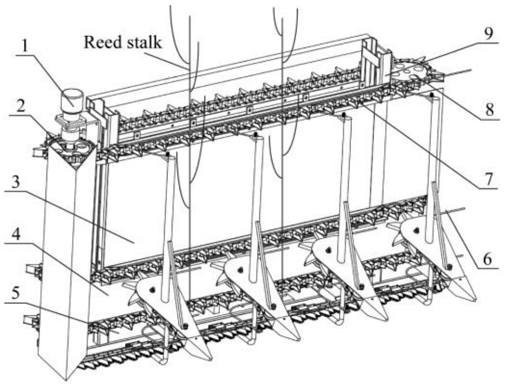
In conclusion, the condition for the clamping of reed stalks is:

$$\alpha\leq\beta \tag{5}$$

That is, the cutting angle of the blade is less than the friction angle between the blade and reed stalk. The blade selected for the reed harvester has a blade height of 79 mm, a blade bottom width of 66 mm, a front axle width of 16 mm, a blade thickness of 4 mm, a bottom edge spacing of 10 mm between adjacent blades, and a cutting angle α of 18°. The friction angle between the blade and reed stalk was measured to be 26°-29°, so the blade selected met the clamping condition.

3.3 Design of the three-layer chain conveyor

The three-layer chain conveyor conveys the reed stalks stably and smoothly to the laying side after the cutting by the reciprocating double-acting cutter, to ensure that there is no tilting, flipping or blocking during the stalk conveying process. It is mainly composed of conveyor frame, upper, middle and lower layers of conveyor chain with teeth, active sprocket and driven sprocket, as shown in Figure 6. The three-layer chain conveyor adopts forced clamping conveying to improve the conveying rate, and the upper, middle and lower layers of active sprockets are connected by universal joints to realize the synchronous conveying by the upper, middle and lower layers of conveyor chain with teeth.



1. Motor 2. Drive sprocket 3. Upper baffle 4. Lower baffle 5. Baseplate 6. Compression spring 7. Conveying chain with teeth 8. Driven sprocket 9. Convey frame

Figure 6 Structure schematic of three-layer chain conveyor

The cut reed stalks enter the lateral conveying device by virtue of the lower stalk-splitting and stalk-holding device, and are conveyed laterally by the conveyor chain with teeth. To ensure that reed stalks are conveyed smoothly without rolling over during the conveying process, the conveying conditions shall be analyzed. The forces on reed stalks during the conveying process are shown in Figure 7, and the lateral conveying mechanics relationship of reed stalks shall meet the following conditions:

$$F_1+F_2+F_3\geq f_1+f_2+f_3+f_4 \tag{6}$$

where, F_1, F_2 and F_3 are the respective force of the upper, middle and lower layers of chain with teeth on reed stalks; f_1 is the frictional resistance of the base plate to reed stalks; f_2 is the frictional resistance of the lower baffle to reed stalks; f_3 is the frictional resistance of the upper baffle to reed stalks; f_4 is the traction between reed stalks.

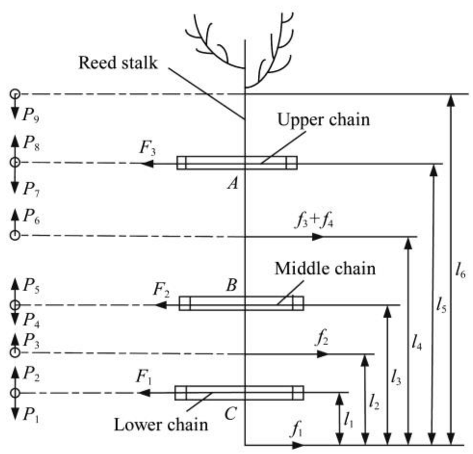


Figure 7 Force analysis of reed stalk

To avoid the falling or rotation of reed stalks, the mechanical relationship shall meet the following requirements: the forces in the horizontal and vertical direction shall be balanced, and the moment to point C is M_c=0.

$$\begin{cases}\sum M_1 = F_1 \cdot l_1 + F_2 \cdot l_3 + F_3 \cdot l_5 - f_2 \cdot l_2 - (f_3 + f_4) \cdot l_4 = 0 \\ \sum M_2 = (P_1 - P_2) \cdot l_1 - P_3 \cdot l_2 + (P_4 - P_5) \cdot l_3 - P_6 \cdot l_4 + \\ \qquad (P_7 - P_8) \cdot l_5 + P_9 \cdot l_6 = 0\end{cases} \tag{7}$$

where, P_9 is the pushing force of the upper stalk-guiding device; P_6 is the support of the upper baffle; P_3 is the support of the lower baffle; P_7, P_4 and P_1 are the forces of the compression spring on reed stalks; P_8, P_5 and P_2 are chain support; l_1, l_2, l_3, l_4, l_5 and l_6 are the vertical distance between the base board and F_1, f_2, F_2, f_3, f_4, F_3 and P_9.

Upon measurement, the height of reed stalks is 3000 mm to 4500 mm. According to the past design experience and *Agricultural Machinery Manual*, the distance between the lower conveyor chain and the base plate is 200 mm, the distance between the middle conveyor chain and the base plate is 450 mm, the distance between the upper conveyor chain and the base plate is 1260 mm, and the height of the header is 1370 mm

4 Cutting-conveying performance test

4.1 Test condition and test plan

The adapted range of reed harvester designed in this paper is not more than 4800 mm, The test was carried out at the test base of Wuxi High-tech Development Zone, Jiangsu from November 3 to 10, 2021 (Figure 8). The variety of reed was unknown because it grows wild, the reeds were 3000-4500 mm tall, the bottom diameter of reeds was 12-16 mm, and the water content of reed stalks was 41.3%-56.5%.

1. Upper stalk-guiding device 2. Three-layer chain conveyor 3. Lower stalk-splitting and stalk-holding device 4. Reciprocating double-acting cutter 5. Chassis system

Figure 8 Field test of reed harvester

Based on the observation and theoretical analysis of the previous single-factor test, the forward speed A, cutting speed B and chain conveying speed C, which had a greater influence on the cutting and conveying performance of the reed harvester, were selected as test factors. The other test parameters were blade length, 120 mm and horizontal distance between the cutting and clamping point, 64 mm. With the failure rate Y_1, cutting efficiency Y_2 and conveying rate Y_3 as the cutting and conveying indexes, and a 3-factor, 3-level orthogonal test was carried out with a total of 17 groups and 5 repetitions at the center point[24-27]. The test factors and levels are listed in Table 2.

Table 2 Coding table of experimental factors and levels

Factor	Experimental level		
	–1	0	1
Forward speed A/m s^{-1}	0.6	0.8	1.0
Cutting speed B/m s^{-1}	1.0	1.2	1.4
Chain conveyor speed C/m s^{-1}	0.9	1.2	1.5

In Design-Expert.V8.0.6.1, a central composite response surface design was adopted, and the results are listed in Table 3. The results were analyzed and a regression model equation of failure rate Y_1, cutting efficiency Y_2 and conveying success rate Y_3 were fitted respectively to study the influence of each factor on the evaluation indexes and influence law of the interaction.

4.2 Test index measurement method

Main evaluation indexes of the cutting device include the cutting quality, cutting efficiency, etc[28-30]. The cutting quality is analyzed and evaluated with the cutting failure rate, while the failure rate Y_1 was calculated by the ratio of the number of uncut stalks to the total number of stalks in the experiment, and the calculation equation is:

$$Y_1 = \frac{N_1}{N} \times 100\% \tag{8}$$

where, Y_1 is the failure rate; N_1 is the number of uncut stalks; N is the total number of stalks.

The cutting efficiency Y_2 was analyzed and evaluated by the number of reed stalks cut per unit time[31]. Since there is no technical standard for reed harvesters, the test index of the conveying device was calculated by referring to the relevant standards for other crop harvesters[32], and the conveying rate Y_3 is the rate of successful conveying of reed stalks.

In the test, three evaluation indexes, namely the failure rate, cutting efficiency and conveying rate, were adopted, and comprehensive analysis was conducted for the test results, to obtain the best combination of motion performance parameters of reed harvesters.

4.3 Test result analysis

4.3.1 Regression modelling and significance analysis

The test results are listed in Table 3. Quadratic regression analysis of the test results was carried out with Design-Expert. V8.0.6.1, and multiple regression fitting was conducted to obtain the regression equations for the failure rate Y_1, cutting efficiency Y_2, and conveying rate Y_3, as shown below:

$$Y_1=9.40-11.13A-1.97B-0.60C-2.59AB-1.70AC-1.44BC+9.77A^2+0.84B^2-1.04C^2 \tag{9}$$

$$Y_2=41.40+5.50A+1.25B+0.25C+2.00AB+1.50AC+1.00BC-4.45A^2-0.95B^2+1.05C^2 \tag{10}$$

$$Y_3=94.12-1.37A-0.75B+4.25C-0.60AB+1.73AC+0.23BC-4.89A^2+0.28B^2-7.34C^2 \tag{11}$$

Table 3 Results and design of tests

No.	Factor level			Response value		
	Forward speed A /m s^{-1}	Cutting speed B /m s^{-1}	Chain conveying speed C/m s^{-1}	Failure rate Y_1 /%	Cutting efficiency Y_2/stalks s^{-1}	Conveying rate Y_3 /%
1	-1	0	-1	28.69	33	80.65
2	1	1	0	5.19	44	86.22
3	0	-1	-1	10.66	41	83.27
4	0	-1	1	12.36	39	92.37
5	0	1	1	4.84	44	91.28
6	0	0	0	11.55	40	93.91
7	1	0	-1	8.77	42	75.65
8	-1	-1	0	29.64	32	91.58
9	1	-1	0	13.64	38	88.85
10	0	0	0	7.99	42	94.56
11	0	0	0	11.38	40	93.36
12	0	0	0	7.98	43	93.23
13	1	0	1	4.17	46	86.57
14	-1	1	0	31.56	30	91.34
15	-1	0	1	30.88	31	84.64
16	0	1	-1	8.92	42	81.27
17	0	0	0	8.11	42	95.52

1) Significance analysis of failure rate Y_1

Through data analysis, the variance of the cutting failure rate Y_1 is listed in Table 4. According to Table 4, the test response surface model p was <0.0001, less than 0.01 as highly significant; the value of misfit term was 0.8247, greater than 0.05, the error of the test was small, so the model could be used to predict and analyze the cutting failure rate of reed harvesters.

Table 4 Variance analysis for failure rate

Variance source	Sum of squares	DOF	*F*-value	*p*
Model	1481.32	9	66.17	<0.0001**
A	990.12	1	398.06	<0.0001**
B	31.17	1	12.53	0.0095**
C	2.87	1	1.15	0.3185
AB	26.88	1	10.81	0.0133*
AC	11.53	1	4.63	0.0683
BC	8.35	1	3.36	0.1096
A^2	401.82	1	161.55	<0.0001**
B^2	2.95	1	1.18	0.3125
C^2	4.58	1	1.84	0.2167
Residual	17.41	7		
Lack of fit	3.20	3	0.30	0.8247
Error	14.21	4		
Total	1498.73	16		

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

According to the significance analysis, the effects of A, B, and A^2 in the response surface model of failure rate Y_1 on the model was highly significant, while the effect of AB on the model was significant. The descending order of significances of the factors on the failure rate was forward speed, cutting speed, and chain conveying speed.

2) Significance analysis of the cutting efficiency Y_2

The variance of the cutting efficiency Y_2 is listed in Table 5. It is clear that the response surface model p was 0.0001, less than 0.01 as highly significant; the value of the misfit term was 0.6716, which was greater than 0.05, the error generated by the test was small and the model can be used to predict and analyze the cutting efficiency of reed harvesters.

Table 5 Variance analysis for cutting efficiency

Variance source	Sum of squares	DOF	*F*-value	*p*
Model	375.68	9	28.65	0.0001**
A	242.00	1	166.08	<0.0001**
B	12.50	1	8.58	0.0221*
C	0.50	1	0.34	0.5764
AB	16.00	1	10.98	0.0129*
AC	9.00	1	6.18	0.0419
BC	4.00	1	2.75	0.1415
A^2	83.38	1	57.22	0.0001**
B^2	3.80	1	2.61	0.1504
C^2	4.64	1	3.19	0.1175
Residual	10.20	7		
Lack of fit	3.00	3	0.56	0.6716
Error	7.20	4		
Total	385.88	16		

According to the significance analysis, A and A^2 in the response surface model of the cutting efficiency Y_2 had an extremely significant impact on the model; while B and AB had a significant impact on the model. The descending order of significances of the factors influencing on the cutting efficiency was forward speed, cutting speed, and chain conveying speed.

3) Significance analysis of the conveying rate Y_3

The variances of the conveying rate Y_3 are listed in Table 6. It is clear that the response surface model p was <0.0001, less than 0.01 as highly significant; the value of the misfit term was 0.2718, which was greater than 0.05, the error generated by the test was small and the model can be used to predict and analyze the conveying rate of reed harvesters.

Table 6 Variance analysis for conveyor rate

Variance source	Sum of squares	DOF	*F*-value	*p*
Model	523.20	9	47.13	<0.0001**
A	14.91	1	12.08	0.0103*
B	4.44	1	3.60	0.0996
C	144.67	1	117.29	<0.0001**
AB	1.43	1	1.16	0.3176
AC	12.01	1	9.73	0.0168*
BC	0.21	1	0.17	0.6943
A^2	100.86	1	81.77	<0.0001**
B^2	0.32	1	0.26	0.6261
C^2	227.11	1	184.12	<0.0001**
Residual	8.63	7		
Lack of fit	5.07	3	1.89	0.2718
Error	3.57	4		
Total	531.83	16		

According to the significance analysis, C, A^2 and C^2 in the response model of the conveying rate Y_3 had an extremely significant impact on the model; while A and AC had a significant impact on the model. The descending order of significances of the factors influencing on the cutting efficiency was chain conveying speed, forward speed, and cutting speed.

4.3.2 Response surface analysis

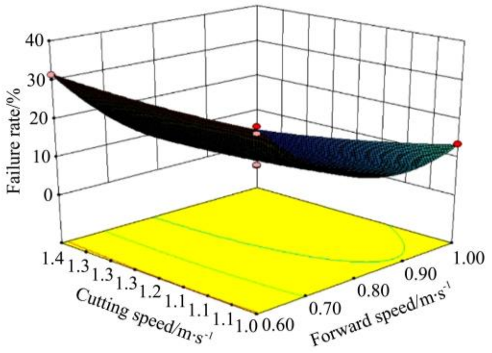
Data processing was conducted with Design-Expert. V8.0.6.1, and the response surface of interactive factors on three test indexes was obtained.

1) Failure rate analysis

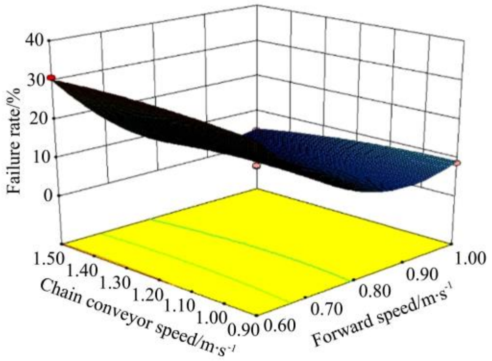
When the chain conveying speed was 1.2 m/s, the interactive effect of forward speed and cutting speed on the failure rate is shown in Figure 9a. At the same cutting speed, the failure rate first decreased rapidly and then increased slowly with the increase of the forward speed, because the increase of the forward speed at the beginning reduced the re-cutting rate of reed stalks and the vibration caused by power waste was favorable for cutting and decreased the failure rate. When the forward speed exceeded the cutting speed, it was prone to uneven stubble, miss cutting and high failure rate.

When the cutting speed was 1.2 m/s, the interactive effect of forward speed and chain conveying speed on the failure rate is shown in Figure 9b. At the same chain conveying speed, the failure rate decreased rapidly with the increase of the forward speed. At the same forward speed, the chain conveying rate had a small effect on the failure rate.

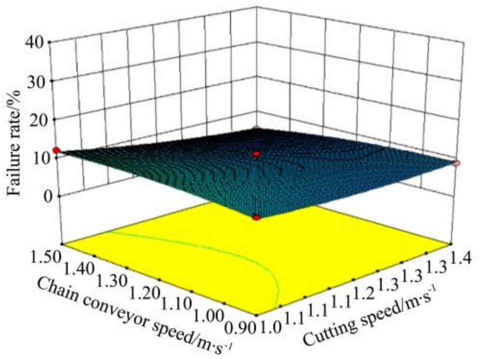
When the cutting speed was 0.8 m/s, the interactive effect of cutting speed and chain conveying speed on the failure rate is shown in Figure 9c. At the same chain conveying speed, the failure rate decreased slowly with the increase of the forward speed. At the same cutting speed, the failure rate basically stayed the same with the increase of the chain conveying speed, while the impact of the chain conveying speed on the failure rate was not as significant as the impact of the cutting speed on the failure rate.



a. $Y_1=f(A, B, 0)$



b. $Y_1=f(A, 0, C)$



c. $Y_1=f(0, B, C)$

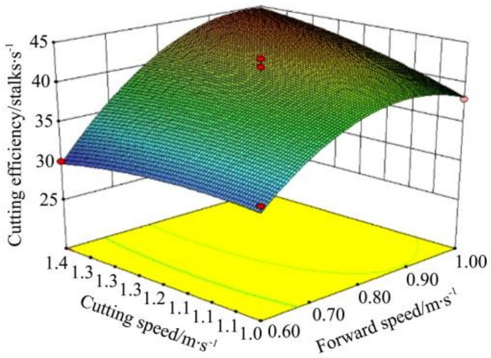
Figure 9 Influence of interactive factors on the failure rate

2) Cutting efficiency analysis

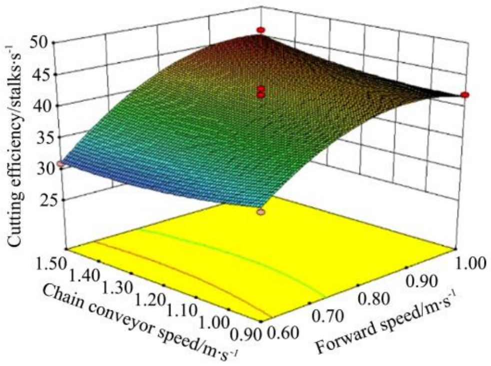
When the chain conveying speed was 1.2 m/s, the interactive effect of forward speed and cutting speed on the cutting efficiency is shown in Figure 10a. When the cutting speed was relatively low, the cutting efficiency increased first and then decreased with the increase of the forward speed. When the cutting speed was relatively high, the cutting efficiency increased rapidly with the increase of the forward speed, and the impact of the cutting speed on the cutting efficiency was not as significant as the impact of the forward speed on the cutting efficiency, because when the cutting efficiency was relatively low, the increase of the forward speed may result in unstable stubble, miss cutting and low cutting efficiency. When the cutting speed was relatively high, it increased the feed of reed stalks and the cutting efficiency.

When the cutting speed was 1.2 m/s, the interactive effect of forward speed and chain conveying speed on the cutting efficiency is shown in Figure 10b. At the same chain conveying speed, the cutting efficiency increased with the increase of the forward speed, because the increase of forward speed increased the feed of reed stalks, and at the same forward speed, the effect of the chain conveying speed on the cutting efficiency was relatively small.

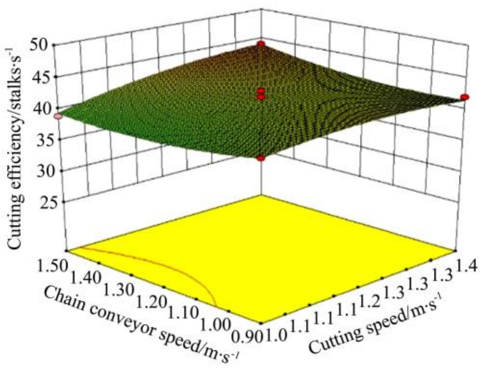
When the forward speed was 0.8 m/s, the interactive effect of cutting speed and chain conveying speed on the cutting efficiency is shown in Figure 10c. At the same cutting speed, the cutting efficiency increased slowly with the increase of the forward speed, because the increase of the chain conveying speed was favorable for conveying the cut reed stalks, and avoiding the reed stalks from blocking the cutting channels. At the same conveying speed, the cutting efficiency increased with the increase of the cutting speed, because the increase of the cutting speed reduced the miss cutting of reed stalks.



a. $Y_2=f(A, B, 0)$



b. $Y_2=f(A, 0, C)$



c. $Y_2=f(0, B, C)$

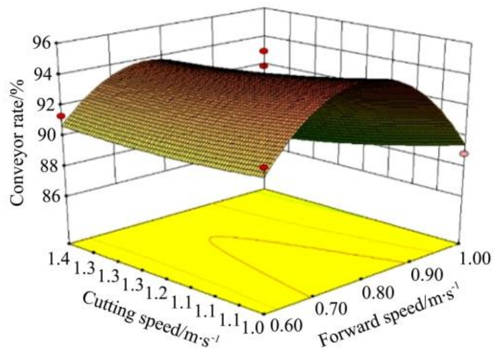
Figure 10 Influence of interactive factors on the cutting efficiency

3) Conveying rate analysis

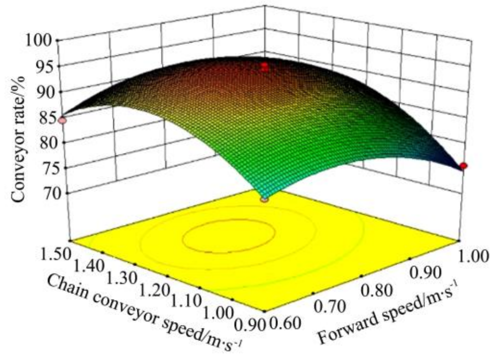
When the chain conveying rate was 1.2 m/s, the interactive effect of forward speed and cutting speed on the conveying rate is shown in Figure 11a. At the same cutting speed, the conveying rate increased rapidly first and then decreased with the increase of the forward speed, because the increase of the forward speed at the beginning reduced the falling of cut reed stalks, which was favorable for chain conveying, and increased the conveying rate rapidly. When the forward speed was too high, reed stalks were too late to cut, pushing the stalks down, resulting in unstable stubble and miss cutting, which was unfavorable for chain conveying and reduced the conveying rate.

When the cutting speed was 1.2 m/s, the interactive effect of forward speed and chain conveying speed on the conveying rate is shown in Figure 11b. At the same chain conveying speed, the conveying rate increased first and then decreased with the increase of the forward speed. At the same forward speed, the conveying rate increased first and then decreased with the increase of the chain conveying rate, because the increase of the chain conveying speed at the beginning decreased the falling of reed stalks, which was favorable for conveying. When the conveying chain speed was too high, the closed surface formed by the chain teeth was unfavorable for reed stalks to enter the chain for conveying, which may reduce the conveying rate.

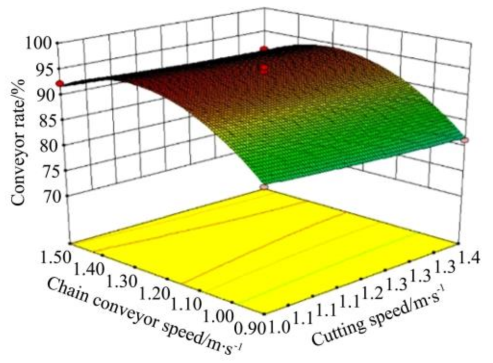
When the forward speed was 0.8 m/s, the interactive effect of cutting speed and chain conveying speed on the conveying rate is shown in Figure 11c. At the same cutting speed, the conveying rate increased first and then decreased with the increase of the chain conveying rate. At the same chain conveying speed, the cutting speed had a small impact on the conveying rate.



a. $Y_3=f(A, B, 0)$



b. $Y_3=f(A, 0, C)$



c. $Y_3=f(0, B, C)$

Figure 11 Influence of interactive factors on the conveyor rate

4.4 Parameter optimization and test verification

4.4.1 Parameter optimization

In conclusion, to achieve the best operating performance of reed harvesters, the failure rate was required to be minimized while the cutting efficiency and conveying rate were required to be maximized. To find the best combination of parameters, several target parameters shall be optimized. According to the actual production design requirements and other relevant standards, the failure rate should be less than 10%, the cutting efficiency should be greater than 35 plants/s, and the conveying rate should be greater than 90%, so the constraints are:

$$\begin{cases} Y_1 \le 10\% \\ Y_2 \ge 35 \\ Y_3 \ge 90\% \\ 0.6 \le A \le 1.0 \\ 1.0 \le B \le 1.4 \\ 0.9 \le C \le 1.5 \end{cases} \tag{12}$$

The software was applied to optimize the solution for each parameter and the optimal solution for the operating parameters of the reed harvester was: forward speed 0.85 m/s; cutting speed 1.40 m/s; chain conveying speed, 1.33 m/s; failure rate, 4.17%; cutting efficiency, 44.21 plants/s, and conveying rate, 93.60%.

4.4.2 Test verification

To verify the accuracy of the above model, a validation test was conducted at the test base of Wuxi High-tech Development Zone, Jiangsu on November 10, 2021. Considering the feasibility of the set test parameters, parameters were optimized as follows: forward speed, 0.85 m/s; cutting speed, 1.40 m/s; chain conveying speed, 1.30 m/s, failure rate, 4.38%, cutting efficiency, 43.82 plants/s, conveying rate, 92.55%. The relative errors of the test values and the optimized values were 9.8%, 5% and 1.1% respectively, displaying perfect match. The research results could provide references for the control of operating parameters and mechanism improvement of reed harvesters.

5 Conclusions

1) In the paper, a machine suitable for reed harvesting was developed, which was composed of an upper stalk-guiding device, a three-layer chain conveyor, a reciprocating double acting cutter, and a lower stalk-splitting and stalk-holding device. It effectively solves the uneven stubble, low cutting efficiency, easy fracture and blockage, and other difficulties during the conveying process of reed harvesters

2) According to the results of comprehensive multi-index response surface test, the designed reed harvester can meet the reed harvesting requirements. The parameters of the optimized reed harvester were as follows: forward speed, 0.85 m/s; cutting speed, 1.40 m/s; chain conveying speed, 1.30 m/s, failure rate, 4.38%; cutting efficiency, 43.82 plants/s; and conveying rate, 92.55%.

Acknowledgements

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