Bench cutting tests and analysis for harvesting hemp stalk

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Abstract: As a study basis in the field of design and research of harvester prototype, bench cutting test is to provide best parameters for the cutter design. In order to obtain the optimal parameters of cutter of the hemp harvester, cutting tests on hemp stalk were conducted to examine the influences of different geometrical parameters (length and edge type) of blade, different cutting speeds and stalk feeding speeds of reciprocating single movable blade and reciprocating double movable blades on the cutting performances (cutting power, cutting quality and synthesis score) by using self-designed test bench. According to features of different test factors, multi-factors orthogonal test was applied to determine the best combination of blade length, blade edge type and number of movable blade. Then with these parameters fixed, the optimal parameters for the factors of cutting speed and stalk feeding speed were obtained by quadratic-regression rotatable orthogonal test. According to the test results, the best combination of hemp stalk cutting was that using cutter with reciprocating double movable blades of long (120 mm) and serrated-edge at cutting speed of 1.1704 m/s and stalk feeding speed of 0.7079 m/s. The tests and analysis results can be applied into subsequent related researches on hemp harvesters.

Keywords: hemp stalk, hemp harvester, blade, bench cutting test, cutter design
DOI: 10.25165/j.ijabe.20171006.3475

Citation: Shen C, Zhang B, Li X W, Yin G D, Chen Q M, Xia C H. Bench cutting tests and analysis for harvesting hemp stalk. Int J Agric & Biol Eng, 2017; 10(6): 56–67.

1 Introduction

Hemp, referring in particular to industrial hemp in this paper, is a kind of crop for fiber or oil use different from marijuana as its tetrahydrocannabinol (THC) content is lower than 0.3%[1]. It mainly grows in China, Canada, and Europe[2,3]. As a stalk fiber crop, hemp fiber plays an important role in the fields of papermaking, building, and especially textile[4-6]. Characterized by comfort, moisture absorption, bacterial inhibition, heat resistance, and anti-static property[6], hemp fiber textiles have been increasingly received and valued by the public at home and abroad, and the hot trend of studying and developing hemp has been created in Europe and America[7]. China is one of the earliest countries to plant and utilize hemp[8], as well as the country with the largest hemp cultivation area around the world at present[9]. Compared with Europe and America, however, China has relatively low mechanization degree in harvesting, which is seriously disjointed with the hemp production requirements[10]. During recent five years, China's cultivation area of fiber crops like hemp has been decreased year by year[11]. As for the major reason, the rise of labor cost has resulted in the increase of hemp

Received date: 2017-07-20 **Revision date:** 2017-10-08
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harvesting cost, which further restrains the hemp growers' enthusiasm of expanding the cultivation scale. Hence, the industry development has encountered the bottleneck of mechanization level restriction[12,13], and the problem of mechanized harvesting for hemp has to be settled urgently. Study on mechanized harvesting technique of hemp is forward-looking in China[14], so it is necessary to carry out the fundamental research on hemp harvesting in the primary study in this field, such as research on hemp cutter.

In the process of studying on the cutting performance of crop stalk, if prototype is directly used to examine cutting performance in the farm field test, it will lead to issues like low repeatability of test, complex influence condition in farm field, poor working condition of sensor, low collection accuracy, and test is easily affected by season and farm field. Therefore, some scholars have developed the indoor cutting benches, and carried out cutting tests for stalk crop like ramie, rice, sugar cane, corn and so on[15-23].

In terms of stalk, the cutting process is affected by various factors, such as its physical property and quality of cutter like material of the cutter, geometric shape of cutting edge of blade[24]. In addition, some scholars studied and found that except for energy consumption, cutting speed is strongly related to the cutting quality. Thus, to obtain the best cutter parameters[25,26] through test is the foundation for the further research and development of prototype.

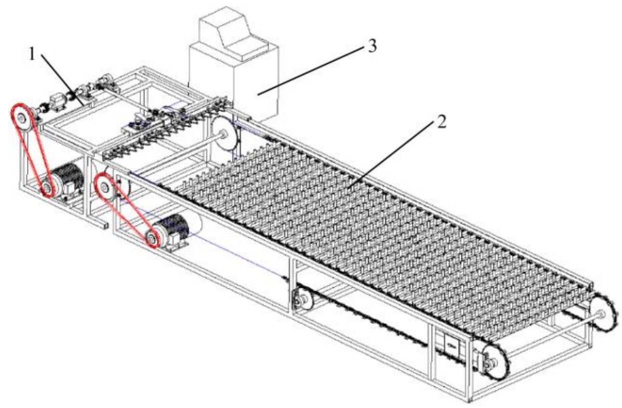
Base on the above, cutting tests of indoor bench was performed to hemp stalk, aimed at providing optimal parameters[27] in the design of cutter of prototype.

2 Materials and methods

2.1 Test equipment and material

2.1.1 Test bench

Self-designed and trial-produced stalk cutting bench[26] was applied in the tests. The bench is composed of cutting bench, stalk feeding bench and measurement and control system, as shown in Figure 1. Its concrete technical parameters are as shown in Table 1. Cutting bench can test cutters with different parameters at different cutting speeds of 0-2 m/s; stalk feeding bench can provide the speed at 0-2 m/s; measurement and control system can regulate and control the cutting speed and stalk feeding speed and record the data of cutting driving force, torque and power consumption.



1. Cutting bench 2. Stalk feeding bench 3. Measurement and control system

Figure 1 Structure schematic of hemp stalk cutting test bench

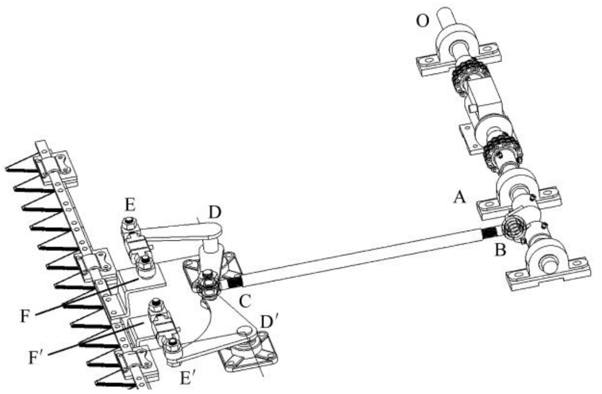
Table 1 Parameters of hemp stalk cutting test bench

Parameters	Values
Cutting speed/m s^{-1}	0-2
Stalk feeding speed/m s^{-1}	0-2
Power of cutting/kW	4
Power of stalk feeding/kW	3
Cutting width/mm	1200
Cutting height/mm	100
Torque range/N m	±20 (±0.2)
Tension force range/N	±5000 (±1)
Acquisition frequency/kHz	10

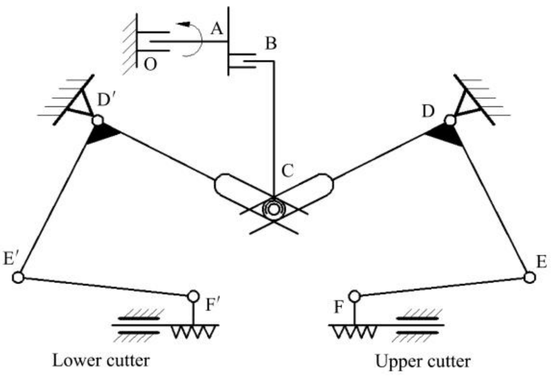
Double chutes of spatial crank-rocker-slider structure is applied in the key structure of test bench cutting transmission mechanism (Figure 2a), and its kinematic diagram is as shown in Figure 2b. In this mechanism, reciprocating motion is implemented in upper and lower cutting blades of cutter, with same speed and opposite direction, and its cutting form is double-blade cutting. If rocker CD'E' of lower cutting knife is dismounted and lower cutting blade is fixed, this mechanism can still drive rocker CDE of upper cutting blade and make it do the reciprocating motion. At this moment, cutting form of the mechanism is single-blade cutting.

3.1.2 Test material

The crop of "Wan Dama #1 (Anhui Hemp No.1)" planted in Lu'an Hemp Comprehensive Test Station of China Agriculture Research System for Bast and Leaf Fiber Crops was selected and its collection time was July 16th, 2016.



a. Cutting transmission mechanism



b. Kinematic diagram of mechanism

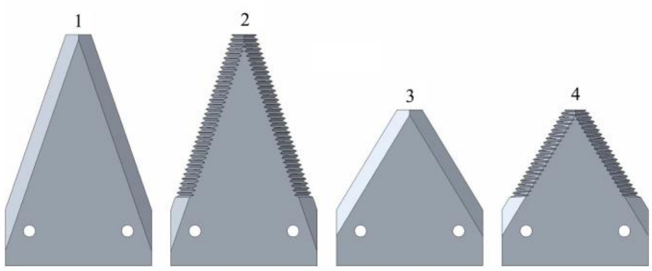
Figure 2 Cutting transmission mechanism and kinematic diagram

In order to ensure other factors were stable except for test elements, the selected hemp were divided into three classes: thin (Φ < 12 mm), medium (12 mm ≤ Φ ≤ 18 mm), thick (Φ > 18 mm), and different classes were averagely distributed into different test groups. Because the distribution of hemp in farm field were ever investigated before the test, and average hemp stalks in hemp ridge during harvesting was 38.57 per square meter, 40 hemp stalks are regularly chosen in 1 m^2 on the stalk feeding bench in each test during the bench tests.

2.2 Test method

2.2.1 Selection of test factors

In the cutting test using indoor bench, influence of different cutting speed and hemp stalk feeding speed on the cutting performance was studied under geometric parameters of different blades of reciprocating single movable blade and double movable blades. For study on the field of hemp mechanized harvest is forward-looking, and even research on the cutting part is still at the starting stage[28,29], general blades were mainly chosen in the experimental studies on geometric parameters. In this study, experimental research was conducted on the blades currently used in grain harvester and corn harvester, and the four chosen groups of blades is as shown in Figure 3. Four groups of selected blades were inter-combination of blades with two lengths (81 mm, widely applied in the grain harvester and 120 mm, widely applied in the crop harvester) and two types of blade edge (smooth-edge blade and serrated-edge blade). Width of all blades was same, i.e. 76 mm, which was equal to the driven distance of cutter arm of the bench. Therefore, geometric parameters of four groups of selected blades could be divided into two factors: blade length and blade edge type.



1. Long blade with smooth edge 2. Long blade with serrated edge 3. Short blade with smooth edge 4. Short blade with serrated edge

Figure 3 Four kinds of blades used in test

Based on above, five designed factors in the test were cutting speed, stalk feeding speed, blade edge type, blade length and number of movable blade. Because width of blades was same, different blade lengths represented different slip cutting angles. Longer the blade is, smaller the slip cutting angle is, and vice versa.

2.2.2 Establishment of appraisal indexes

Bench test is the basic research part of design of harvester prototype, aimed at theoretically providing optimal parameters in design of cutter of prototype, so its appraisal indexes are mutually connected with the indicators of cutting performance of harvester prototype. According to the condition of bench test and requirement of prototype performance indexes, energy consumption and cutting quality were mainly estimated in terms of cutting part, so the determined appraisal indexes were cutting power and number of failed stubbles (no cutting off or phloem tearing) and smaller indexes will be better. In addition, for many applied appraisal indexes will mutually contradict, the appraisal model would be built based on numerous indicators and score would be applied to comprehensively reflect the multiple index value.

‘Weight allocation’ was applied in the establishment of scoring model. In order to make the score more visualized and optimized, the non-dimensional score model was set up as follows:

$$\begin{cases} z_i = 100 - \dfrac{w_x \cdot [x_i - \min(x)]}{\max(x) - \min(x)} - \dfrac{w_y \cdot [y_i - \min(y)]}{\max(y) - \min(y)} \\ w_x + w_y = 100 \end{cases} \quad (1)$$

where, z_i is the test score of level combination of group i; x_i is the test value of cutting power of level combination of group i; y_i is the test value of number of failed stubbles of level combination of group i; min(x) is the minimum test value of cutting power of all level combination in the test; max(x) is the maximum test value of cutting power of all level combination in the test; min(y) is the minimum text value of number of failed stubbles of all level combination in the test; max(y) is the maximum text value of number of failed stubbles of all level combination in the test; w_x is the weight of cutting power factors; w_y is the weight of factors of number of failed stubbles.

For study on field of hemp harvester is forward-looking, and research on cutting parameters is still at the starting stage[28,29], it is more important to ensure the rate of cutting success of prototype than to ensure its energy-saving optimization. Thus, in the paper, weight w_x of factor of cutting power was set as 40, and weight w_y of factor of number of failed stubbles was set as 60.

In summary, appraisal indexes of the test are cutting power, cutting quality (number of failed stubbles) and synthesis score.

2.2.3 Test arrangement

Among the five factors, blade edge type, blade length and number of movable blades are obtained by type selection with two levels, and cutting speed and stalk feeding speed are continuous variables. Therefore, according to features of different factors, multi-factors orthogonal test was applied in the bench tests to determine the best parameters of two-level factors, and then the optimal parameters of factors of cutting speed and stalk feeding speed were obtained by quadratic-regression rotatable orthogonal test.

2.2.4 Test steps

Tests were orderly implemented in accordance with multi-factors orthogonal test and quadratic-regression rotatable orthogonal test. Before the test, connection of various parts, data collection system and communication system should be checked whether normal or not; hemp stalk would be inserted in stalk clamping hole on stalk feeding bench and be tightened and fixed by the rubber stopper. In the test, 40 hemp stalks were selected for each test group, and the arrangement of hemp stalks in the stalk feeding bench within the area of 1 m^2 was shown as Figure 4a; power of cutting bench was initiated to regulate the cutting speed of cutter and make it be equal to the required one; data collection channel was opened and computer was ready to collect and record the data; feeding transmission speed of stalk feeding bench was regulated, and hemp stalk would feed into the cutter and finish the cutting process at the required speed in the test. Information like torque of cutting process was collected and recorded by data collection system; power of cutting bench was off, jogging transmission bench, and then hemp stubble (as shown in Figure 4b) would return to the upper layer of the bench and number of failed stubbles would be counted and recorded; at the end of each group of test, hemp stubble on the bench and ground should be cleaned up, and each level combination was repeated for three times. Cutting parameters should be replaced after the storage of information. Test was continuously carried on in accordance the above designed operation sequence.

In the cutting process, the data collection system acquired and recorded torque signals of torque sensor in time (Figure 5). Besides, the cutting power was gained and recorded through follow-up processing for torque data (Equation (2)). The swath in every group of tests is 1 m, so the cutting power recorded every time is the cutting power less than 1 m swath.

$$P = \frac{\omega \cdot \int M(t)dt}{T} \quad (2)$$

which, P means the cutting power, W; ω indicates the crank rotational angular speed of cutting transmission mechanism, rad/s; $M(t)$ denotes the undulant curve of torque timely gained from the torque sensor, N·m; t is the time variable, s; T represents the total cutting time, s.

a. Distribution of hemp stalks in cutting test

b. Hemp stubble after cutting on the bench

Figure 4 Hemp stalk and stubble on the bench

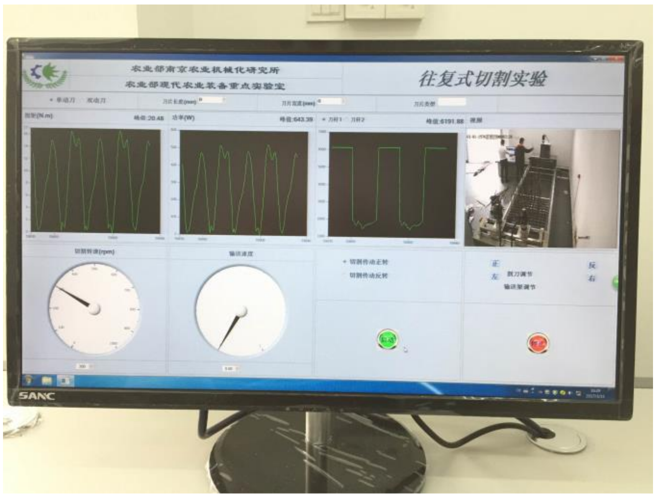


Figure 5 Real-time recording software of torque sensor

3 Multi-factors orthogonal test

3.1 Determination of factors and levels and orthogonal table

Taken cutting speed (*A*), stalk feeding speed (*B*), blade edge type (*C*), blade length (*D*), number of movable blade (*E*) as the test factors, and the factors and levels are shown in Table 2. The test was aimed at examining the interaction between cutting speed (*A*) and stalk feeding speed (*B*). For five factors were two levels, two-level orthogonal table was selected in the test. Sum of degree of freedom of five factors and interaction was:

$$\begin{aligned} & f_A + f_B + f_C + f_D + f_E + f_{A\times B} \\ & = 1+1+1+1+1+1+1 = 6 \end{aligned} \tag{3}$$

Lines of the selected orthogonal table should meet: $n \geq 6+1=7$, so $L_8(2^7)$ was chosen.

Table 2 Factors and levels of orthogonal tests

Factors/Levels	Level 1	Level 2
A: Cutting speed	High (1.2 m s^{-1})	Low (0.8 m s^{-1})
B: Stalk feeding speed	high (0.9 m s^{-1})	low (0.6 m s^{-1})
C: Blade edge type	Smooth	Serrated
D: Blade length	Long (120 mm)	Short (81 mm)
E: Number of movable blade	Double	Single

3.2 Results and analysis

3.2.1 Cutting power

Result of cutting power in each group of orthogonal test and variance calculation for given repeat tests is shown in Table 3; ANOVA of cutting power is as shown in Table 4. By ANOVA of test result of cutting power, factors *A* and *E* were significant in significance level 0.01, while factors *B*, *C*, *D* and interaction $A\times B$ were not significant. It was shown in results that cutting speed and number of movable blade were main factors for cutting power, while effect of stalk feeding speed, blade edge type, blade length and interaction between cutting speed and stalk feeding speed were not significant on cutting power. The level combination of best and smallest cutting power was *E*1*A*2 i.e. double-movable blade, and low cutting speed should be applied for cutting.

It was shown in the experimental results that driven power of cutter itself to a large extent could determine the power of cutter in the process of cutting hemp. Faster the cutting speed is, larger the cutting power is; when using the group of double movable blade, it could drive one more group of movable blade than that of single blade group, and the mass of driven movable blade was twice of single movable blade group, but under the same cutting speed, the speed of single blade of double movable blades was half of that of single movable blade. For kinetic energy of cutter was proportional to its mass and quadratic of speed, the driven power of single movable blade group was larger.

Table 3   Variances calculation for cutting power and number of failed stubbles

Table header		*A*	*B*	*A*×*B*	*C*	*D*	*E*		Cutting power/W				Number of failed stubbles			
		1	2	3	4	5	6	7	x_{i1}	x_{i2}	x_{i3}	Sum x_i	y_{i1}	y_{i2}	y_{i3}	Sum y_i
1		1	1	1	1	1	1	1	469	502	448	1419	25	21	20	66
2		1	1	1	2	2	2	2	877	865	932	2674	18	15	26	59
3		1	2	2	1	1	2	2	804	776	787	2367	19	20	17	56
4		1	2	2	2	2	1	1	605	552	522	1679	17	15	11	43
5		2	1	2	1	2	1	2	475	396	406	1277	44	33	38	115
6		2	1	2	2	1	2	1	554	537	571	1662	9	14	8	31
7		2	2	1	1	2	2	1	558	641	528	1727	28	37	40	105
8		2	2	1	2	1	1	2	407	569	310	1286	8	5	8	21
Cutting power	T_1	8139	7032	7106	6790	6734	5661	6487	$\Sigma\Sigma x_{ij}^2$=8924963 T=14091 Σx_i^2=26614865 S_T=651784.63 S_{T1}=598443.29				$\Sigma\Sigma y_{ij}^2$=13092 T=496 Σy_i^2=38474 S_T=2841.33 S_{T1}=2574			
	T_2	5952	7059	6985	7301	7357	8430	7604								
	k_1	2034.75	1758	1776.5	1697.5	1683.5	1415.25	1621.75								
	k_2	1488	1764.75	1746.25	1825.25	1839.25	2107.5	1901								
	S	199290.38	30.38	610.04	10880.04	16172.04	319473.38	51987.04								
Number of failed stubbles	T_1	224	271	251	342	174	245	245								
	T_2	272	225	245	154	322	251	251								
	k_1	56	67.75	62.75	85.5	43.5	61.25	61.25								
	k_2	68	56.25	61.25	38.5	80.5	62.75	62.75								
	S	96	88.17	1.5	1472.67	912.67	1.5	1.5								

Note: *A* is cutting speed, *B* is stalk feeding speed, *C* is blade edge type, *D* is blade length, *E* is number of movable blade, *A*×*B* is interaction of cutting speed and stalk feeding speed, x_{ij} is the cutting power value of *i*th test level combination and *j*th repeated test, y_{ij} is the number of failed stubbles of *i*th test level combination and *j*th repeated test, x_i is the sum value of cutting power of *i*th test level combination, y_i is the sum value of number of failed stubbles of *i*th test level combination, *T* is sum of test value, S_T is total sum of deviation squares, S_{T1} is sum of deviation squares of each column, T_1 is sum of level 1, T_2 is sum of level 2, k_1 is average of level 1, k_2 is average of level 2, *S* is sum of deviation squares. The same below.

Table 4   ANOVA for cutting power and number of failed stubbles

source	Sum of squares		*df*	Mean square		*F*- ratio	
	Cutting power	Number of failed stubbles		Cutting power	Number of failed stubbles	Cutting power	Number of failed stubbles
A	199290.38	96	1	199290.38	96	32.17***	6.07**
B	30.38	88.17	1	30.38	88.17	0.00	5.57**
A×*B*	610.04	1.5	1	610.04	1.5	0.10	0.09
C	10880.04	1472.67	1	10880.04	1472.67	1.76	93.13***
D	16172.04	912.67	1	16172.04	912.67	2.61	57.71***
E	319473.38	1.5	1	319473.38	1.5	51.563***	0.09
e_1	51987.04	1.5	1	51987.04	1.5		
e_2	53341.33	267.33	16	3333.83	16.71	$F_{0.90}(1, 17)$=3.03 $F_{0.95}(1, 17)$=4.45 $F_{0.99}(1, 17)$=8.40	
e	105328.38	268.83	17	6195.79	15.81		
T	651784.63	2841.33	23	28338.46	123.54		

Note: e_1 is error of empty column, e_2 is error of repetition, *e* is total error, *T* is the sum value. *, ** and *** respectively means significant differenced at p<0.1, p<0.05 and p<0.01. The same below.

3.2.2 Cutting quality

Number of failed cutting stubbles (no cutting off or phloem tearing) was taken as the appraisal index of cutting quality, and the experimental result of number of failed stubbles in each group of orthogonal test and variance calculation for given repeat tests is as shown in Table 3; ANOVA of number of failed stubbles is shown in Table 4.

Through ANOVA of experimental result of number of failed stubbles, factors *C* and *D* were significant in significance level 0.01, factors *A* and *B* were significant in significance level 0.05, while factor *E* and interaction *A*×*B* were not significant. It was shown in result that blade edge type and blade length were main factors that affected the cutting quality, and cutting speed and stalk feeding speed were secondary factors that affected the cutting quality, while influence of number of movable blade and interaction between cutting speed and stalk feeding speed on cutting quality were not significant. The best combination of cutting quality was *C*2*D*1*A*1*B*2, i.e. faster cutting speed, lower stalk feeding speed, and serrated- long edge blade should be used.

The experimental result showed that cutting and feeding speed and geometrical shape of blade would have influence on the success rate of hemp cutting.

3.2.3 Synthesis score

Calculation should be taken based on the established score model (Equation (1)), test results and variance calculation of score of each group of orthogonal test are shown in Table 5; ANOVA of score analysis is shown as Table 6. For the degree of freedom of error in the empty column was only one, and variance of item *A*, *B* and interaction item $A\times B$ were relatively small, *A*, *B* and interaction $A\times B$ were classified as the errors to calculate the variance of corrected error.

Through variance analysis on experimental results of score, factor *C*, *D* and *E* were significant at significance level 0.05. The result showed that blade edge type, blade length and the number of movable blade were the factors that affected the score. The combination with the highest and best score was *D*1*C*2*E*1, i.e., serrated-long edge blade and cutter with double movable blades should be applied.

Table 5 Variances calculation for scores

Table header	*A*	*B*	$A\times B$	*C*	*D*	*E*		Score z_i
	1	2	3	4	5	6	7	
1	1	1	1	1	1	1	1	67.21
2	1	1	1	2	2	2	2	35.74
3	1	2	2	1	1	2	2	46.45
4	1	2	2	2	2	1	1	74.45
5	2	1	2	1	2	1	2	40.00
6	2	1	2	2	1	2	1	82.59
7	2	2	1	1	2	2	1	33.50
8	2	2	1	2	1	1	2	99.74
T_1	223.85	225.54	236.19	187.16	295.99	281.4	257.75	
T_2	255.83	254.14	243.49	292.52	183.69	198.28	221.93	T=479.68
k_1	55.96	56.39	59.05	46.79	74.00	70.35	64.44	Σz_{i2}=32987.25
k_2	63.96	63.56	60.87	73.13	45.92	49.57	55.48	S_T=4224.79
S	127.85	102.25	6.67	1387.60	1576.42	863.62	160.39	

Note: z_i is the score of *No.i* test level combination.

Table 6 ANOVA for scores

Source	Sum of squares	*df*	Mean square	*F*-ratio
A	127.85	1	127.85	
B	102.25	1	102.25	
$A\times B$	6.67	1	6.67	
C	1387.60	1	1387.60	13.98**
D	1576.42	1	1576.42	15.88**
E	863.62	1	863.62	8.70**
e	160.39	1	160.39	$F_{0.90}(1,4)$=4.55
Crt. e	397.15	4	99.29	$F_{0.95}(1,4)$=7.71
T	4224.79	7	464.45	$F_{0.99}(1,4)$=21.20

Note: *e* is error, *Crt. e* is corrected error.

4 Quadratic regression of orthogonal rotating combinatorial test

4.1 Determination of factors and levels

Among five factors of bench test, blade edge type (*C*), blade length (*D*) and number of movable blade (*E*) are obtained by type selection, and level number is fixed as two, and only cutting speed (*A*) and stalk feeding speed (*B*) are continuous variables which could be obtained by regulated by transducer. Therefore, two factors would be chosen to perform the test in the quadratic regression of orthogonal rotating combinatorial test: cutting speed (*A*) and stalk feeding speed (*B*). Other factors that were not involved in the quadratic regression of orthogonal rotating combinatorial test should be fixed as the best level combination of score value in the orthogonal test.

According to methods of quadratic regression of orthogonal rotating combinatorial test [30], the test number n should meet the following equation:

$$n = m_c + 2p + m_0 \tag{4}$$

where, p is number of test factors, and that is 2 in this test; $2p$ is the number of test point on the sphere with diameter $\rho=\gamma$ in the scope of canonical variate, and γ is the asterisk arm; m_c is the number of test point on the sphere with diameter $\rho=p^{0.5}$ in the scope of canonical variate; m_0 is the number of test point in the center of factor domain.

When p=2, the design parameters could be concluded by querying the parameter table of quadratic regression of orthogonal rotating combinatorial test that: γ=1.414, m_0=5, which totally needed 16 times. When quadratic orthogonal design is conducted directly, coding will be performed as follows:

The value range can be set as:

$$x_{1j} \le x_j \le x_{2j} \qquad j = 1, 2, \ldots p \tag{5}$$

Now, let the code value of x_{1j} and x_{2j} be $-\gamma$ and γ, so the zero level is:

$$x_{0j} = \frac{x_{1j} + x_{2j}}{2} \qquad j = 1, 2, \ldots p \tag{6}$$

Radius is:

$$\Delta_j = \frac{x_{2j} - x_{1j}}{2\gamma} \qquad j = 1, 2, \ldots p \tag{7}$$

Then the code value –1 and 1 should respectively correspond to $x_{0j} - \Delta_j$ and $x_{0j} + \Delta_j$.

The code table of factors in the test is shown in Table 7.

Table 7 Factors and levels of the test

Factor	Cutting speed x_1/m s^{-1}	Stalk feeding speed x_2/m s^{-1}
Radius Δ	0.2828	0.2121
$-\gamma$	0.8000	0.5000
–1	0.9172	0.5879
0	1.2000	0.8000
1	1.4828	1.0121
γ	1.6000	1.1000

Note: γ is asterisk arm, and value is 1.414.

4.2 Results and analysis

4.2.1 Test results

Three tests were repeated for each level combination. For the convenience of recording and calculation, decimals were cut down as far as possible. The cutting power and number of failed stubbles were analyzed with the sum of three tests. Table 8 shows the sum of evaluation indexes in the three repeated tests. At this time, the cutting power is equal to the cutting power under the swath of 3 m, and the number of failed stubbles is equal to the number of failed stubbles in 3 m^2. In addition, the calculation method of synthesis score is the same as the calculation method of synthesis score in orthogonal test (as shown in Equation (1)).

Table 8 Results of test

Number	Cutting speed x_1/m s^{-1}	Stalk feeding speed x_2/m s^{-1}	Cutting power y_{1i}/W	Failed stubbles y_{2i}	Scores y_{3i}
1	1.4828	1.0121	1987	47	27.21
2	1.4828	0.5879	2123	31	47.75
3	0.9172	1.0121	1225	56	36.19
4	0.9172	0.5879	1476	33	64.06
5	0.8000	0.8000	1098	53	44.62
6	1.6000	0.8000	2433	29	41.54
7	1.2000	0.5000	1570	24	75.09
8	1.2000	1.1000	1473	50	37.99
9	1.2000	0.8000	1421	22	82.63
10	1.2000	0.8000	1497	28	71.12
11	1.2000	0.8000	1579	21	79.43
12	1.2000	0.8000	1326	19	90.09
13	1.2000	0.8000	1373	17	91.76
14	1.2000	0.8000	1421	27	74.93
15	1.2000	0.8000	1385	22	83.70
16	1.2000	0.8000	1311	19	90.54

4.2.2 Regression model

According to the test result of Table 8, DPS software[31] was applied to conduct quadratic polynomial stepwise regression analysis for data, and consequently to obtain regression models of cutting power, number of failed stubbles and synthesis score.

$$\begin{aligned} y_1 = {} & 4776.4502 - 4641.70453x_1 \\ & - 3320.15280x_2 + 2381.438460x_1^2 \\ & + 1522.557263x_2^2 + 479.311419x_1x_2 \end{aligned} \tag{8}$$

$$\begin{aligned} y_2 = {} & 283.854012 - 304.0589078x_1 \\ & - 213.7141215x_2 + 128.1398606x_1^2 \\ & + 183.3597522x_2^2 - 29.17547766x_1x_2 \end{aligned} \tag{9}$$

$$\begin{aligned} y_3 = {} & -420.67645 + 606.756950x_1 \\ & + 428.217252x_2 - 268.4581925x_1^2 \\ & - 327.703453x_2^2 + 30.55089304x_1x_2 \end{aligned} \tag{10}$$

where, y_1 is cutting power, W; y_2 is number of failed stubbles; y_3 is synthesis score; x_1 is cutting speed, m/s; x_2

is the stalk feeding speed, m/s.

4.2.3 Model test

(1) Fitting

By using the DPS software, in the regression equation of cutting power in Equation (8), it calculated and obtained that correlation coefficient R=0.972585, determination coefficient R^2=0.9459, residual standard deviation SSE=99.2863, adjusted correlation coefficient R_a=0.958583; in the regression equation of number of failed stubbles in Equation (9), it calculated and obtained that correlation coefficient R=0.962802, determination coefficient R^2=0.9270, residual standard deviation SSE=4.3180, adjusted correlation coefficient R_a=0.943654; in the regression equation of scores in Equation (10), it calculated and obtained that correlation coefficient R=0.963107, determination coefficient R^2=0.9276, residual standard deviation SSE=7.2991, adjusted correlation coefficient R_a=0.944120. Overall data of regression model reflected that regression equation was equipped with high degree of fitting.

(2) F-examination

F-examination could reflect the significance of regression equation and Table 9 is ANOVA table of regression model.

According to Table 9, F-examination of regression model of cutting power was 34.9831, and the significant level p was 0.0000, which were respectively larger than F in the loss-faulty test, i.e. 1.8422 and far less than p in the loss-faulty test, i.e. 0.2275. Therefore, the model could be applied.

Table 9 ANOVA of regression model

Index	Source of variation	Sum of squares	*df*	Mean square	*F* value	*p* value
Cutting power	Regression	1724276.0509	5	344855.2102	34.9831	0.0000
	Residual	98577.6991	10	9857.7699		
	Testing lack of fit	43490.8241	3	14496.9414	1.8422	0.2275
	Error	55086.8750	7	7869.5536		
	Total	1822853.7500	15			
Number of failed stubbles	Regression	2367.2960	5	473.4592	25.3928	0.0000
	Residual	186.4540	10	18.6454		
	Testing lack of fit	81.5790	3	27.1930	1.8150	0.2322
	Error	104.8750	7	14.9821		
	Total	2553.7500	15			
Score	Regression	6823.4164	5	1364.6833	25.6149	0.0000
	Residual	532.7686	10	53.2769		
	Testing lack of fit	129.2852	3	43.0951	0.7477	0.5572
	Error	403.4834	7	57.6405		
	Total	7356.1850	15			

Test value in the regression model of number of failed stubbles is 25.3928 and the significant level p was 0.0000, which were respectively larger than F in the loss-faulty test, i.e. 1.8150 and far less than p in the loss-faulty test, i.e. 0.2322. Therefore, the model could be applied.

Test value in the regression model of number of failed stubbles was 25.6149 and the significant level p was 0.0000, which were respectively larger than F in the loss-faulty test, i.e. 0.7477 and far less than p in the loss-faulty test, i.e. 0.5572. Therefore, the model could be applied.

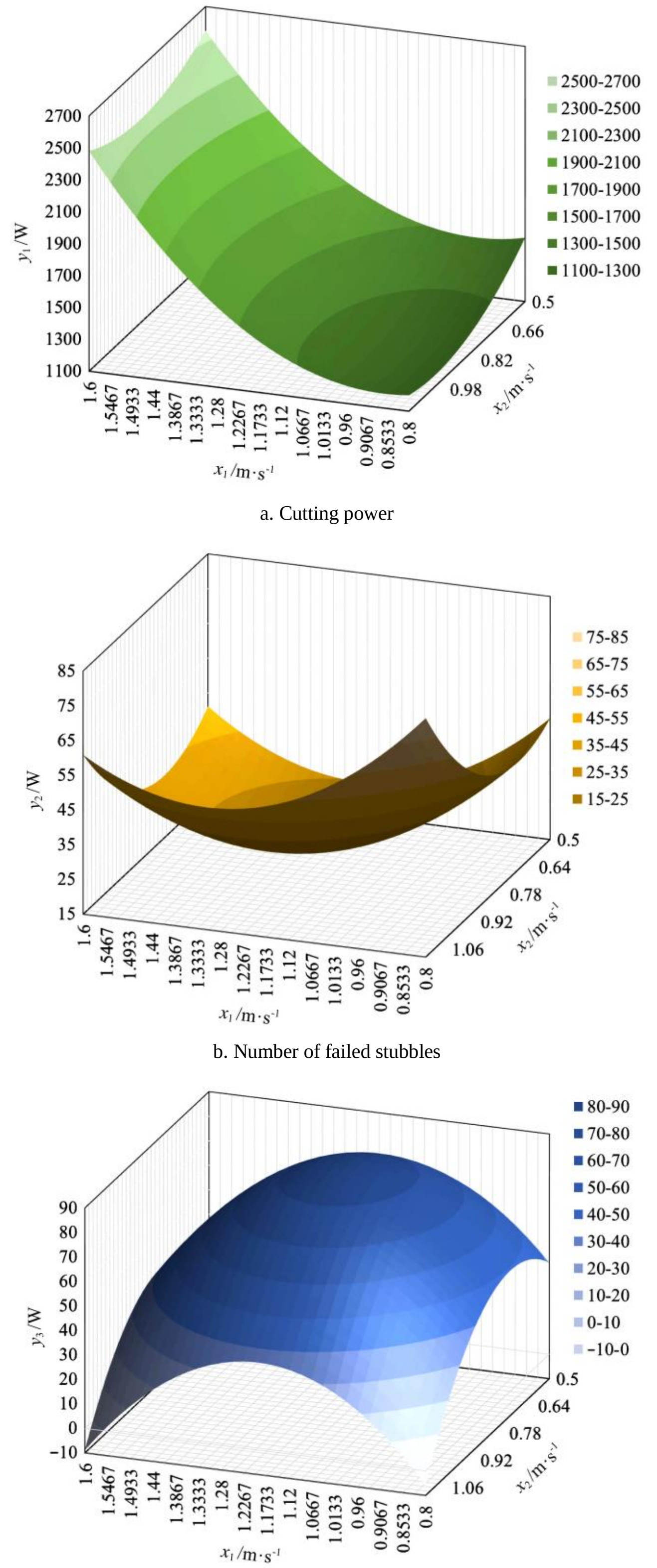
(3) Durbin-Watson statistic

Durbin-Watson statistic (D-W statistic) is the magnitude that is used to estimate whether residual distribution will follow normal distribution or not, and normal distribution characteristics of residual is one of the reference values to inspect whether regression model is applied or not. When D-W statistic is 2, it meant that residual distribution is consistent with normal distribution, so if D-W statistic is close to 2, then the established regression model will be more consistent with the real condition. By calculation of DPS software, D-W statistic of regression model of cutting power was 2.1019, and that of number of failed stubbles was 1.9520, and that of scores was 1.8748. Therefore, the value met the requirement, and the established model was close to the real condition.

4.2.4 Optimum values of model

The surface of regression model is drawn as Figure 6.

Optimum values on the surface of regression model of cutting power were (0.8788, 0.9520, 1156.5946); that of number of failed stubbles were (1.2642, 0.6834, 18.6331); that of score were (1.1704, 0.7079, 85.9558).



a. Cutting power

b. Number of failed stubbles

c. Score

Note: y_1 is cutting power, y_2 is number of failed stubbles, y_3 is score, x_1 is cutting speed, x_2 is stalk feeding speed.

Figure 6 Surface of regression mode of cutting power, number of failed stubbles and score

In conclusion, for cutting power, when cutting speed was 0.8788 m/s, stalk feeding speed was 0.9520 m/s, cutting power would be minimum, i.e. 1156.5946 W (for 3 m swath, equal to 385.5315 W/m); for cutting quality, the evaluation index was number of failed stubbles (no cutting off or phloem tearing), and when cutting speed was 1.2642 m/s, stalk feeding speed was 0.6834 m/s, the number of failed stubbles would be minimum, i.e. 18.6331 (in 3 m^2 area, equal to 6.2110/m^2); for synthesis score, when cutting speed was 1.1704 m/s, stalk feeding speed was 0.7079 m/s, the score was highest, i.e. 85.9558, at this situation, the cutting power was 1415.7523 W (equal to 471.9177 W/m), and the number of failed stubble was 19.9389 (equal to 6.6463/m^2).

4.2.5 Analysis

The cutting power is mainly comprised of driving power of cutter and the power of stalk being cut off. When the cutting speed is high, the cutting power will be great. Theoretically, the driving power of cutter is in direct proportion to the square of speed, and increases sharply with the rise of cutting speed. Such phenomenon is also reflected in the test results. In addition, in terms of the stalk feeding speed, if the stalk feeding speed is high, more hemp stubbles can be cut, and the work consumed by material damage will be great. In theory, the stalk material damage power is in direct proportion to the stalk feeding speed. But the model surface of test results shows that the factor of stalk feeding speed does not have a huge influence on the cutting power. Therefore, it is obtained that cutting power is generated by driving power of cutter to a great extent, while the influence of power produced by hemp stalk material damage is relatively small.

As for the number of failed stubbles, when the cutting speed is low and stalk feeding speed is high, some hemp stalks will be transported before cutting, so cutting failure will happen easily. On the contrary, when the cutting speed is high and stalk feeding speed is low, the phenomenon of repeated cutting will happen, and the cutting stubbles might be torn or destroyed easily. The test results also reflected this phenomenon. Therefore, the theoretical optimum speed combination with the minimum number of failed stubbles should be selected according to the test.

In terms of the score, the speed combination with optimum score is closer to the speed combination with optimum number of failed stubbles, and cutting quality has a greater influence on the synthesis score than cutting power. As for the reason, the weight of cutting quality selected in evaluation model establishment is higher.

5 Conclusions

(1) In order to obtain the optimal parameters of cutter for design of the hemp harvester, cutting tests (Multi-factors orthogonal test and quadratic regression of orthogonal rotating combinatorial test) on hemp stalk were conducted in this study.

(2) Multi-factors orthogonal test was applied in the bench test using the self-designed test bench; according to the test objective, the influences of cutting speed, stalk feeding speed, blade edge type, blade length and number of movable blade on cutting power, cutting quality and synthesis score were examined. For cutting power, factors with significant influence were number of movable blade, and cutting speed in order of significance, and the best level combination was that the cutting speed should be slow (0.8 m/s), and cutter of reciprocating double movable blades should be applied, in addition that stalk feeding speed, blade length and type of blade edge have no significant influence on cutting power; for cutting quality, taken cutting failed stubbles (no cutting off or phloem tearing) as the appraisal index, factors with significant influence were respectively type of blade edge, blade length, cutting speed and stalk feeding speed in order of significance, and the best combination was that using serrated-edge blade and long blade (120 mm), with fast cutting speed (1.2 m/s) and low stalk feeding speed (0.6 m/s). In addition, influence of number of movable blade on cutting quality was not significant; for synthesis score, factors with significant influence were respectively blade length, type of blade edge and number of movable blade in order of significance, and the best level combination was that long (120 mm) serrated edge blade and cutter of reciprocating double movable blade.

(3) Combined with the level combination with highest score in the orthogonal test, quadratic regression of orthogonal rotating combinatorial test was conducted on the two groups of parameters which could be adjustable continuously, i.e. cutting speed and stalk feeding speed, to examine the influence of cutting speed, stalk feeding speed and mutual effect of these two factors on cutting power, cutting quality and synthesis score, and to build the quadratic regression function respectively. The optimal solution could be gained from regression function. For cutting power, when cutting speed was 0.8788 m/s, stalk feeding speed 0.9520 m/s, the cutting power was minimum, i.e. 385.5315 W/m; for cutting quality, taken cutting failed stubbles as the appraisal index, when cutting speed was 1.2642 m/s, stalk feeding speed 0.6834 m/s, the number of cutting failed stubbles was smallest, i.e. 6.2110/m^2; for synthesis score, when cutting speed was 1.1704 m/s, stalk feeding speed 0.7079 m/s, the score was highest, i.e. 85.9558, and at this situation, the cutting power was 471.9177 W/m, the number of failed stubble was 6.6463/m^2.

(4) The tests results showed that the best combination of hemp cutting test was that using cutter of reciprocating double movable blades and long (120 mm) serrated edge blade with cutting speed of 1.1704 m/s, stalk feeding speed of 0.7079 m/s. The optimal parameters combination of hemp cutting adopted in the test was reasonable, and experimental analysis results can be applied into subsequent related researches on hemp harvester.

Acknowledgments

We greatly appreciate the careful and precise reviews by the anonymous reviewers and editors. This research was financially supported by the National Key R&D Program of China (2016YFD0701405-02), China Agriculture Research System for Bast and Leaf Fiber Crops (CARS-19-E22) and the Agricultural Science and Technology Innovation Program of Chinese Academy of Agricultural Sciences (ASTIP, CAAS).

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