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Development and experiment on 4LZ-4.0 type double speed and double action rice combine harvester

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ABSTRACT. *This research was conducted to assess the performance of a combine harvester, model number 4LZ-4.0 under different threshing functional parameters such as Speed of high/low speed cylinder, cylinder-concave clearance and linear speed of concave sieve. An indoor experiment was conducted using the double-speed double-action threshing and separating unit. These functional parameters were set at 5 levels. The responses were obtained in terms of broken rate, impurity rate and loss rate. Multi-objective variable optimization was performed using Design-Expert software. Analysis of variance was done to determine the significant effects of the factor variations on the response values. Design-Expert software was used to present response surface graphs that were used to describe the variations of the responses as the factors changed from one level to the other. Results showed that with an increase in speed of high/low speed cylinder from 15.42/18.50-22.92/27.50m/s, the percentage of broken rate increased significantly from 0.15-1.13% respectively. At cylinder speeds of 15.42/18.50m/s and 22.92/27.50m/s rpm, the impurity rate increased from 0.31-1.62% respectively. It was also realised that varying the speed of high/low speed cylinder had a significant effect on the broken rate and impurity rate. The impurity rate increased with an increase in Linear speed of concave sieve from 0.40-1.60 m/s, the percentage of impurity rate increased significantly from 0.31-1.62% respectively. However, the lowest impurity rate was obtained at an average linear speed of concave sieve of 0.99 m/s.Furthermore, it was realised that increasing the cylinder-concave clearance from 16-30 mm, equally increased the percentage of loss rate from 1.78%-2.93%. From the results obtained, it was suggested that operating the threshing cylinder at a speed of high/low speed cylinder of 18.31/21.97 m/s, cylinder-concave clearance of 22.60 mm and linear velocity of rotary concav of 0.99m/s , gave a better performance of the machine. Field tests show that the prototype has stable performance, with the loss rate, impurity rate and breakage rate of 1.74%, 0.45% and 0.34% respectively. With each performance index superior to the test standard, this device solves the contradiction between impurity removal, entrapment and grain breakage loss during the harvest of Yongyou 15 super hybrid rice effectively.*

KEYWORDS: *Longitudinal axial flow; Threshing and separating unit; Functional parameters; Speed of high/low speed cylinder; Linear speed of concave sieve*

1. Introduction

Compared with conventional rice, super hybrid rice is characterized by high yield, dense growth, thick stems, large residue to product ratio (RPR), high moisture content in stems, etc(Xu et al., 2019;Hao et al., 2018;Wei et al., 2018). There are lots of mountains and hills in the Southern part of China, and the fields are small with dispersed heights. This makes the work environment unfit for large-size combine harvesters. Tracked whole-feeding combine harvesters are mainly used in rice harvesting in the hilly areas of Southern China currently, and these characteristics of super hybrid rice have posed higher requirements for the operating performance of combine harvesters(Xin et al., 2018;Chen, 2019). In order to adapt to the bad working conditions and improve the operation quality and efficiency of mechanized paddy harvesting in the South of China, a medium sized rice combined harvester was designed with low loss rate and high cleaning efficiency.

As the main component of the combine harvester, the threshing and separation device plays a decisive role in the performance of the whole machine. Most whole-feeding rice combine harvesters use longitudinal axial flow threshing and separating units. In order to optimize longitudinal axial flow threshing and separating units and improve the efficiency and quality of mechanized harvesting of rice, domestic and foreign scholars have conducted a lot of research on threshing and separating units of harvesters(Chen et. al., 2011). Alizadeh et al researched on an axial flow grain thresher to determine and select the appropriate threshing drum speed and crop moisture content for reducing grain damage and producing better quality of grain in post-harvest operations. Results revealed that the highest broken grains of 0.677% was recorded at drum speed of 850 rpm and paddy moisture content of 17% and the least value was obtained at drum speed of 450 and 550 rpm and paddy moisture content of 23%(Alizadeh et al., 2010). Liu Zhenghuai et al(Liu et al., 2018;Liu et al., 2018).studiyd the threshing and separating unit with a "single speed cylinder & rotary concave" structure in response to the difference in the connection force of grains on the same panicle. The working efficiency and performance of this unit are significantly improved in comparison with the threshing and separating unit with a fixed grid concave structure. Results revealed that the least broken rate of 0.34% was recorded at drum speed of 550 rpm and paddy moisture content of 24.6%.Li Yaoming et al(Li et al., 2018).developed a concave sieve structure supported by a hydraulic cylinder. The position of the concave sieve is changed by the hydraulic cylinder to achieve cylinder-concave clearance adjustment. More concretely, when the feeding rate was increased from 3.4 kg/s to 6.0 kg/s, and separating loss was increased from 0.54% to 1. 08%．Xie Fangping et al(Xie et al., 2019).designed a threshing cylinder with adjustable diameter. By adjusting the diameter of the threshing cylinder, the cylinder-concave clearance is changed to meet threshing and separating requirements at different feed rates.

The assessment of performance of the threshing unit in the 4LZ-4.0 model combine harvester is very important for an efficient utilization of the machine. Threshing speed of high/low speed cylinder, linear speed of concave sieve,cylinder-concave clearance and grain moisture content are some of the functional parameters of a threshing machine that affects the broken rate, impurity rate and loss rate in the threshing unit. This research sought to determine the optimum threshing conditions for a 4LZ-4.0 model combine harvester. Probes into the comprehensive efficiency of the new double-speed rotary threshing and separating unit in terms of threshing and separating performance improvement and loss reduction, thereby providing a reference for the design of the adaptive regulatory threshing and separating system of combine harvesters.

2. Materials and method

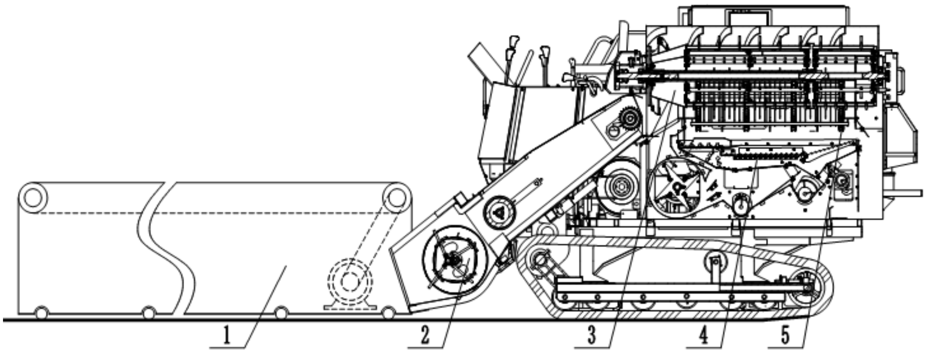
An indoor performance evaluation test was carried out to investigate the effect of varying levels of factors such as threshing cylinder speed, concave clearance and linear speed of concave sieve on the performance of a self-propelled 4LZ-4.0 type rice combined harvester threshing loss rate , broken rate and impurity rate. Regression analysis was then performed on the values of responses obtained after the experiment. Regression equations obtained, were then used to determine the optimum values of the cylinder speed, concave clearance and speed of concave sieve for a more efficient and effective functioning of the threshing and separation device.

2.1. Test conditions

The performance test bench for the double-speed double-action threshing and separating unit is mainly composed of rice plant conveying table, double-speed double-action threshing and separating unit, adjustable-speed motor, console, etc., as shown in Figure1.The rice plant conveying table is a height-adjustable conveyor belt, and its conveying speed is 0~3 m/s adjustable steplessly. The power of the adjustable-speed motor is 15 kW, and the speed of the threshing cylinder is adjustable steplessly. The power of the driving motor of the rotary concave sieve is 2 kW. Each motor is adjusted by the variable-frequency console, and related data are statistically analyzed by the acquisition system. The selected test material is "Yongyou 15#", which is widely planted in Zhejiang province, China. The basic characteristic parameters of rice are as shown in table 1, the feed rate is 4.0 kg/s.

Table 1 Basic characteristic parameters of rice

Items	Parameters
Height of plants/cm	100 ~ 115
Length of ears /cm	17.5 ~ 26.4
Moisture content of grains/%	23.3 ~ 24.5
Moisture content of stems/%	45.4 ~ 48.6
Grain-grass ratio (stubble height 15cm)	3:1
Thousand kernel weight/g	30.6
Yield per unit area/ kg/hm^2	10020



1. Conveying device 2. Head feeding device 3. Double-speed threshing cylinder 4. Grain Outlet 5. Rotary concave sieve

Fig. 1. Schematic diagram of the experimental set up

Figure 1 shows a schematic diagram of how the experiment was set up with the conveyor belt and the combine harvester. It also shows some components of the combine harvester that was used for the experiment. For each experimental run n, harvested crops were fed into the threshing machine using the conveyor belt, and then transferred into the threshing unit by an auger. Crops of peculiar masses were placed on the conveyor belt over a length of 8 m. Each metre length had equal mass of paddy. This was to ensure uniform material flow rate onto the cutter bar.

The double-speed threshing cylinder is mainly composed of feed section, low speed threshing cylinder section, high speed threshing cylinder section, intermediate device, low speed cylinder shaft, high speed cylinder shaft, etc., as shown in Figure 2. Both the high and low speed threshing cylinders are composed of spoke plates, rack bars (6 in total), nail teeth (81 in total), etc., and the feed auger is consolidated with the low speed threshing cylinder. The low speed cylinder shaft is a hollow structure, and the high speed cylinder shaft is mounted in the low speed cylinder shaft by means of the bearing housing. The bevel gears driving the high/low speed threshing cylinders are mounted in the driving box, which is located on the left side of the low speed threshing cylinder. The bevel gears are respectively consolidated with the high/low speed cylinder shafts to drive the high/low speed threshing cylinders at different transmission ratios.

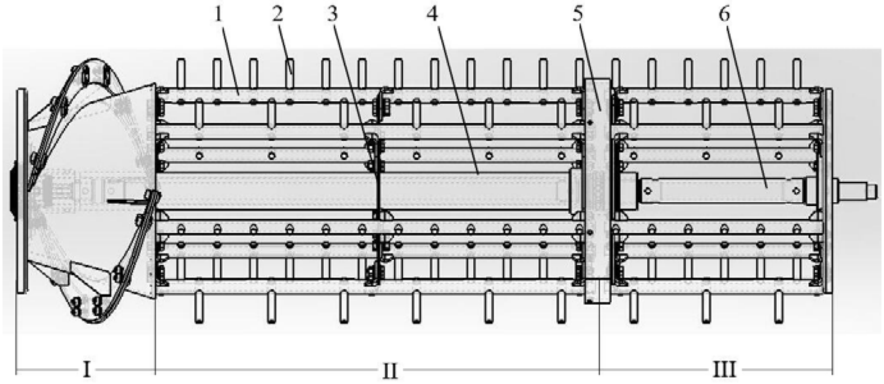
The high/low speed threshing cylinders thresh panicles mainly relying on the nail teeth combined with the rotary concave sieve, so that grains obtain energy and are separated from panicle heads, thereby achieving threshing and separation. According to the mathematical model established by domestic and foreign scholars between the connection force of grains and the linear speed of threshing components, the linear speed is 18~26m/s during rice threshing with longitudinal axial-flow cylinder nail teeth, so the relation between the high/low speed cylinder speeds is determined below:

$$n_2 = k \bullet n_1 \tag{1}$$

where; n_1 is low speed threshing cylinder speed, m/s;

n_2 is high speed threshing cylinder speed, m/s;

k is ratio of the minimum linear speed required by the threshing cylinder to optional linear speed, taken as $k=22$ m/s /18 m/s≈1.2.

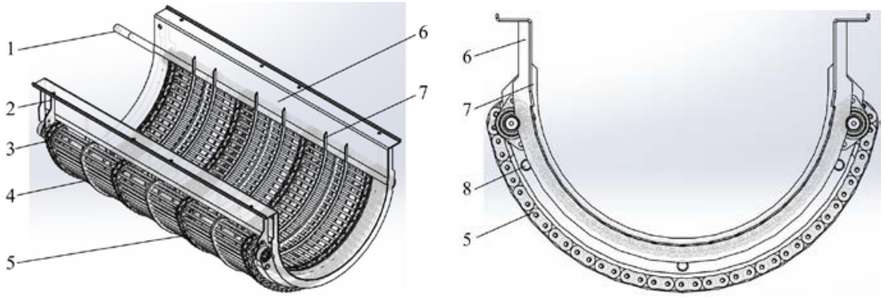


I. Feed section II. Low speed threshing cylinder section III. High speed threshing cylinder section
1. Rack bar 2. Nail tooth 3. Spoke plate 4. Low speed cylinder shaft 5. Intermediate device 6. High speed cylinder shaft

Fig. 2. Double-speed threshing cylinder

The rotary concave sieve, an important part of the double-speed double-action threshing and separating unit, was developed on the basis of the fixed grid concave sieve of whole-feeding longitudinal axial flow combine harvesters. The three-dimensional structure of the rotary concave sieve is shown in Figure 3. The concave grid strips are installed on the curved concave sieve frame. The inner cores of the concave grid strips use φ6 mm steel wires, and the housing is fitted with steel pipes of 8 mm inner diameter, which can be rotated around the inner cores. Several supporting cross shafts are fixed at the lower part of the concave sieve frame. The concave grid strips pass through multiple concave grid strip chains and are driven by the driving wheel to run cyclically; the power is provided by the high speed threshing cylinder shaft, and the upper and lower layers of movable grids with a spacing of 80 mm are formed.

The rotary concave sieve is installed on the curved concave sieve frame, and some cross shafts are fixed at the lower part of the sieve frame. The lower finalizing sheets (3.0 mm thick) connected and fixed at equal spacing support the upper sieve surface of the circular grid strip sieve pieces. Multiple 3.0 mm thick upper finalizing sheets are fixed at the upper part of the sieve frame and pressed on the upper sieve surface. The radial space formed by the upper and lower finalizing sheets is the motional orbit of the rotary grid concave. The inner cores of the concave grid strips use φ5.0 mm steel wires, and the housing is fitted with φ8.0 mm steel pipes, which can be rotated around the inner cores. When the concave sieve rotates, the steel pipes roll between the upper and lower finalizing sheets to ensure that the cylinder-concave clearance is stable. Passing through pin holes, multiple sets of A12 roller chains and A12 roller chain sheets (center distance 19.05 mm) are mounted at the two ends and middle of the grid strips so as to from the circular rotary concave sieve surface. The cross baffles of the rotary grid concave as well as the lower finalizing sheet, grid strip chain sheets and grid strips form a series of grids with a hole width of 11.00 mm and a hole length of 50.00 mm.



1. Concave sieve driving shaft 2. Lower finalizing sheet 3. Grid strip chain sheet 4. Concave grid strip;5. Concave grid strip chain 6. Concave sieve frame 7. Upper finalizing sheet 8. Cross shaft

Fig. 3. Rotary concave sieve

2.2. Experimental design methodology

Central Composite rotatable Design(CCD) was considered as experimental design method, with three independent parameters; cylinder speed, Linear speed of concave sieve, and concave clearance. Responses were obtained in loss rate, broken rate and impurity rate. The operational parameters were fixed at 5 levels (Table 2) as per CCD and a total number of 23 experiments were obtained using Design-Expert.

Table 2 Test factor level

Code value	Speed of high/low speed cylinder x_1/ (m/s)	Linear speed of concave sieve x_2/(m/s)	Cylinder-concave clearance x_3/(mm)
+1.682	22.92/27.50	1.60	30
+1	21.40/25.68	1.36	27.16
0	19.17/23.00	1.00	23
-1	16.93/20.32	0.64	18.84
-1.682	15.42/18.50	0.40	16

Repeated experiments were conducted at the central points of the coded variables to calculate the error sum of squares and the lack of fit of the developed regression equation between the responses and independent variables. The responses were analyzed using the model graphs technique in Design-Expert. Analysis of Variance (ANOVA) was also done to determine the significant effects of the factors on the variations in the response values. Design-Expert. was used to bring out the response surface graphs that were used to describe the variations of the responses as the factors changed from one level to the other. Variable coefficients for the regression equations were also obtained using the model graphs technique in Design-Expert.

For each experimental run, the values of cylinder speed , Linear speed of concave sieve , and cylinder-concave clearance were all adjusted based on the design plan to meet the required values for the next experimental run. This was done for all the experiments in the design. In the course of the experiment, data such as mass of broken/damaged grains, mass of unthreshed processing so as to obtain the responses required for the optimization of the operational parameters of the system.

2.3. Experumental deign methodology

To determine the percentage of broken rate, samples of threshed grains were collected from the grain outlets at a random order. The mass W_1 (g) was determined with an electronic digital balance. Physically broken/damaged grains were visually inspected carefully and manually sorted out. The mass of the broken/damaged grains was noted as W_p (g) using an electronic digital balance. The percentage of broken/damaged grains was determined as a ratio of the mass of broken rate to the total mass of sample taken. The percentage of broken grains (% y_1) was determined using Equation 2. This procedure was repeated for each experimental run 3.

$$\%y_1=(w_p/w_1)\times 100\% \tag{2}$$

According to the feed rate and RPR, the total mass of the grains obtained in each test is calculated, which is denoted as W. Broken grains and impurities are selected manually and weighed respectively, and their mass is denoted as W_p and W_z respectively. Discharged materials are collected from the cleaning chamber outlet and the straw discharging box, grains and grain-bearing broken panicles are selected and weighed, and their mass is denoted as cleaning loss W_q and entrainment loss W_j respectively. Then the impurity rate y_2 and loss rate y_3 of grains are calculated using the following formulas:

$$\%y_2=(w_z/w_1)\times 100\% \tag{3}$$

$$\%y_3=[(w_q+ w_j)/w]\times 100\% \tag{4}$$

3. Resulte

3.1. Test content and method

Table 3 presents the experimental design arrangement of the central composite rotatable design test with 3 functional parameters and the values of the responses variables that were obtain after the experiment was completed.

Table 3 Arrangements and results of the central composite rotatable design test

Test no.	Test factors			Test indicators		
	Speed of high/low speed cylinder (m/s)	Linear speed of concave sieve (m/s)	Cylinder-concave clearance (mm)	Breakage rate y_1 (%)	Impurity rate y_2 (%)	Loss rate y_3 (%)
1	16.93/20.32	0.64	18.84	0.56	0.85	1.78
2	21.40/25.68	0.64	18.84	1.03	0.95	2.34
3	16.93/20.32	1.36	18.84	0.53	0.85	1.96
4	21.40/25.68	1.36	18.84	1.13	1.62	2.28
5	16.93/20.32	0.64	27.16	0.17	0.78	2.86
6	21.40/25.68	0.64	27.16	0.39	0.71	2.62
7	16.93/20.32	1.36	27.16	0.27	0.67	2.82
8	21.40/25.68	1.36	27.16	0.42	1.12	2.40
9	15.42/18.50	1.00	23.00	0.33	0.63	2.42
10	22.92/27.50	1.00	23.00	0.96	1.17	2.91
11	15.42/23.00	0.40	23.00	0.32	0.74	2.61
12	15.42/23.00	1.60	23.00	0.37	0.75	2.40
13	15.42/23.00	1.00	16.00	1.12	1.35	1.78
14	15.42/23.00	1.00	30.00	0.17	0.65	2.93
15	15.42/23.00	1.00	23.00	0.33	0.41	1.55
16	15.42/23.00	1.00	23.00	0.15	0.47	1.92
17	15.42/23.00	1.00	23.00	0.16	0.43	2.07
18	15.42/23.00	1.00	23.00	0.25	0.44	1.94
19	15.42/23.00	1.00	23.00	0.27	0.42	1.75
20	15.42/23.00	1.00	23.00	0.18	0.31	1.95
21	15.42/23.00	1.00	23.00	0.17	0.35	1.66
22	15.42/23.00	1.00	23.00	0.28	0.52	1.98
23	15.42/23.00	1.00	23.00	0.31	0.78	1.88

In order to apply the Expert 6.0.10 software to the regression analysis of test data, the speed of high/low speed cylinder x_1, linear velocity of rotary concave plate x_2 and cylinder-concave clearance x_3 were selected as parameters, and the corresponding regression equation was obtained.

$$y_1=11.6741-0.6920x_1-0.8544x_2-0.2733x_3+0.0079x_1x_2-0.0079x_1x_3+0.0051x_2x_3+0.0203x2\ 1+0.3079x_2^2+0.0084x2\ 3 \tag{5}$$

$$y_2=18.7406-1.0209x_1-4.3733x_2-0.4085x_3+0.1558x_1x_2-0.0055x_1x_3-0.0311x_2x_3+0.0228x_1^2+0.8541x_2^2+0.0115x_3^2 \tag{6}$$

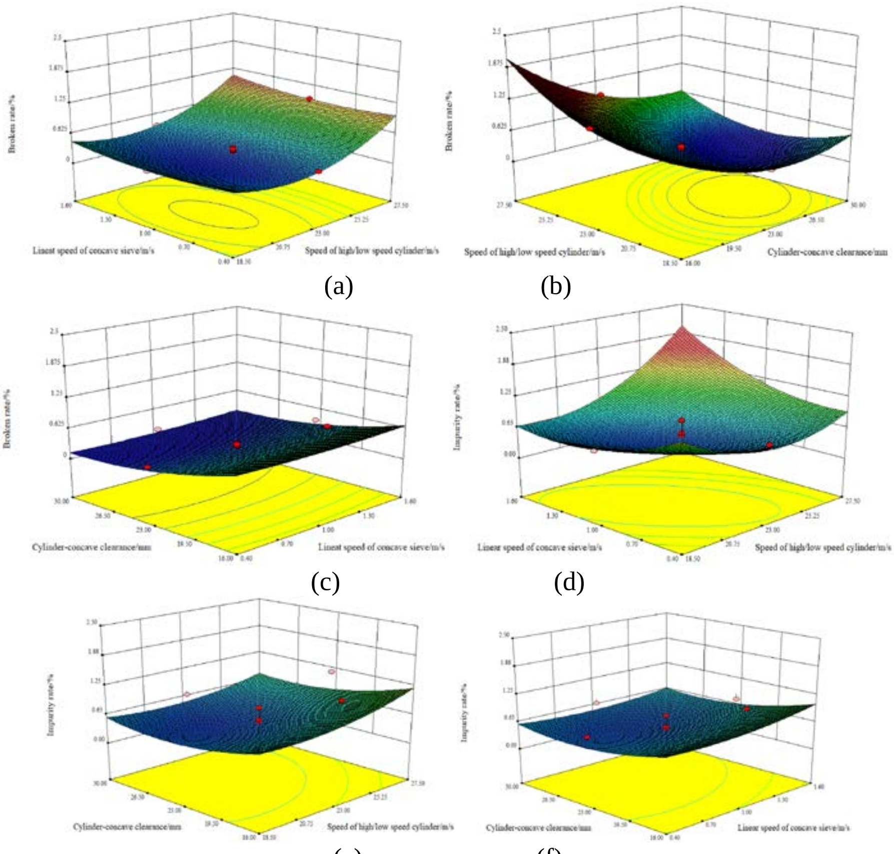
$$y_3=12.9194-1.1372x_1-1.1696x_2+0.1270x_3-0.0550x_1x_2-0.0173x_1x_3-0.0320x_2x_3+0.0352x_1^2+1.5345x_2^2+0.0082x_3^2 \tag{7}$$

Table 4 shows results of analysis of variance for the response values, indicating the degree of significance that each functional parameter variation hard on the value of the response. It also shows the significance of the functional parameter interaction on the values of the response variables.

Table 4 Analysis of variance for breakage rate, impurity rate and loss rate

Source of Variation	Degree of freedom	Breakage rate		Impurity rate		Loss rate	
		Mean square	P - value	Mean square	P - value	Mean square	P - value
x_1	1	0.46	<0.0001**	0.34	0.0006**	0.080	0.1197
x_2	1	0.006	0.2244	0.071	0.0624	0.018	0.4455
x_3	1	0.95	<0.0001**	0.34	0.0006**	1.34	<0.0001**
$x_1 \times x_2$	1	0.0005	0.7305	0.18	0.0068**	0.022	0.3972
$x_1 \times x_3$	1	0.061	0.0012**	0.03	0.2089	0.30	0.0068**
$x_2 \times x_3$	1	0.0005	0.7305	0.017	0.3363	0.018	0.4425
Pure error	8	0.038		0.15		0.23	
Cor total	22						

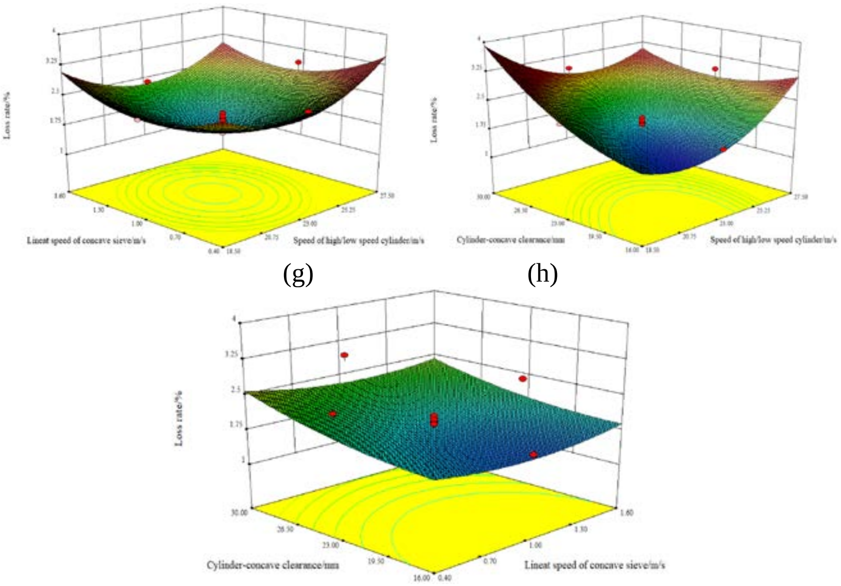
P values≤0.05 indicates a significant difference in the variations between the means. All the values indicated with the * are significant at the 5% probability level. ** are highly significant at the5%.



(a) (b)

(c) (d)

(e) (f)



(g) (h)

(*i*)

Fig. 4. Response surface graphs showing effects of changing levels of functional parameters on the values of response variables

From the analysis in Table 4, determined that varying the speed of high/low speed cylinder had a significant effect on breakage rate, trash content and loss rate. Changing the linear velocity of rotary concave plate for this experiment did not have any significant effect on the responses as seen on table 4. The p values were all higher than 0.05 and so indicated an insignificant result. It was determined from Table 4 that varying cylinder-concave clearance had a significant effect on the breakage rate. Furthermore, from Table 4 we determine that factor interactions such as speed of high/low speed cylinder and cylinder-concave clearance, cylinder-concave clearance and linear speed of concave sieve all had a significant effect on the breakage rate, trash content and loss rate with $p < 0.05$.Figure 4 shows response surface graphs that were used to graphically show the effects of changing the levels of the functional parameters on the values of the response variables.

3.2. Optimization and verification

In October 2019, Zhejiang Provincial Institute of Mechanical and Electrical Products Quality Inspection was entrusted to carry out the prototype performance test of 4LZ-2.1 double-speed and double-acting rice combine harvester, as shown in FIG. 8, the test method is in accordance with national standard GB10395.7-2006 ”Agricultural and Forestry Tractors and Machinery Safety Technical Requirements part 7: combine harvesters, feed and cotton harvesters”, mechanical industry standard JB/T5117-2017”Technical Conditions for Full Feeding Combine harvester” and national standard GB/T8097-2008”Harvester: Test method for combine harvester” stipulated that the loss rate, crushing rate and impurity rate were tested respectively.

Fig. 5. Field trials scene

Table 5 Verification test result

Item	Loss rate	Broken rate	Impurity rate
Industrial standard	≤2.8%	≤1.0	≤2.0
Verification result	1.74%	0.45%	0.34%

The verification test result is shown in Table 5. According to the verification test result, the three performance indexes such as grain loss rate, broken rate and impurity rate of the double-speed double-action threshing and separating unit are all better than as specified in the industrial standard.

4. Analysis and discussions

According to the analysis of equation (5)- equation (7) and figure 4.

4.1. Speed of high/low speed cylinder, linear speed of concave sieve and cylinder-concave clearance on broken rate

It can be seen from figure 4(a)- figure 4(c) shows that in the interaction between rotate speed of high-speed/low-speed threshing drum x_1 and cylinder-concave clearance x_3, the rotate speed of high-speed/low-speed threshing drum influences the broken rate more significantly. As the rotate speed of high-speed/low-speed threshing drum decreased, the cylinder-concave clearance increases, and the broken rate of threshing and separating unit decreased.

Varying the speed of high/low speed cylinder had a significant effect ($p<0.05$) on the breakage rate of the threshing separation device as seen in Table 4. The rice plants are firstly threshed and separated by carding and impact effect in the low-speed threshing drum, then threshed and separated by the high-speed threshing drum. During the threshing process, most grains with small connection force are threshed and separated in the low-speed drum, which reduces grain breakage rate. A few grains with large connection force are threshed and separated in the high-speed drum, which increases threshed rate and separation rate and reduces grain loss rate. The breakage rate increased with an increase in cylinder speed from 18.5-27.5 m/s. At a speed of high/low speed cylinder of 15.42/18.50 m/s, the percentage of broken rate was 0.15%, lower than when the least cylinder speed of 22.92/27.50 m/s was used 1.13%. Equally, when the cylinder speed was decreased, the breakage rate also decreased(Srivastava et al., 2006). This could be attributed to the fact that at higher drum speeds, the peripheral speed at the tip of peg tooth increased, leading to more impact on the grains.

Varying the cylinder-concave clearance had a significant effect ($p<0.05$) on the threshing percentage of the threshing separation device as seen in Table 4. Cylinder-concave clearance ranged from 16-30mm. However, the lowest broken rate was obtained at an average cylinder-concave clearance of 30 mm. With a wider concave clearance, there is less likelihood of an impact force on the grain panicles, resulting in less probability of the grains being threshed.

4.2. Speed of high/low speed cylinder, linear speed of concave sieve and cylinder-concave clearance on impurity rate

It can be seen from figure 4(d)-figure 4(f) that in the interaction between rotate speed of speed of high/low speed cylinder x_1 and linear speed of concave sieve x_2, both of them have significant impact on the impurity rate of threshing and separating unit. Varying the speed of high/low speed cylinder had a significant effect ($p<0.05$) on the impurity rate of the threshing separation device as seen in Table 4. The impurity rate increased with an increase in speed of high/low speed cylinder from 15.42/18.50-22.92/27.50 m/s, the percentage of impurity rate increased significantly from 0.63- 1.17% respectively. Equally, when the cylinder speed was decreased, the impurity rate also decreased. This could be attributed to the rotate speed of threshing drum increases, the broken stems and leaves in the threshing chamber increases, causing that the grain impurity rate gradually increases(Amponsah et al., 2017).

The difficulty in rice threshing differs from variety to variety, and there is also a difference in the connection force between easily threshed grains and difficultly threshed grains of the same panicle(Wang, Lv, Chen & Ma, 2017). Therefore, the double-speed double-action threshing and separating unit reduces the broken loss of grains and stems in the threshing process by means of the low speed threshing cylinder; in addition, the unit reduces un-threshing loss and improves separating efficiency by means of the high speed threshing cylinder. Through the cyclic running of the rotary concave sieve, there will not be grains or stems left on the sieve surface (especially during operation with dew), so as to prevent the grid holes of the concave sieve from being blocked. When falling from the upper sieve surface to the lower sieve surface, grains are spread more uniformly on the vibrating sieve surface due to cyclic running of the concave sieve, which is favorable for improving subsequent cleaning performance. The impurity rate increased with an increase in Linear speed of concave sieve from 0.40-1.60 m/s, the percentage of impurity rate increased significantly from 0.31- 1.62% respectively. However, the lowest impurity rate was obtained at an average linear speed of concave sieve of 0.99 m/s.

4.3. Speed of high/low speed cylinder, linear speed of concave sieve and cylinder-concave clearance on loss rate

It can be seen from figure 4(g)-figure(i) that in the interaction between rotate speed of high-speed/low-speed threshing drum x_1 and cylinder-concave clearance x_3, the rotate speed of high-speed/low-speed threshing drum has a significant impact on the loss rate($p<0.05$).

As shown in Table 4, it can be observed that with an increase in speed of high/low speed cylinder from 15.42/18.50-22.92/27.50m/s, the loss rate increased significantly from 2.42-2.91% respectively. This may be attributed to the fact that with the increase of speed of high/low speed cylinder the collision energy between grains and spike teeth increased and the seeds are loaded with a greater force . Furthermore, it can be suggested from figure 4(g)-figure(i) that with an increase in cylinder speed, there was a significant increase in grain damage and with a decrease in cylinder speed, there was a decrease in grain damage. This increase in grain damage was due to higher impact forces imparted to the crop during threshing at higher cylinder speeds.

The percentage of loss rate was influenced significantly ($p< 0.05$) by the cylinder-concave clearance. From Table 4, it is realized that increasing the cylinder-concave clearance from 16-30 mm equally increased the percentage of loss rate from 1.78%-2.93%. However, the lowest loss rate is obtained at an average cylinder-concave clearance of 22.60 mm.Figure 4(h) shows that increasing cylinder-concave clearance increased the percentage of loss rate, while decreasing the cylinder-concave clearance decreased the percentage of loss rate. With a wider cylinder-concave clearance, there is less likelihood of an impact force on the grain panicles, resulting in less probability of the grains being threshed. Hence the percentage of unthreshed grains increased with an increased concave clearance. Decreasing the clearance led to an increased probability of an impact force on the grain panicles, hence leading to more grain panicles being threshed. This shows that a decrease in the cylinder-concave clearance causes the intensity of compression of the grains to increase leading to more breakage, thus the weight percentage of damaged grains increased.

5. Conclusion

(1) The contradiction of un-threshing loss and entrainment loss with the broken loss of grains was alleviated by reasonably using coaxial double-speed threshing

cylinder speed and concave sieve rotation motion technologies. Increasing the threshing speed of high/low speed cylinder increased the threshing percentage of the combine harvester. Varying the cylinder speed had a significant effect on the broken rate, percentage of impurity rate and the loss rate. It was observed that with an increase in speed of high/low speed cylinder from 15.42/18.50-22.92/27.50m/s, the percentage of broken grains increased significantly from 0.15-1.13% respectively. At a Speed of high/low speed cylinder of 15.42/18.50-22.92/27.50m/s, the percentage of impurity rate increased from 0.63-1.17% respectively. At a Speed of high/low speed cylinder of 15.42/18.50-22.92/27.50m/s, the percentage of loss rate increased from 1.9-2.9% respectively. Lowest broken rate and impurity ratewas registered at an average speed of high/low speed cylinder of 18.31/21.97m/s.

(2) The effect of varying linear speed of concave sieve on the broken rate,impurity rate and loss ratewas found to be inconsistent. The impurity rate increased with an increase in Linear speed of concave sieve from 0.40-1.60 m/s, the percentage of impurity rate increased significantly from 0.31- 1.62% respectively. However, the lowest impurity rate was obtained at an average linear speed of concave sieve of 0.99 m/s.

(3) Varying the cylinder-concave clearance had a significant effect on the broken rate, percentage of impurity rate and the loss rate. However, the lowest broken rate was obtained at an average cylinder-concave clearance of 30 mm. The cylinder-concave clearance from 16-30 mm equally increased the percentage of loss rate from 1.78%-2.93%. That increasing cylinder-concave clearance increased the percentage of loss rate, while decreasing the cylinder-concave clearance decreased the percentage of loss rate. With a wider cylinder-concave clearance, there is less likelihood of an impact force on the grain panicles, resulting in less probability of the grains being threshed. Decreasing the clearance led to an increased probability of an impact force on the grain panicles, hence leading to more grain panicles being threshed. This shows that a decrease in the cylinder-concave clearance causes the intensity of compression of the grains to increase leading to more breakage, thus the weight percentage of damaged grains increased.When Cylinder-concave clearance is 22.60mm, the loss rate will be lowest.

(4) Field tests show that the prototype has stable performance, with the loss rate, impurity rate and breakage rate of 1.74%, 0.45% and 0.34% respectively. With each performance index superior to the test standard, this device solves the contradiction between impurity removal, entrapment and grain breakage loss during the harvest of "Yongyou 15" super hybrid rice effectively.

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