DESIGN AND PERFORMANCE EXPERIMENTS OF THRESHING AND SEPARATING DEVICE FOR HEAD-FEEDING COMBINE HARVESTER
/
半喂入联合收割机脱粒分离装置设计与性能试验

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ABSTRACT
To address the issues of incomplete threshing, separation loss, and grain breakage during the harvesting of super hybrid rice with conventional threshing and separating units in head-feed combine harvesters, a segmented-differential threshing and separating unit was developed. This unit mainly consists of a coaxial segmented-differential threshing drum and a rotary concave screen. Its structure and working principle are described in detail. A three-factor quadratic regression orthogonal rotation combination test was conducted, with the rotational speed of the segmented-differential drum, the linear velocity of the rotary concave screen, and the clamping chain speed as test factors. The grain loss rate, breakage rate, and impurity rate were taken as performance indicators. The test results were analyzed using Design-Expert 8.0.6 software to establish a mathematical model for the performance indicators and to determine the optimal combination of working parameters. Additionally, a comparative test was carried out between the segmented-differential unit and a conventional single-speed unit. The results showed that when the rotational speed of the low-speed/high-speed drum in the segmented-differential unit was 520/630 r·min^{-1}, the linear velocity of the rotary concave screen was 1.20 m·s^{-1}, and the clamping chain speed was 1.10 m·s^{-1}, the grain loss rate, breakage rate, and impurity rate were 1.95%, 0.20%, and 0.56%, respectively.

摘要
为解决半喂入联合收割机脱粒分离装置在超级杂交稻收获过程中脱粒不全、分离损失和断粒率的矛盾，研制了半喂入联合收割机分段差动脱粒分离装置。该装置主要由同轴分段-差动脱粒滚筒和旋转凹筛组成。阐述了分段式差动脱粒分离装置的结构和工作原理。以分段差动滚筒转速、旋转凹筛线速度、夹紧链速度为试验因素，以籽粒损失率、破碎率、杂质率为性能指标，进行三因素二次回归正交旋转组合设计试验。本文利用 Design-Expert8.0.6 软件对试验结果进行分析，建立脱粒分离装置性能指标数学模型，确定最佳工作参数组合。此外，本文还对分段脱粒分离装置与常规单速脱粒分离装置进行了对比试验。结果表明:当分段装置低速/高速滚筒转速为 520/630 r•min-1，转凹筛线速度为 1.20 m•s-1，夹紧链速度为 1.10 m•s-1 时，籽粒损失率、破碎率和杂质率分别为 1.95%、0.20%和 0.56%。

INTRODUCTION
Rice is one of the main crops in China, accounting for about 65% of all the grain consumption (*Xin et al., 2018*). In recent years, the planting area of super hybrid rice has been gradually expanded, and the yield has been continuously increased. Compared with conventional rice, the biological characteristics of super hybrid rice are significantly different, such as high yield per unit area, thick stems, large grain-grass ratio, and high moisture content of stems (*Xu et al, 2019; Hao et al, 2018; Wei et al, 2018*). These characteristics bring new problems to the conventional threshing and separating unit for a head-feed combine harvester (*Gao et al, 2017*).

To improve operational efficiency and reduce losses, combine harvester manufacturers at home and abroad mostly take action to increase power, increase the threshing drum length and so on. The power of Kubota PRO888 head-feed combine harvester is 66.1 kW, its threshing drum length is 1000 mm, and its maximum operating efficiency is 0.67 hm^2/h. The parameters of other foreign and domestic machines are similar.

These measures have improved the operational efficiency but failed to solve the problem that the super hybrid rice is incompletely threshed and has large losses during harvest. The current threshing and separating unit for the head-feed combine harvester is mostly composed of a single-speed drum with a fixed concave plate. For super hybrid rice or when feeding thick rice stalks, a low threshing drum speed results in insufficient threshing capacity, leading to incomplete threshing, separation losses, and even potential blockages within the drum. If the drum's rotation speed is increased, it may lead to a higher grain breakage rate and more broken stems, causing the operation quality to fall short of national standards for the three key indicators: loss rate, breakage rate, and impurity rate. To reduce incomplete threshing losses in super hybrid rice, *Wang (2016)* and *Chen et al. (2011)* studied the application of differential threshing drums for head-feed combine harvesters. *Wang, Xie & Li, (2019),* designed a threshing drum with an adjustable diameter, enabling threshing clearance adjustment by varying the drum's diameter. Also, as a part of the combine harvester, the grid concave plate has a significant influence on the performance of the threshing and separating unit. *Wang et al., (2017),* studied the threshing and separating units (with concave plate) of different structures and established the motion model of threshed materials. *Ding, (1987),* established a mathematical model for the separation rate and hole size of grid concave plate. *Li et al, (2018),* developed an adjusting mechanism for concave plate clearance to adjust the threshing clearance through a hydraulic cylinder. *Liu et al., (2018),* studied a threshing and separating unit equipped with a single-speed drum and rotary concave plate. Its operational efficiency and performance were significantly improved compared to the unit with a fixed concave plate. However, the studies were limited to units with either a single-speed drum and fixed concave plate, or a single-speed drum combined with a rotary concave plate.

To address the issues of incomplete threshing, separation loss, and high grain breakage during the harvest of super hybrid rice using conventional threshing and separating units in head-feed combine harvesters, a segmented-differential threshing and separating unit was developed. This unit consists of a segmented-differential threshing drum and a rotary grid concave plate. This paper details the structure and working principle of the new unit, evaluates its performance through a multi-factor optimization experiment, and investigates its overall efficiency. The goal is to enhance threshing effectiveness and reduce losses, thereby providing a theoretical foundation for the innovative design of key components in head-feed combine harvesters.

MATERIALS METHODS

Main structure and working principle

The segmented-differential threshing and separating unit for a head-feed combine harvester is mainly composed of low-speed threshing drum, drum linkage, high-speed threshing drum, threshing drum shaft. The threshing drum consist of a leading-in spiral, rotary grid concave plate, belt wheel for high-speed drum, belt wheel for low-speed drum, and the driving wheel for grid concave plate, etc., as shown in figure 1 (the fairing cap on threshing and separating unit is not shown). The power of the machine is transferred from a driving wheel to each mechanism through a belt. In the segmented-differential threshing drum, the high-speed threshing drum and the low-speed threshing drum share the same draft and diameter. The high-speed and low-speed threshing drums are connected with the drum linkage and driven respectively by the belt wheel for high-speed/low-speed drums. The rotary grid concave plate is installed in the arc-shaped concave screen frame. The concave plate grid strips are also in the arc-shaped concave screen frame. They are driven by the driving wheel for the grid concave plate to rotate. Meanwhile, this guarantees the threshing clearance between the high-speed/low-speed threshing drum and the rotary concave plate to be 20 mm (*Wang & Ge, 1982*).

When the head-feed combine harvester operates, cut rice plants are clamped by the feeding chain into the threshing area through the leading-in spiral. 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. The threshed grains afterwards fall onto the vibrating screen surface through the rotary grid concave plate, and will be put into subsequent cleaning operation. During the threshing process, most grains with small connection force are threshed and separated in the low-speed drum, which reduces the 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 the grain loss rate. The rotary grid concave plate rotates, and the linear velocity direction of the upper grid surface is the same as that of the threshing drum. The rotary grid surface can thresh the ears of rice plants got to the grid concave plate and prevent blockage in the threshing drum.

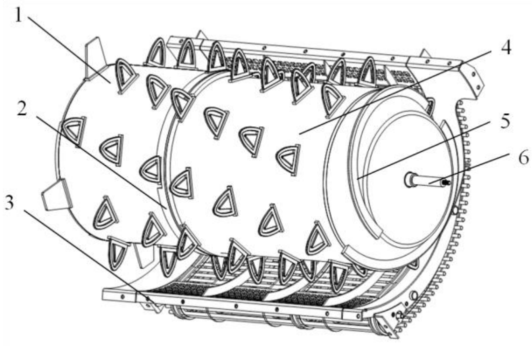


Fig. 1 - Segmented-differential threshing and separating unit
1. High-speed threshing drum; 2. Drum linkage; 3. Rotary grid concave plate; 4. Low-speed threshing drum; 5. Leading-in spiral; 6. Threshing drum shaft

Threshing drum

The structure of the threshing drum is closed, mainly composed of a coaxial straight high/low-speed threshing drum, drum linkage, threshing arcuate teeth, low-speed drum shaft, high-speed drum shaft, leading-in spiral, grass cutter, etc., as shown in figure 2. The leading-in spiral and the low-speed threshing drum are firmly attached, and two spiral guiding blades are set to comb and push the rice ears (*Wang, Lv & Chen, 2017*). The high-speed and low-speed threshing drums are connected by a linkage, which rotates with the low-speed threshing drum. The low-speed drum shaft is a hollow shaft, which is driven by the low-speed belt wheel and drives the low-speed threshing drum simultaneously. The high-speed drum shaft is set in the low-speed drum shaft through a bear, which is driven by the high-speed belt wheel and drives the high-speed threshing drum simultaneously. The high-speed and low-speed belt wheels are set on the left side of the drum shaft and driven respectively by the belt wheel of the machine power-output shaft with different drive ratios. The threshing arcuate teeth are helically arranged on the drum surface with an equal pitch, featuring a 4-start thread, a helical angle of 50°, and a total of 15 rows of threshing arcuate teeth.

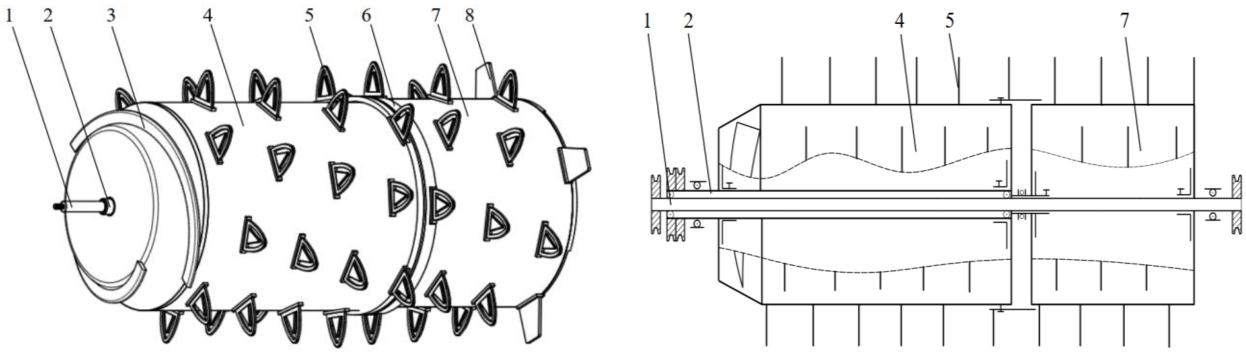


Fig. 2 - Threshing drum
1. High-speed drum shaft; 2. Low-speed drum shaft; 3. Leading-in spiral; 4. Low-speed threshing drum; 5. Threshing arcuate teeth; 6. Drum linkage; 7. High-speed threshing drum; 8. Grass cutter

The segmented-differential rotary threshing and separating unit for the head-feed combine harvester mainly utilize the carding and impact of threshing arcuate teeth on the ears of rice, so that the grains get the energy to fall off from the ears, thus achieving threshing and separation. Threshing drum length determines the threshing process. Generally, the longer the drum is, the longer the rice ears stay in the threshing chamber, and the longer the threshing arcuate teeth act on the rice ears, but it increases the threshing power consumption. According to the overall structure of the segmented-differential threshing and separating unit and the research results of the distribution law of threshed materials in the early stage (*Peng et al, 2016*), the total length of the threshing drum is determined to be 1000 mm, and the length of low-speed threshing drum (that is, the length of the grid concave plate in low-speed section) can be obtained from formula (1).

$$L = \frac{\varepsilon Q}{\eta \gamma R_1} \tag{1}$$

where: L – length of grid concave plate in the section of low-speed threshing drum (length of low-speed threshing drum), m; ε – ratio of the feeding rate undertaken by the low-speed threshing drum, taken as 0.85.

By substituting the relevant values into equation (1), L is 0.682 m, 2/3 (that is, 0.667 m) of the threshing drum length is taken as the low-speed threshing drum, and the remaining 1/3 is the high-speed threshing drum.

Rotary grid concave plate

The structure of the rotary grid concave plate is as shown in figure 3. Several grid strips are set in three groups of A12 type sleeve roller chain pin holes at two ends and the middle part to form a flexible screen surface consisting of grid strips. The two ends of the roller chain are connected to form a semicircular grid strip concave screen with a width of 800 mm. The width of each grid hole (that is, the spacing of grid strips) is 11 mm, and the length of grid holes is 50 mm. The inner core of the concave grid strip is a steel wire with a diameter of 5 mm, and fit together with steel tube with a diameter of 8 mm outside. The steel tube can rotate around the inner core. The screen surface can vibrate, making the threshed materials separate quickly and preventing blockage in the threshing drum. Concave plate grid strips use the upper and lower shaping platen as rotary track, using the threshing drum belt wheel to drive the grid concave plate driving wheel, and using a coaxial driving chain wheel with the driving wheel to drive the concave plate grid strip chain, so that the grid concave plate rotates around the driven chain wheel along the rotary track.

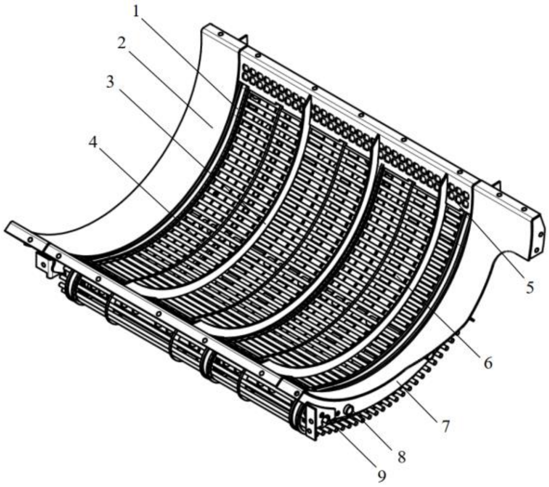


Fig. 3 - Rotary grid concave plate

1. Grid strip driving chain; 2. Concave screen frame; 3. Upper shaping platen; 4. Grid strip mounting chain; 5. Multi-hole side plate; 6. Lower shaping platen; 7. Grid strip; 8. Horizontal axis; 9. Driven shaft

The operation efficiency of the Segmented-differential rotary threshing and separating unit is related to the action area of the grid concave plate (the surrounding area of rotary grid concave plate) (*Jin & Liu, 1980*).

$$S = \frac{Q}{\eta} = \mathrm{E} \cdot \mathrm{R}_1 \cdot \gamma \tag{2}$$

where: S – surrounding area of rotary grid concave plate, m^2;

η – productivity per unit area of grid concave plate, taken as 2.0 kg/(m^2 s);

Q – feeding quantity (i.e. working flow), taken as 1.5 kg/s;

E – width of head-feed grid concave plate, taken as 0.8 m;

R_1 – radius of rotary grid concave plate, taken as 0.295 m;

γ – wrap angle of rotary grid concave plate, rad.

By substituting the relevant values into equation (2), the surrounding area of the rotary grid concave plate is 0.75 m^2, and the wrap angle is rounded to 180º.

TEST APPARATUS

Based on theoretical analysis and practical experience in the threshing and separating operations of head-feed combine harvesters, this study investigates how the working parameters of the segmented-differential threshing and separating unit, including the rotational speeds of the high-speed and low-speed threshing drums, the linear velocity of the rotary grid concave plate, and the clamping chain speed, affect the grain loss rate, breakage rate, and impurity rate. A segmented-differential threshing and separating test bench was designed for the head-feed combine harvester, and performance tests were conducted using a three-factor quadratic regression orthogonal rotation combination design.

Test bench

The segmented-differential threshing and separating test bench for the head-feed combine harvester includes: rice plants conveying platform, segmented-differential threshing and separating unit (high-speed/low-speed threshing drum, clamping chain, rotary grid concave plate, and cleaning vibrating screen), adjustable-speed motor and control box, etc., as shown in figure 4. The rice plant conveying platform consists of two conveyors connected in series, with adjustable height and a stepless variable conveying speed ranging from 0 to 2 m·s^{-1}. The power of the threshing drum adjustable-speed motor is 15kW, and the rotational speed of the high-speed/low-speed threshing drum is stepless speed changing. The power of the clamping chain driving motor is 7.5 kW, and the power of the rotary grid concave plate driving motor is 2 kW. The motor speed is adjusted by the frequency converter and the relevant data are recorded.

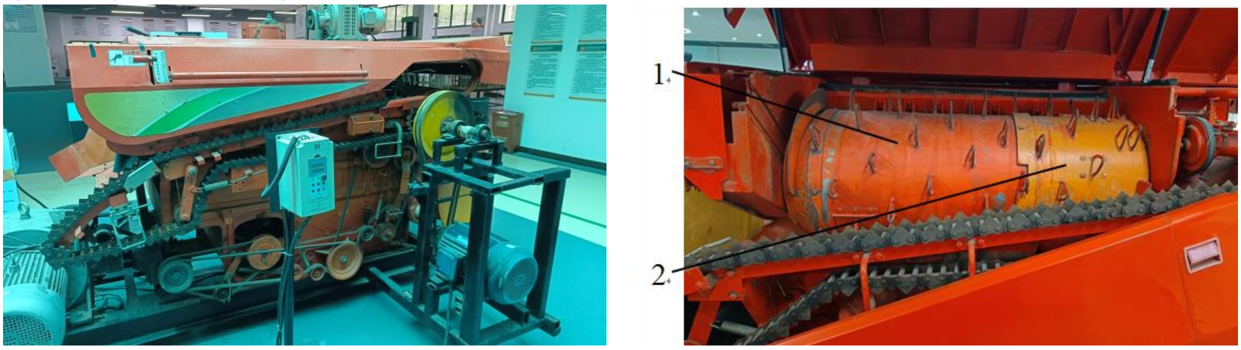


Fig. 4 - Threshing and separating test bench

1. Low-speed threshing drum; 2. High-speed threshing drum

Test material

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.

Table 1

Basic characteristic parameters of rice

Items	Parameters
Height of plants / cm	95 ~ 110
Length of ears / cm	18.5 ~ 25.5
Moisture content of grains / %	23.2~24.6
Moisture content of stems / %	66.4
Grain-grass ratio (stubble height 15 cm)	2.56:1
Thousand kernel weight / g	28.9
Yield per unit area / kg / ha	9890

RESULTS AND ANALYSIS

Performance indicators

Before the test, the conveyor speed was set according to the set feeding rate (working flow) of 1.5 kg/s. In each group of tests, rice plants were evenly spread in the designated range of conveyor. The lengthwise direction of rice plants was perpendicular to the conveying direction, and the rice ears were toward the threshing drum. Based on "Thresher-Testing method" (GB/T 5982-2017), the test was carried on.

According to the feeding rate and grain-grass ratio, the total grain weight obtained in each test was calculated and denoted as W. The total weight of grains sampled at the grain receiving port was denoted as W_1. The broken grains and impurities were picked by hand and weighed respectively, and denoted as W_p and W_z. In the discharges collected at the cleaning chamber outlet and straw outlet, the broken ears containing grains and the unthreshed grains were picked and weighed, which were denoted as the cleaning loss W_q and separation loss W_j. Thus, the loss rate y_1, breakage rate y_2 and impurity rate y_3 can be calculated by the following formulas.

$$y_1=\frac{W_q+W_j}{W}\times100\% \tag{3}$$

$$y_2=\frac{W_p}{W_1}\times100\% \tag{4}$$

$$y_3 = \frac{W_z}{W_1} \times 100\% \quad (5)$$

Test scheme

To explore how the parameters such as the rotational speed of high-speed/low-speed threshing drum, the linear velocity of rotary grid concave plate and the clamping chain speed influence the threshing and separating performance, the parameter variation range was controlled properly according to the production practice and single-factor test, and the three-factor quadratic regression orthogonal rotation combination design test was performed. The levels of individual factors are shown in table 2.

Table 2

Levels of test factors

Coded value	Rotational speed of low-speed / high-speed drum x_1 / (r·min^{-1})	Linear velocity of rotary concave plate x_2 / (m·s^{-1})	Clamping chain speed x_3 / (m·s^{-1})
-1.682	480/590	0.40	0.60
- 1	500/610	0.72	0.80
0	530/640	1.20	1.10
1	560/670	1.68	1.40
1.682	580/690	2.00	1.60

According to 23 groups of quadratic regression orthogonal rotation combination design tests, the test scheme and results are shown in table 3. Where y_1 is the loss rate, y_2 is the breakage rate and y_3 is the impurity rate.

Table 3

Test scheme and results

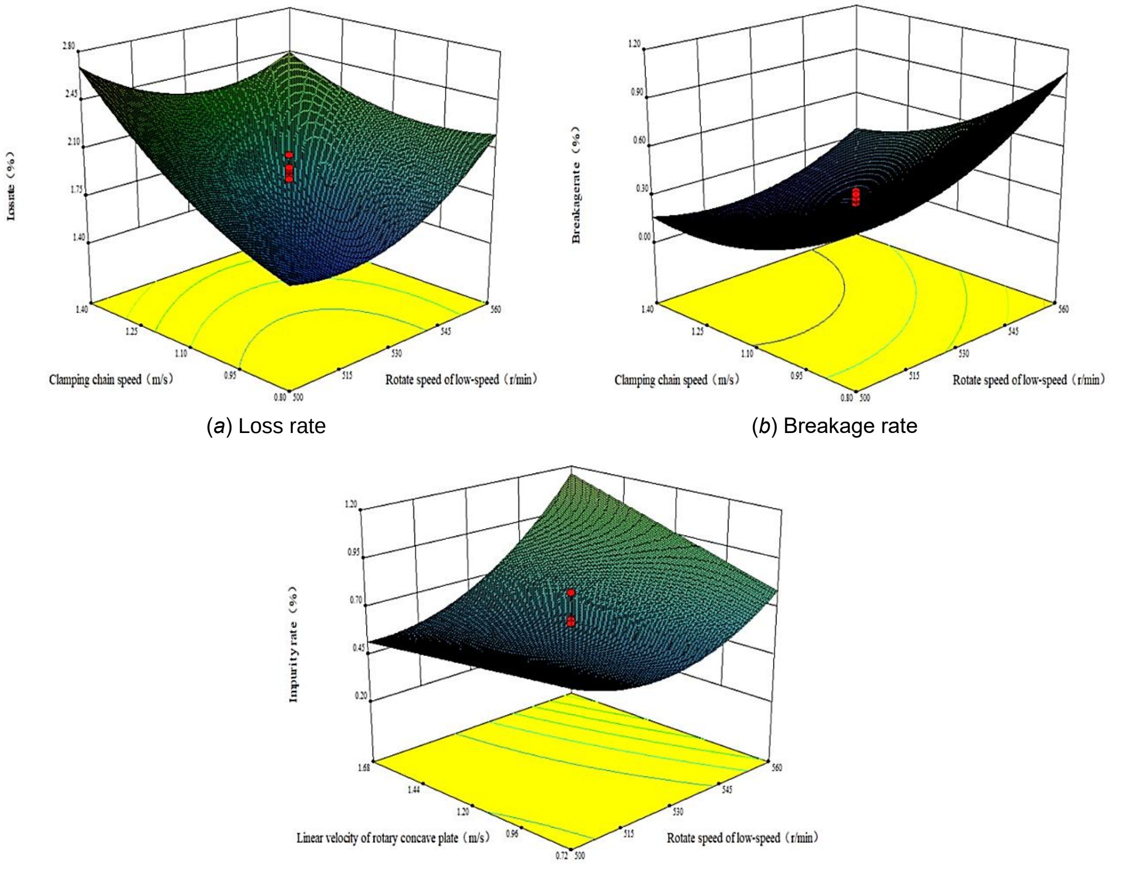
Test no.	Test factors			Test indicators		
	Rotational speed of low-speed / high-speed drum x_1 (r·min^{-1})	Linear velocity of rotary concave plate x_2 (m·s^{-1})	Clamping chain speed x_3 (m·s^{-1})	Loss rate y_1 (%)	Breakage rate y_2 (%)	Impurity rate y_3 (%)
1	500/610	0.72	0.80	1.77	0.56	0.84
2	560/670	0.72	0.80	2.34	1.04	0.94
3	500/610	1.68	0.80	1.96	0.53	0.85
4	560/670	1.68	0.80	2.28	1.14	1.42
5	500/610	0.72	1.40	2.88	0.17	0.78
6	560/670	0.72	1.40	2.62	0.40	0.71
7	500/610	1.68	1.40	2.82	0.27	0.67
8	560/670	1.68	1.40	2.40	0.42	1.12
9	480/590	1.20	1.10	2.42	0.34	0.63
10	580/690	1.20	1.10	2.91	0.97	1.57
11	530/640	0.40	1.10	2.61	0.32	0.74
12	530/640	2.00	1.10	2.39	0.37	0.75
13	530/640	1.20	0.60	1.78	1.12	1.36
14	530/640	1.20	1.60	2.93	0.17	0.64
15	530/640	1.20	1.10	1.54	0.33	0.62
16	530/640	1.20	1.10	1.92	0.15	0.37
17	530/640	1.20	1.10	2.06	0.17	0.43
18	530/640	1.20	1.10	1.94	0.25	0.64
19	530/640	1.20	1.10	1.75	0.27	0.62
20	530/640	1.20	1.10	1.95	0.18	0.60
21	530/640	1.20	1.10	1.66	0.16	0.50
22	530/640	1.20	1.10	1.97	0.28	0.62
23	530/640	1.20	1.10	1.88	0.31	0.78

To apply the Expert8.0.6 software to the regression analysis of test data, the rotational speed of low-speed threshing drum x_1, the linear velocity of rotary concave plate x_2 and clamping chain speed x_3 were selected as parameters, and the corresponding regression equation was obtained.

$$\begin{cases} y_1 = 70.31 - 0.28x_1 - 2.15x_2 + 9.24x_3 + 0.0003x_1^2 + 0.86x_2^2 + 1.63x_3^2 - 0.02x_1x_3 \\ y_2 = 41.54 - 0.16x_1 - 0.37x_2 + 0.82x_3 + 0.0002x_1^2 + 0.17x_2^2 + 1.64x_3^2 - 0.01x_1x_3 \\ y_3 = 60.23 - 0.21x_1 - 4.51x_2 - 3.93x_3 + 0.0002x_1^2 + 1.57x_3^2 + 0.009x_1x_2 \end{cases} \quad (6)$$

Test results and analysis

To intuitively analyze the relationship between individual parameters and the threshing and separating performance indicators, the Design-Expert8.0.6 software was used to obtain the response surface, as shown in figure 5.



(*a*) Loss rate (*b*) Breakage rate

(*c*) Impurity rate

Fig. 5 - Response surfaces of individual factor's influence on performance indicators

According to the analysis of equation (6) and figure 5, it can be seen from figure 5(*a*) that in the interaction between the rotational speed of high-speed/low-speed threshing drum x_1 and clamping chain speed x_3, the rotational speed of high-speed/low-speed threshing drum influences the loss rate more significantly. As the rotational speed of the high-speed/low-speed threshing drum increases, the clamping chain speed increases, and the loss rate of the threshing and separating unit increases gradually. It can be seen from figure 5(*b*) that in the interaction between the rotational speed of high-speed/low-speed threshing drum x_1 and clamping chain speed x_3, both of them have a significant impact on the breakage rate of threshing and separating unit, indicating that when the clamping chain speed is low, the activation times of threshing drum on grains in rice ears increases, and the higher the rotational speed of the drum is, the higher the grain breakage rate is. It can be seen from figure 5(*c*) that in the interaction between the rotational speed of high-speed/low-speed threshing drum x_1 and the linear velocity of rotary concave plate x_2, the rotational speed of high-speed/low-speed threshing drum has a significant impact on the impurity rate. As the rotational speed of the threshing drum increases, the broken stems and leaves in the threshing chamber increases, causing that the grain impurity rate gradually increases.

The grain loss rate, breakage rate and impurity rate are important indicators to evaluate the performance of the segmented-differential threshing and separating unit, and should be minimized under their individual constraint conditions. To obtain the optimal combination under the constraint conditions, the multi-objective variables optimization method is adopted to establish the nonlinear model by combining the boundary conditions of each factor, as follows:

$$\begin{cases} \min \ y_1 \\ \min \ y_2 \\ \min \ y_3 \\ s.t. \ (480/590)\,r/\min \le x_1 \le (580/690)\,r/\min \\ \qquad 0.4\,m/s \le x_2 \le 2.0\,m/s \\ \qquad 0.6\,m/s \le x_3 \le 1.6\,m/s \\ \qquad 0 \le y_i(x_1, x_2, x_3) \le 1 \end{cases} \tag{7}$$

Formula (7) was used to optimize multi-objective parameters based on the Optimization module of Design-Expert6.0.10 software. It was found that when the rotational speed of the high-speed/low-speed threshing drum was 518/626 r·min^{-1}, the linear velocity of rotary grid concave plate was 1.21 m·s^{-1} and the clamping chain speed was 1.10 m·s^{-1}, the corresponding grain loss rate, breakage rate and impurity rate were 1.87%, 0.18% and 0.56%, respectively.

Discussion and analysis

To verify the performance of the segmented-differential threshing and separating unit and contrast it to the conventional single-speed threshing and separating unit, the boundary dimension and structure of the two units are basically the same, which are "two-speed drum (arcuate-tooth) + rotary concave plate" and "single-speed drum (arcuate-tooth) + fixed concave plate" respectively. The rice variety for the contrast test is YongyouNo.15, and the characteristic parameters are shown in table 1. The feeding rate of the two units is both 1.5 kg/s, which is artificial feeding. The rotational speed of the high-speed/low-speed threshing drum in the segmented-differential threshing and separating unit is set to 520/630 r·min^{-1}, and the rotational speed of the threshing drum in single-speed threshing and separating unit is set to 600 r·min^{-1}. After threshing, the threshed materials are collected and counted by a sampling tray. The sampling tray is divided into 6 grids along the axial direction of the threshing drum with each grid length of 167 mm, of which 4 grids are located under the low-speed threshing drum and 2 grids are located under the high-speed threshing drum.

Performance analysis of two kinds of threshing and separating units

In terms of the grain loss rate, breakage rate and impurity rate in the front 2/3 part of the threshing drum in the axial direction, the conventional single-speed threshing and separating unit was higher than the segmented-differential threshing and separating unit in the axial direction, indicating that the rotational speed of threshing drum had a significant influence on the three indicators of threshing and separating performance. In the back 1/3 part of the threshing drum in the axial direction, although the rotational speed of high-speed threshing drum is higher than that of single-speed threshing drum, the breakage rate and impurity rate of the conventional single-speed threshing and separating unit were still higher than those of the segmented-differential threshing and separating unit. The reason is that the broken grains produced in the forepart of the single-speed threshing and separating unit were mixed up with the stem layer to the posterior to separate. The impurities in the forepart of the conventional single-speed threshing and separating unit were not separated enough, which caused that the posterior impurity rate was higher than that of the segmented-differential threshing and separating unit. This also indicated that the posterior drum played an important role to threshing and separating.

Through determination, the contrast of performance indicators between the segmented-differential threshing and separating unit and the conventional single-speed threshing and separating unit is shown in table 4. It can be seen that the performance of the segmented-differential threshing and separating unit is significantly better than that of conventional single-speed threshing and separating unit.

Table 4

Comparison of grain breakage rate, impurity rate and loss rate

Threshing and separating unit	Breakage rate / %	Impurity rate / %	Loss rate / %
Single-speed drum + fixed concave plate	0.38	0.70	2.07
Two-speed drum + rotary concave plate (segmented-differential)	0.20	0.56	1.95

CONCLUSIONS

Taking the segmented-differential threshing and separating unit of a head-feed combine harvester as the research focus, a model describing the grain stress and movement within the unit was developed, and the structure and working principle of the unit were thoroughly analyzed. By effectively utilizing the dual-speed threshing drum and the rotary grid concave plate, the performance of the head-feed threshing mechanism and the operational efficiency of the head-feed combine harvester were significantly improved.

(1) With the rotational speed of high-speed/low-speed drum, the linear velocity of rotary grid concave screen, and the clamping chain speed as the test factors, the grain loss rate, breakage rate and impurity rate as the performance indicators, three-factor quadratic regression orthogonal rotation combination design method was used to establish the mathematical model between the factors and indicators. The results of the test were processed using the Design-Expert8.0.6 software and showed that the rotational speed of the high-speed/low-speed threshing drum was 518/626 $r \cdot min^{-1}$, the linear velocity of rotary grid concave plate was 1.21 $m \cdot s^{-1}$ and clamping chain speed was 1.10 $m \cdot s^{-1}$. The grain loss rate, breakage rate and impurity rate were 1.87%, 0.18% and 0.56%, respectively.

(2) The loss rate is significantly affected by the rotational speed of the high-speed/low-speed threshing drum. The loss rate will increase gradually with the increase in the rotational speed of the high-speed/low-speed threshing drum. Both the rotational speed of the high-speed/low-speed threshing drum and clamping chain speed significantly affect the breakage rate. The grain breakage rate would increase when the clamping chain speed decreases or the rotational speed of the drum increases. The rotational speed of high-speed/low-speed threshing drum has a significant impact on the impurity rate. The grain impurity rate will gradually increase with the increase in the rotational speed of the threshing drum.

(3) The performances contrast test between the segmented-differential threshing and separating unit and the conventional single-speed threshing and separating unit showed that: the drum speed of the segmented-differential threshing and separating unit was 520/630 $r \cdot min^{-1}$, the linear velocity of rotary grid concave plate was 1.20 $m \cdot s^{-1}$ and clamping chain speed was 1.10 $m \cdot s^{-1}$. The grain loss rate, breakage rate and impurity rate were 1.95%, 0.20% and 0.56%, respectively. The performance indicators were better than the regulations of the industry standard.

(4) This study was conducted using the Yongyou No.15 rice variety, with a moisture content ranging from 23.3% to 24.5%. Future research will evaluate the performance of the segmented-differential threshing and separating unit when processing other rice varieties. Additionally, the impact of higher throughput on the unit's threshing and separating performance will also be investigated.

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