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Research and Experiment on Variable-Diameter Threshing Drum with Movable Radial Plates for Combine Harvester

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Abstract: In order to solve the problem of the threshing performance of a large combine harvester being reduced due to the non-adjustable diameter of the threshing drum, a variable-diameter threshing drum with movable radial plates based on the principle of concentric regulation was studied. It was mainly composed of a mechanism for adjusting the diameter by moving the radial plates, six fixed threshing tooth rods, six retractable threshing tooth rods and the single piston rod hollow hydraulic cylinder. The threshing gap can be adjusted by a stepless change of the drum diameter. By using RecurDyn simulation and field performance tests, the adjustable ranges of diameter and gap of the movable variable-diameter threshing drum were 670~710 mm and 10~30 mm. Based on the feed amount of the combine, the rotation speed of the threshing drum and the threshing gap (the diameter of the drum) as the influencing parameters, and the grain entrainment loss rate, grain un-threshed rate and grain breakage rate as the evaluation indexes, the three-factor and three-level response surface tests were carried out, and the result data were analyzed using Design-Expert 13.0. The optimal threshing gap and rotation speed of the threshing drum were determined under different feeding quantities. A comparative test was carried out to adjust and fix the threshing gap and rotation speed of the threshing drum in real time according to the change in feeding amount. The results showed that when the working parameter combination under different feeding amounts was adjusted in real time, the entrainment loss rate was 0.65%, the un-threshed rate was 0.063% and the breakage rate was 0.47%. Compared with the threshing gap and the rotation speed of the threshing drum being fixed, the entrainment loss rate, the un-threshed rate and the breakage rate were reduced by 44.9%, 27.6% and 34.1%, respectively. A threshing drum with variable diameter was provided for a large multi-crop harvesting combine to realize the concentric stepless adjustment of the threshing gap.

Keywords: variable-diameter threshing drum; movable radial plates; threshing gap; rotation speed of the threshing drum; feed quantity; response surface test

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1. Introduction

Harvesting machinery, as the main operational tool for grain crop pellets to be returned to the warehouse, is of great significance to maintain national food security. The threshing device is an important working part of the combine harvester [1–4], which changes the intensity of threshing action and improves the threshing performance by adjusting working parameters such as the rotation speed of the threshing drum and threshing gap in order to adapt to various types, varieties, maturity and humidity of grains.

Studies have shown that by changing the diameter of the threshing drum and concentrically adjusting the threshing gap, there was better transport separation capacity, more uniform distribution of the threshing material and less breakage of the grain straw [5]. For this reason, researchers have investigated variable-diameter threshing drums. Conventional threshing drums [6,7] adjust the drum diameter by manually replacing the threshing element or changing the installation position of the threshing tooth bar, which is time-consuming and laborious to adjust. The structure of mechanically driven variable-diameter threshing drums was complex and it was not easy to achieve stepless adjustment and adaptive control [8–11]. Yanbin Liu et al. [12] invented a hydraulically driven variable-diameter threshing drum, in which the diameter of the drum was changed by the radial movement of the threshing gear rod driven by the telescopic control linkage of the hydraulic cylinder, thus realizing the adjustment of the threshing gap. Su Zhan [13] designed an electronically controlled self-locking variable-diameter grain roller. By rotating the Archimedean constant speed spiral disk, the six grippers are driven to expand and expand, and then the tooth rod is driven by the connecting rod to change the diameter of the drum. Chen Lipeng [14] used gear drive to change the diameter of threshing drum. However, the current research on variable-diameter threshing drums was only for small feeding-capacity combine harvesters, and there were no intermediate support radial plates or the threshing tooth bar was not fixed with the intermediate support radial plates needed in order to achieve the change in drum diameter. With the development of grain combine harvesters at large, the torque and load on the threshing drum are increasing, which can easily deform the threshing tooth bar and even lead to damage of the threshing separation device, affecting the operational efficiency.

Many researchers have now conducted a large number of multi-factor interaction tests based on orthogonal test methods to determine the operating parameters of combine harvester threshing and separating devices [15–22]. However, the current parameter treatments after field trials are obtained under the specified operating conditions corresponding to an optimal combination of parameters [19–22], while there are large differences in the physical properties and biomass of grains in different areas of the same plot [23], and a single parameter leads to the problem of poor harvesting adaptation of the combine harvester with reduced threshing performance.

Therefore, in this paper, based on the principle of concentric adjustment and the advantages and disadvantages of the existing adjustment structures, a variable-diameter threshing drum with movable radial plates was designed. A three-factor, three-level response surface test [19–22,24] was conducted based on the combination harvester feed rate, rotation speed of the threshing drum and threshing gap (drum diameter) as the influencing parameters, and the grain entrainment loss rate, grain un-threshed rate and breakage rate as the evaluation indexes, to provide a grain combination harvester operation parameter adjustment scheme for the feed rate fluctuation in different areas of the same plot.

2. Materials and Methods

2.1. Design and Development

The design was based on the threshing drum of the Super Rui Long combine harvester produced by Jiangsu WROLD Agricultural Machinery Co. (Danyang, China). The specific parameters are shown in Table 1.

Table 1. Technical parameters of Super Rui Long 4LZ-8.0G(Q) combine harvester.

Model Structure Type		**4LZ-8.0G (Q) Crawler Self-Propelled Full Feed Type**
Overall size	Length (mm)	6200/6200
	Width (mm)	3170/3170
	Height (mm)	3080/2900
Whole machine quality		4500/4300
Motor	Model	YC4DK140-T301
	Power (kW)	103
	Rated rotation speed (r/min)	2600

Table 1. *Cont.*

Model Structure Type		4LZ-8.0G (Q) Crawler Self-Propelled Full Feed Type
Harvesting part	Width of cutting platform (mm)	2.36/2.56/2.8
	Feeding amount (kg/s)	8
Minimum Ground gap (mm)		320
Operational efficiency		3.3–16.5 Acresper hour
Harvest wheel	Type	Eccentric pivot tooth (pop-up) type
	Diameter (mm)	φ900
	Number of paddle wheel plates (pieces)	5
Threshing drum	Threshing method	Longitudinal axial rod-tooth type
	Threshing drum size (mm)	φ700 × 2520

2.1.1. Variable-Diameter Threshing Drum with Movable Radial Plates

The design of the variable-diameter threshing drum with movable radial plates was based on the principle of the hydraulic-driven variable-diameter threshing drum structure [12] using the Solid Works software, and the structure of the whole machine is shown in Figure 1. The designed threshing drum is mainly composed of the mechanism for adjusting the diameter by moving the radial plates, side disc adjustment mechanism, six fixed threshing gear rods, six retractable threshing gear rods, single piston rod hollow hydraulic cylinder, main shaft, displacement sensor, feeding wheel and hydraulic rotary joint.

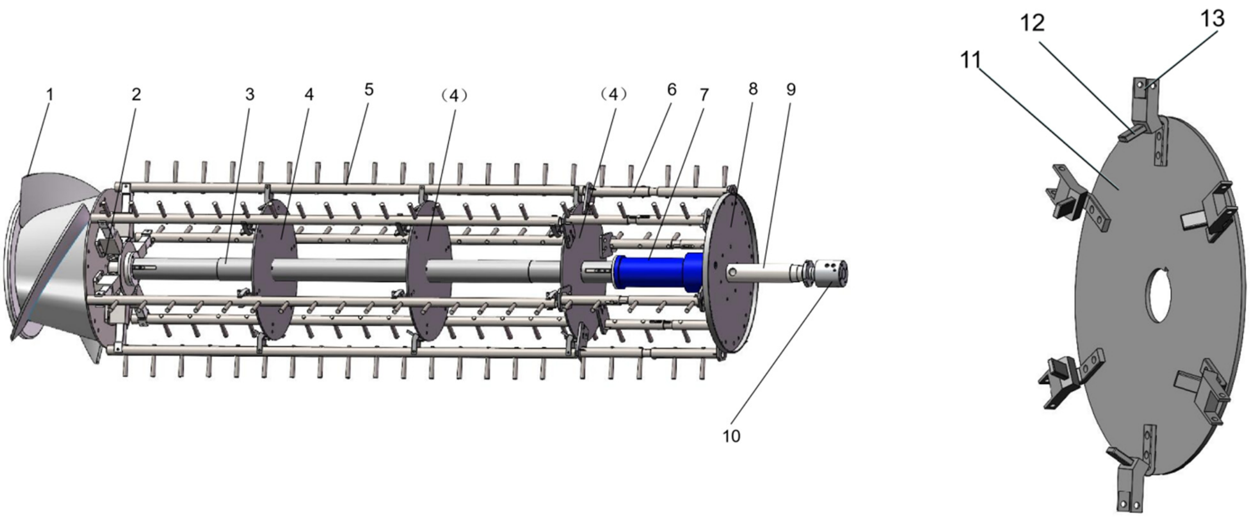


Figure 1. Schematic diagram of the structure of the variable-diameter threshing drum with movable radial plates: 1. feeding wheel, 2. side width plate adjustment mechanism, 3. sleeve, 4. support width plate mobile type adjustment mechanism, 5. fixed gear rod, 6. telescopic gear rod, 7. single piston rod hollow hydraulic cylinder, 8. rear side width plate, 9. spindle, 10. hydraulic rotary joint, 11. width plate, 12. adjustment slide, 13. slider type linkage.

When the diameter of the threshing drum needs to be adjusted, the hydraulic oil will enter the rod or rodless cavity of the single piston rod hollow hydraulic cylinder through the hydraulic swivel joint, pushing the piston rod to expand and contract, thus driving the axial movement of the axial sleeve, and then pushing the guide rail to push the disc along the axial movement, driving the hinge pin to slide along the bevel of the guide rail, driving the connecting rod to move radially along the slide groove; the axial movement of the axial sleeve also drives the movable adjustment structure of the width disc and the diameter adjustment slide on the width disc to move axially together; under the action of the connecting rod and the slider connecting rod, the fixed gear rod moves radially to realize the drum diameter adjustment. The diameter adjustment slide in the movable adjusting structure of the support disk also drives the disk and the diameter adjustment slide on the disk to move axially together, thus pushing the slide linkage to slide along the slide; under the action of the linkage and slide linkage, the fixed gear rod moves radially to realize the drum diameter adjustment. When the diameter of the threshing drum does not need to be moved, the hydraulic oil does not flow so that the piston cylinder of the hollow hydraulic cylinder is at rest, resulting in each adjustment mechanism at rest, ensuring that the position of the threshing tooth rod remains unchanged to achieve a constant diameter. The threshing tines between the two discs near the end (debris removal area) are designed as retractable tines, following the retraction of the hollow hydraulic cylinder.

2.1.2. Hydraulic System

The principle of the hydraulic system scheme is shown in Figure 2. A three-way four-way solenoid proportional reversing valve is used to switch the piston rod of the hollow hydraulic cylinder between telescopic and stationary states. The hydraulic lock is used to ensure that the hydraulic cylinder is self-locking after the diameter adjustment of the threshing drum by preventing the flow of hydraulic oil.

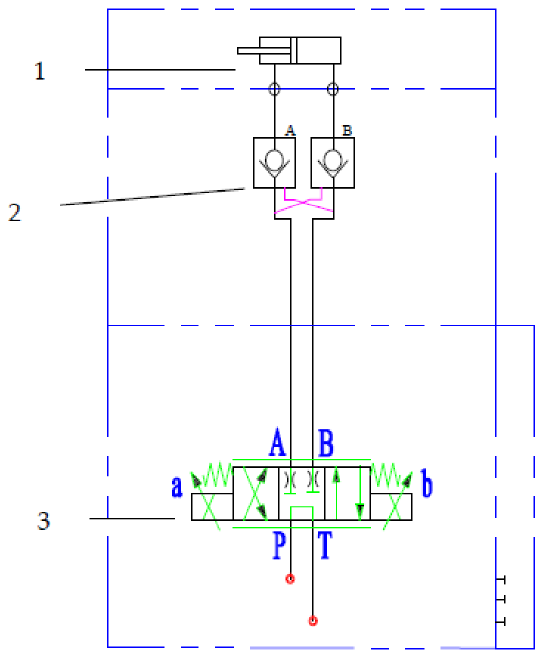


Figure 2. Hydraulic system schematic: 1. hollow hydraulic cylinder, 2. hydraulic lock, 3. three-way four-way solenoid proportional reversing valve.

2.1.3. Diameter Adjustment Performance Verification

At present, when applying the grain combine harvester to a multi-crop harvesting direction, different crops need different threshing gaps, and the threshing gap is also different for different varieties and different operating environments. According to a large number of experimental studies, the optimum threshing gap for wheat and rice is between 18 mm and 25 mm [11,25,26], for soybean between 24 and 30 mm [27,28], and for Oilseed rape between 11 and 23 mm [29,30]. Therefore, the maximum difference of threshing gap between various crops is 19 mm, and the diameter range of the designed mobile variable-diameter threshing drum was 670~710 mm, i.e., the adjustable range of threshing gap was 30~10 mm.

The angle of the guide rail is shown in Figure 3, and the relational expression between the angle of the adjustment slide and the amount of radius adjustment and horizontal travel is as follows:

$$\tan\theta = \frac{d_r}{d_s} \tag{1}$$

where d_r is the length of the variable-diameter threshing drum radius adjustment; d_s is the horizontal stroke of the diameter adjustment mechanism.

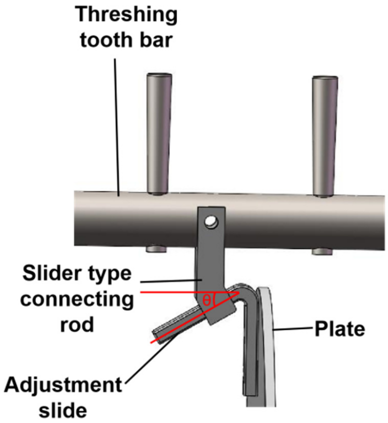


Figure 3. Diagram of adjusting the angle of the slide rail.

The angle was determined to be 30° according to the preliminary study [12].

RecurDyn Simulation

The 3D model of variable-diameter threshing drum with movable radial plates designed by Solidworks was imported into RecurDyn in blocks as required, and the constraints were added to the imported model according to the assembly relationship to simulate its diameter adjustment performance. A total of 1 Revolute constraint, 38 Translate constraints and 88 Fixed constraints were set on the model, and the constraints were added as shown in Figure 4. The gravitational acceleration was applied in the −Y direction, and the material of the model was set to steel. A drive control was added to Trajoint 8, which was the sliding constraint between the piston rod of the hydraulic cylinder and the spindle (simulation time was 8 s), with the expression STEP (time, 0, 0, 4, STEP (time, 4, −34.64, 8, 0)), and a marker point Marker 6 was added to the tip of the peg tooth of any fixed rod to monitor its trajectory.

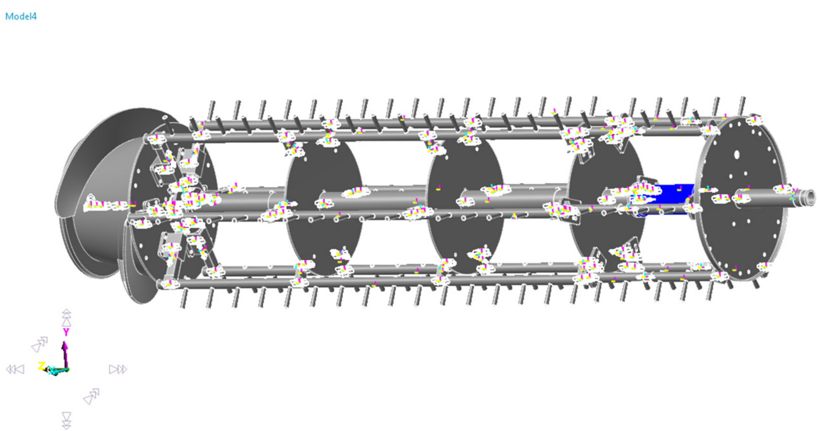


Figure 4. Simulation model diagram in RecurDyn.

Performance Verification

The variable-diameter threshing drum with movable radial plates and hydraulic system were assembled in Jiangsu WORLD and integrated into the WORLD Super Rui Long 4LZ-8.0G(Q). The drum diameter adjustment performance was verified by controlling the hydraulic cylinder in the cab through the switch of the proportional valve and reversing valve.

2.2. Field Trials

In order to obtain a scheme for the variable-diameter threshing drum with movable radial plates combine harvester to adjust the rotation speed of the threshing drum and threshing gap according to different feeds, a rice field trial [31] was conducted in December 2022 at Happy Farm, Danyang, Jiangsu, China.As shown in Figure 5. The rice variety is Zhendao32. Before the trial, tarpaulins were bundled to the discharge opening of the combine harvester to collect the threshing material, and a 20 m long test area was marked using a marker. After the test, the entrained loss seeds and un-threshed seeds in the detritus were screened to calculate the entrained loss rate and un-threshed rate, and the seeds from the grain bin were unloaded and weighed and randomly sampled to measure the seed breakage rate. Each group of tests was repeated three times, and the performance indexes were averaged.

Figure 5. Field trial.

2.2.1. Test Protocol

Box–Behnken Center Combination Test

In order to investigate the pattern of influence of combine harvester operating parameters on threshing performance indexes, field experiments were conducted using the combine harvester feed rate, rotation speed of the threshing drum, and threshing gap as influencing factors [32,33]. The adjustment of the feed rate was achieved by changing the forward speed of the combine harvester [34]. The speed of the threshing drum is regulated by the drum gearbox. According to the pre-harvest experiments of rice, the feed rate, rotation speed of the threshing drum and threshing gap were set to 6 kg/s~9 kg/s, 700 r/min~900 r/min and 15 mm~25 mm, respectively, and a three-factor, three-level response surface test was conducted using Design Expert software according to the Box–Behnken central combination test design theory [35,36]. The factor level codes are shown in Table 2.

In order to obtain the optimal combination of operating parameters for different feeding rates of variable-diameter detachment drums, the Optimization function of Design-Expert 13.0 was used to set the constraints for each test factor and evaluation index in Numerical, and the threshing drum speed and threshing gap were set at 700 r/min to 900 r/min. The rotation speed of the threshing drum and threshing gap were set between 700 r/min~900 r/min and 15 mm~25 mm, respectively. The entrained loss rate, un-threshed rate and breakage rate were all taken as the minimum values, while the specific gravity was "3:3:4". The feed rate was entered in the range of 6 kg/s to 9 kg/s to obtain the combination of threshing gap and rotation speed of the threshing drum parameters that satisfy the constraints for the corresponding feed rate.

Table 2. Factor level coding table.

Code	Factors		
	Feeding Volume (kg/s)	**Rotation Speed of the Threshing Drum (r/min)**	**Threshing Gap (mm)**
−1	6	700	15
0	7.5	800	20
+1	9	900	25

Comparative Test Protocol

Due to the different crop growth and crop density in the field, as well as combining with the habits of the mechanic driving the combine harvester and the turning needs, the feeding amount of the combine harvester is different in different areas of the same field. Therefore, it is necessary to adjust the threshing gap and drum speed of the combine harvester in real time according to different feeding amounts to improve the operational performance of the combine harvester. According to the study by Lele Wei et al. [25], it was found that the rice density distribution in the field block could be analyzed using UAV photography, while the size of the feeding volume could be deduced based on parameters such as yield and grain-to-grass ratio, and after regularization, the field feeding volume distribution map was obtained as shown in Figure 6. In order to verify that the combine harvester can improve the threshing performance by adjusting the threshing gap and drum speed according to different feeding amounts, two sets of tests were designed for comparison: (i) the drum diameter was adjusted in real time to achieve the required threshing gap according to the optimal combination of parameters at different feeding amounts, and the drum speed was adjusted accordingly; (ii) the combine harvester harvested with a fixed threshing gap and drum speed, which were not adjusted due to changes in the feeding amount. The test procedure was the same as above, with each group of tests conducted three times and the threshing performance averaged.

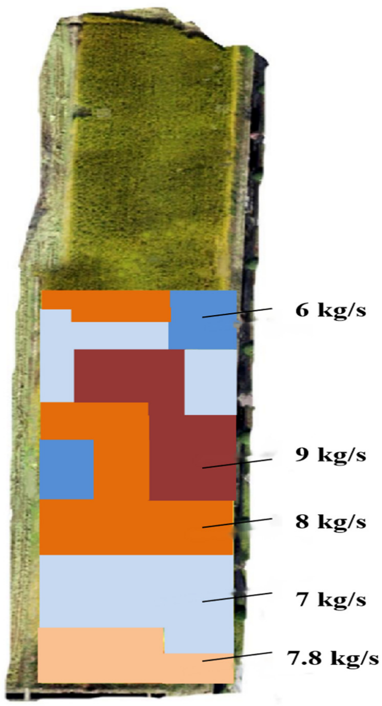


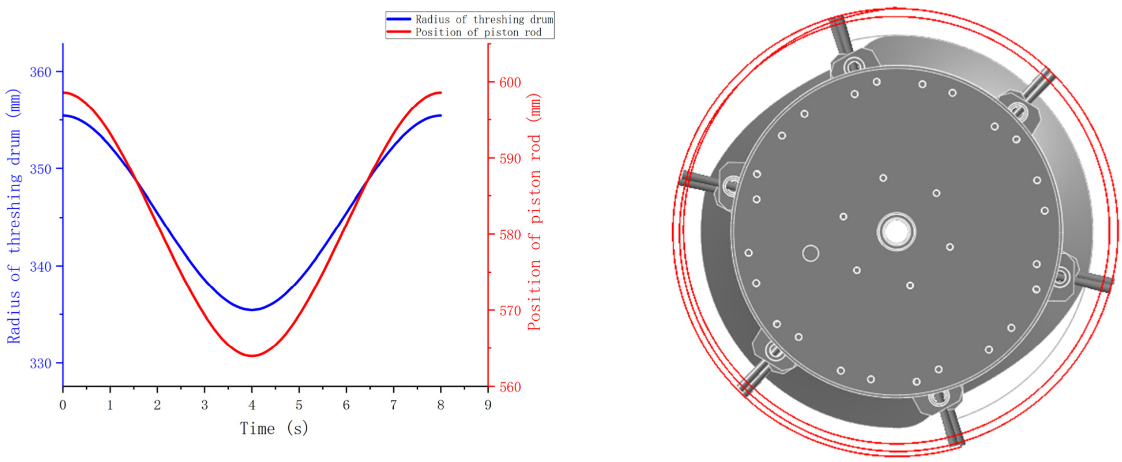
Figure 6. Distribution of feeding volume in the field.

3. Results and Discussion

3.1. Performance Verification Results

3.1.1. RecurDyn Simulation Results

After setting all the parameters and conditions, the simulation was carried out and the results are shown in Figure 7. In 0~4 s, the piston rod of the hydraulic cylinder slowly shrinks with time, and the piston rod shrinks 34.64 mm. At this time, the radius of the variable-diameter threshing drum with movable radial plates changes. The radius change range is 355.44~335.45 mm; that is, the adjustable range of threshing gap is 19.99 mm. In 4~8 s, the piston rod of the hydraulic cylinder extends 34.64 mm with time. The piston rod of the hydraulic cylinder extends 34.64 mm with time at 4~8 s, and the radius change range is 335.45~355.45 mm, which proves that the variable-diameter threshing drum with movable radial plates is adjustable back and forth and the adjustment range is in accordance with the design requirements.



(**a**) (**b**)

Figure 7. Simulation of diameter adjustment of RecurDyn-based variable-diameter threshing drum with movable radial plates. (**a**) Piston rod position along the main shaft and drum diameter variation diagram; (**b**) Marker 6 motion track.

3.1.2. Installed Performance Verification

Figure 8 shows the installation positions. The diameter adjustment of the variable-diameter threshing drum with movable radial plates can be realized by manipulating the switch of the proportional valve and reversing valve in the cab. By pushing the switch back and forth, the hydraulic oil is controlled from the hydraulic system through the hydraulic oil pipe into and out of the hollow hydraulic cylinder of the variable-diameter threshing drum with movable radial plates, thus controlling the piston rod of the hollow hydraulic cylinder to expand and retract and achieve the role of diameter adjustment. The monitoring of the threshing gap is indirectly obtained by monitoring the diameter of the threshing drum, and the change value of the threshing drum diameter is obtained by the displacement sensor, and is displayed on the instrument in the cab; the monitoring accuracy is 0.1 mm. After testing, the diameter of the threshing drum can be adjusted freely and the radius can be adjusted by 20 mm, i.e., the range of threshing gap is 20 mm, which meets the design requirements and verifies the rationality of the mechanism and the reliability of the adjustment range.

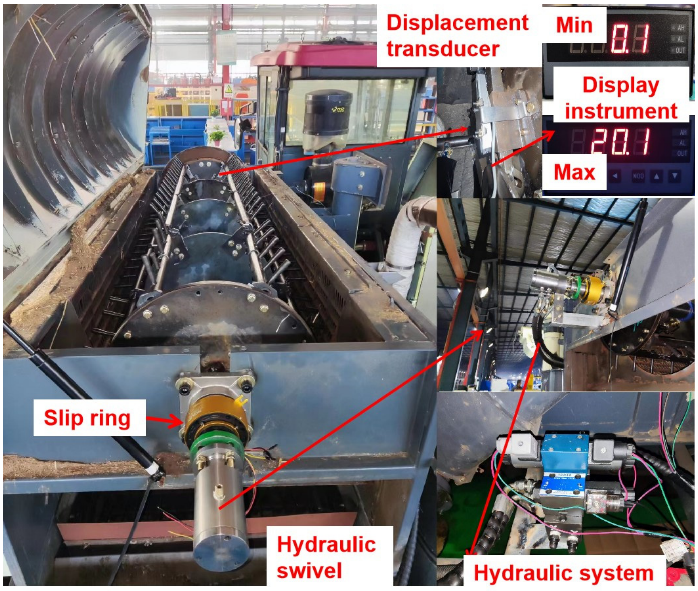


Figure 8. Variable-diameter threshing drum with movable radial plates and hydraulic system and related accessories.

3.2. Results of Field Trials

The results were summarized and analyzed according to the formulae of each evaluation index, and the experimental scheme and results are shown in Table 3.

Table 3. Experimental protocol and results.

Test No.	A:Feeding Volume kg/s	B:Drum Speed r/min	C:Threshing Gap mm	Entrainment Loss Rate %	Un-Threshed Rate %	Breakage Rate %
1	6	800	25	0.63	0.073	0.415
2	7.5	700	15	0.69	0.075	0.514
3	9	800	25	0.81	0.098	0.651
4	9	900	20	0.83	0.081	1.138
5	7.5	800	20	0.59	0.057	0.345
6	7.5	900	15	0.65	0.059	0.912
7	9	700	20	0.97	0.128	0.723
8	7.5	700	25	0.79	0.126	0.456
9	6	800	15	0.48	0.044	0.367
10	7.5	800	20	0.61	0.056	0.315
11	7.5	800	20	0.59	0.063	0.356
12	7.5	800	20	0.62	0.059	0.332
13	9	800	15	0.92	0.074	0.862
14	7.5	900	25	0.75	0.079	0.698
15	7.5	800	20	0.61	0.061	0.362
16	6	700	20	0.57	0.068	0.398
17	6	900	20	0.61	0.068	0.562

3.2.1. Entrainment Loss Rate

An analysis of variance (ANOVA) was performed on the entrapment loss rate by Design-Expert 13.0 [37], and the results are shown in Table 4.

Table 4. Analysis of variance for entrapment loss rate.

Source	Sum of Squares	df	Mean Square	F-Value	*p*-Value	Significance
Model	0.2827	9	0.0314	55.39	<0.0001	Extremely significant
A-Feeding volume	0.1922	1	0.1922	338.89	<0.0001	Extremely significant
B-Rotation speed of the threshing drum	0.0040	1	0.0040	7.14	0.0319	Significant
C-Threshing gap	0.0072	1	0.0072	12.70	0.0092	Extremely significant
AB	0.0081	1	0.0081	14.28	0.0069	Extremely significant
AC	0.0169	1	0.0169	29.80	0.0009	Extremely significant
BC	0.0000	1	0.0000	0.0000	1.0000	Non-significant
A^2	0.0181	1	0.0181	31.85	0.0008	Extremely significant
B^2	0.0240	1	0.0240	42.32	0.0003	Extremely significant
C^2	0.0069	1	0.0069	12.18	0.0101	Significant
Residual	0.0040	7	0.0006			
Lack of Fit	0.0032	3	0.0011	6.02	0.0578	Insignificant
Pure Error	0.0007	4	0.0002			
Cor Total	0.2867	16				
R^2	0.9862					

The regression equation for the entrainment loss rate is as follows:

$$S_j = 0.604 + 0.155A - 0.0225B + 0.03C - 0.045AB - 0.065AC + 0.0655A^2 + 0.0755B^2 + 0.0405C^2 \quad (2)$$

As can be seen from Table 4, the model *p*-value for the entrainment loss rate is less than 0.01 and the model F-value is 55.39, which indicates that the model is significant. Also, the model coefficient of determination $R^2 = 0.9862$ indicates that the regression model obtained for the entrained loss rate reflects 98.62% of the variation in response values and the misfit term is not significant, indicating that the error in the experimental data is small while the regression equation obtained is a good fit. A *p*-value less than 0.05 indicates that the model term is significant; in this case, A, B, C, AB, AC, A^2, B^2 and C^2 are the model terms with significant entrainment loss rates.

From Table 4, it can be seen that the feeding amount, rotation speed of the threshing drum and threshing gap are the significant terms of entrainment loss, and the response surface of the significant terms and the entrainment loss rate were analyzed comprehensively. From Figure 9, the entrainment loss rate increased with increasing feed volume, which was attributed to the fact that the density and thickness of rice in the threshing chamber increased with increasing feed volume, resulting in increased difficulty in getting the already threshed seeds through the straw to reach the underside of the concave sieve [38]. The entrainment loss rate decreased and then increased with the increase in rotation speed of the threshing drum because the intensity of the action of the threshing element on the crop increased as the speed of the threshing drum increased, and the entrained seeds were more easily separated out, but as the speed continued to increase, the time that the crop remained in the threshing drum decreased, resulting in an increase in entrainment losses. The entrainment loss varies little with the threshing gap, and the overall trend is to increase, because the threshing gap determines the thickness of the crop inside the threshing chamber, and the greater the crop thickness the greater the entrainment loss.

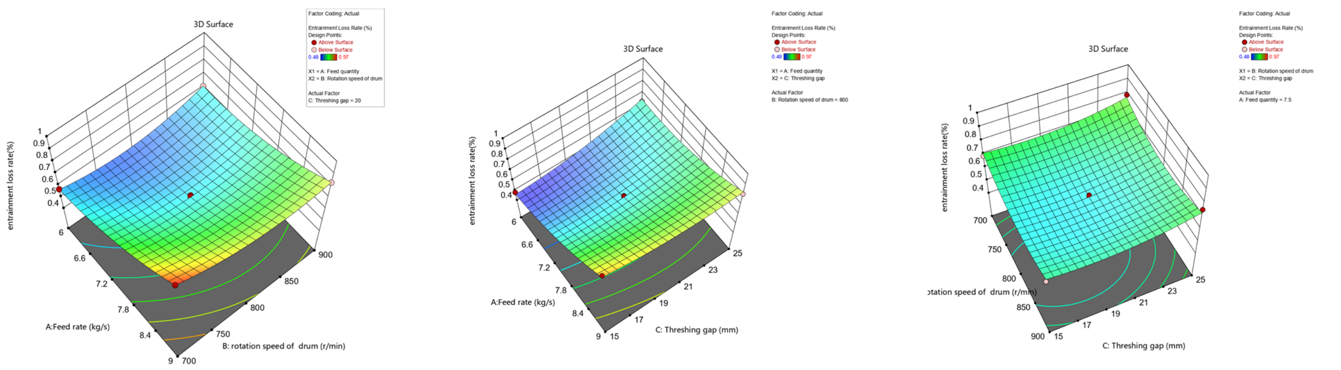


Figure 9. Response surface of each factor on entrainment loss rate.

3.2.2. Un-Threshed Rate

An analysis of variance (ANOVA) was performed by Design-Expert 13.0 on the un-threshed rate, and the results are shown in Table 5.

Table 5. Analysis of variance (ANOVA) for the un-threshed rate.

Source	Sum of Squares	df	Mean Square	F-Value	*p*-Value	Significance
Model	0.0084	9	0.0009	45.05	<0.0001	Extremely significant
Feeding volume	0.0020	1	0.0020	98.33	<0.0001	Extremely significant
B-Rotation speed of the threshing drum	0.0015	1	0.0015	72.62	<0.0001	Extremely significant
C-Threshing gap	0.0019	1	0.0019	92.28	<0.0001	Extremely significant
AB	0.0006	1	0.0006	26.51	0.0013	Extremely significant
AC	6.250×10^{-6}	1	6.250×10^{-6}	0.3001	0.6009	Not significant
BC	0.0002	1	0.0002	11.53	0.0115	significant
A^2	0.0002	1	0.0002	10.70	0.0137	significant
B^2	0.0016	1	0.0016	79.05	<0.0001	Extremely significant
C^2	0.0001	1	0.0001	6.74	0.0356	significant
Residual	0.0001	7	0.0000			
Lack of Fit	0.0001	3	0.0000	4.59	0.0874	Not significant
Pure Error	0.0000	4	8.200×10^{-6}			
Cor Total	0.0086	16				
R^2	0.9830					

The regression equation for the un-threshed rate is as follows:

$$W = 0.0592 + 0.016A - 0.0137B + 0.0155C - 0.0118AB - 0.0012AC - 0.0078BC + 0.0073A^2 + 0.0198B^2 + 0.0058C^2 \quad (3)$$

From Table 5, it can be seen that the model *p*-value for the un-threshed rate is less than 0.01 and the model F-value is 45.05, which indicates that the model is significant. Also, the model coefficient of determination $R^2 = 0.983$, indicating that the regression model obtained for the un-threshed rate reflects 98.3% of the variation in response values and the misfit term is not significant, indicating that the error in the experimental data is small while the regression equation is a good fit. A *p*-value less than 0.05 indicates that the model term is significant; in this case, A, B, C, AB, BC, A^2, B^2, and C^2 are the model terms with significant un-threshed rates.

As can be seen from Table 5, for the un-threshed rate, the feeding amount, rotation speed of the threshing drum and threshing gap were significant terms, and the response effects of the significant terms and the un-threshed rate were analyzed comprehensively. As can be seen from Figure 10, the un-threshed rate increased with the increase in feeding volume, because the increase in feeding volume led to the thickness and density of the crop layer inside the threshing chamber, which resulted in the rice spike head interspersed in the middle of the stalk not being in full contact with the threshing element, resulting in some of the seeds not being threshed out and the un-threshed rate increasing. The reason is that when the drum speed increases, the force of the threshing element on the spike head becomes larger, which makes the seeds easier to be threshed out and reduces the un-threshed rate; as the drum speed continues to increase, the crop residence time and the number of threshing actions decrease, resulting in some of the seeds being discharged from the machine before being threshed out. The un-threshed rate increases with the increase in the threshing gap, because the increase in the threshing gap will lead to the contact between the threshing element and the head of the rice spike, which increases the un-threshed rate.

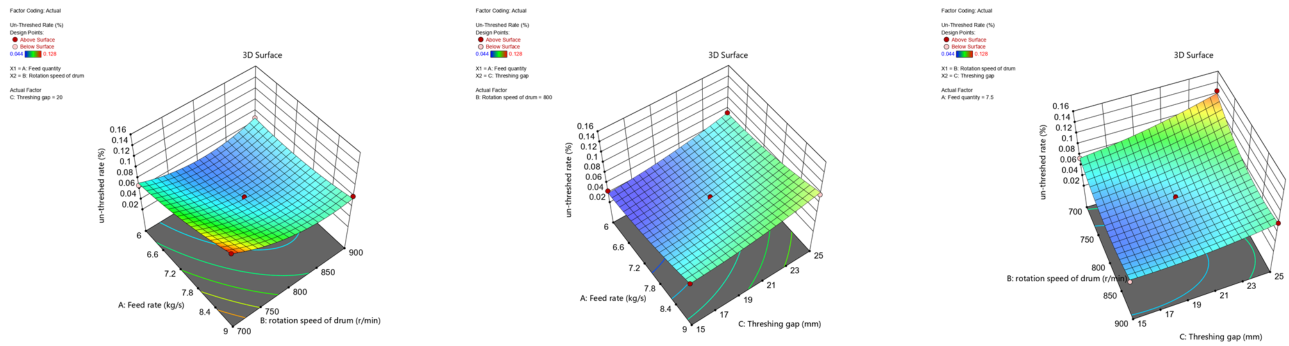


Figure 10. Response surface of each factor on the un-threshed rate.

3.2.3. Breakage Rate

An analysis of variance (ANOVA) was performed on the breakage rate by Design-Expert 13.0 and the results are shown in Table 6.

Table 6. Analysis of variance for breakage rate.

Source	Sum of Squares	df	Mean Square	F-Value	*p*-Value	Significance
Model	0.9318	9	0.1035	103.59	<0.0001	Extremely significant
A-Feeding volume	0.3329	1	0.3329	333.08	<0.0001	Extremely significant
B-Rotation speed of the threshing drum	0.1857	1	0.1857	185.83	<0.0001	Extremely significant
C-Threshing gap	0.0237	1	0.0237	23.66	0.0018	Extremely significant
AB	0.0158	1	0.0158	15.76	0.0054	Extremely significant
AC	0.0168	1	0.0168	16.78	0.0046	Extremely significant
BC	0.0061	1	0.0061	6.09	0.0430	Significant
A^2	0.0898	1	0.0898	89.79	<0.0001	Extremely significant
B^2	0.1987	1	0.1987	198.82	<0.0001	Extremely significant
C^2	0.0310	1	0.0310	30.97	0.0008	Extremely significant
Residual	0.0070	7	0.0010			
Lack of Fit	0.0056	3	0.0019	5.17	0.0732	Not significant

Table 6. *Cont.*

Source	Sum of Squares	df	Mean Square	F-Value	*p*-Value	Significance
Pure Error	0.0014	4	0.0004			
Cor Total	0.9388	16				
R^2	0.9925					

The regression equation for the breakage rate is

$$P = 0.342 + 0.204A + 0.1524B - 0.0544C + 0.0627AB - 0.0648AC - 0.039BC + 0.146A^2 + 0.2172B^2 + 0.0858C^2 \quad (4)$$

As can be seen from Table 6, the model *p*-value for breakage rate is less than 0.01 and the model F-value is 103.59, indicating that the model is significant. Also, the model coefficient of determination $R^2 = 0.9925$ indicates that the regression model obtained for the crushing rate reflects 99.25% of the variation in response values and the misfit term is not significant, indicating that the error in the experimental data is small while the regression equation is a good fit. A *p*-value less than 0.05 indicates that the model term is significant; in this case, A, B, C, AB, AC, BC, A^2, B^2 and C^2 are the model terms with significant breakage rates.

A comprehensive analysis of the response effect of significant factors and the breakage rate was performed. As can be seen from Figure 11, the breakage rate decreases and then increases with the increase in feeding volume; because of the increase in feeding volume, threshing by threshing element striking decreases, and the increase in rubbing threshing between crops reduces the crushing of the threshing element on the seeds, but as the feeding volume continues to increase, a large number of seeds are produced, which increases the probability of striking on the seeds by the threshing element and increases the breakage rate. The breakage rate decreases and then increases with the increase in the threshing drum speed, which is due to the fact that when the drum speed starts to increase, the crop stay time decreases and the probability of impact on the seeds decreases, reducing the breakage rate; the drum speed continues to increase and the striking force of the threshing element for each material becomes larger, increasing the breakage rate of the seeds. The breakage rate decreases as the threshing gap increases, because the material becomes fluffy when the threshing gap increases, reducing the chance of contact between the seeds and the threshing parts and thus reducing the breakage rate.

3.2.4. Comparison Test

According to Figure 6 the optimal parameters at the corresponding feeding rates were found and analyzed using Design-Expert software to obtain the required operational prescription. The optimal parameter combinations are shown in Table 7.

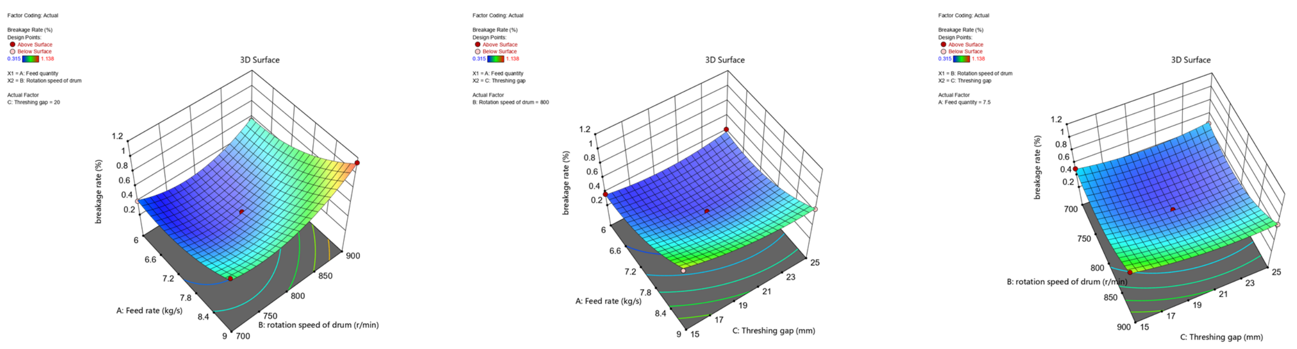


Figure 11. Response surface of each factor on breakage rate.

Table 7. Optimal combination of parameters at different feeding rates.

Feed Rate (kg/s)	Optimal Combination of Parameters						
	Rotation Speed of the Threshing Drum (r/min)	Optimized Drum Speed (r/min)	Threshing Gap (mm)	Optimized Threshing Clearance (mm)	Entrainment Loss Rate (%)	Un-Threshed Rate (%)	Breakage Rate (%)
6	775.000	775	16.000	16	0.464	0.041	0.314
7	791.362	791	17.572	17.6	0.545	0.049	0.315
7.8	799.460	800	18.944	18.9	0.636	0.060	0.406
8.2	803.942	804	19.634	19.6	0.689	0.066	0.483
8.5	807.324	807	20.181	20.2	0.733	0.072	0.555
9	812.928	813	21.180	21.2	0.811	0.083	0.699

Since the threshing device was adjusted with limited accuracy and could not achieve the accuracy predicted by the optimal combination of parameters, the parameters were adjusted: the rotation speed of the threshing drum was adjusted to an integer level and the threshing gap was kept to one decimal place. Tests were conducted according to the comparative test scheme, and the results are recorded in Table 8.

Table 8. Comparison test results.

No.	Real-Time Adjustment of Threshing Gap and Drum Speed			No Adjustment		
	S_j	W	P	S_j	W	P
1	0.65	0.061	0.563	0.98	0.079	0.762
2	0.63	0.066	0.379	1.34	0.087	0.683
3	0.67	0.062	0.468	1.22	0.095	0.694
Mean	0.65	0.063	0.47	1.18	0.087	0.713

According to Table 8, it can be seen from the three evaluation indexes that the real-time adjustment of the drum diameter to change the threshing gap and rotation speed of the threshing drum during operation reduces the entrainment loss rate by 44.9%, the un-threshed rate by 27.6%, and the breakage rate by 34.1% compared with the fixed parameters. It shows that the real-time adjustment of the working parameters according to the field conditions is effective, and the amplitude disc moving variable-diameter threshing drum has good threshing performance, which improves the operating performance of the combine harvester and lays a firm foundation for the intelligent adaptive adjustment of the threshing gap.

4. Conclusions

(1) In order to solve the problem of the complicated adjustment of the threshing gap in large-size, large-feeding combine harvester and to provide a basis for an adaptive adjustment of the threshing gap, a hydraulically driven variable-diameter threshing drum with movable radial plates based on a concentric adjustment principle is studied, which can quickly adjust the threshing gap by changing the drum diameter.

(2) Through RecurDyn simulation and practical validation, it is verified that the diameter of the variable-diameter threshing drum with movable radial plates can be adjusted, and the drum diameter can be changed by 40 mm when the hollow hydraulic cylinder goes back and forth by 34.64 mm, i.e., the threshing gap can be adjusted by 20 mm.

(3) Through the field test, the evaluation index model of the variable-diameter threshing drum with movable radial plates for a single species of rice was established, and the optimal combination of operating parameters of the threshing drum under different feeding amounts was obtained. The results showed that when the operating parameters were adjusted in real time at different feed rates, the entrainment loss rate was 0.65%, the un-threshed rate was 0.063%, and the breakage rate was 0.47%, compared

with the fixed threshing gap and drum speed. Compared with the fixed threshing gap and rotation speed of the threshing drum, the entrained loss rate, un-threshed rate and breakage rate were reduced by 44.9%, 27.6% and 34.1%, respectively. Therefore, the real-time adjustment of threshing parameters is obviously better than the fixed parameters, and the variable-diameter threshing drum with movable radial plates of the amplitude disc can meet the requirements of use and lay a good foundation for adaptive adjustment of the threshing gap.

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