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RESEARCH ARTICLE

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Structural and parameter design of transverse multi-cylinders device on rice agronomic characteristics

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Abstract

Rice panicles which have reached a mature state must be harvested, requiring differently specialized threshing devices and operating parameters to achieve favorable threshing and separating results. The primary objective of this study is to design a transverse multi-cylinders device that operates under the most effective possible variables to harvest rice in different states of maturity. The attachment forces between the grain and pedicel on the panicle were measured at different moisture contents. Based on rice agronomic characteristics, a transverse multi-cylinders device test bench was developed to conduct threshing and separating experiments. The threshing and separating capability of each transverse cylinder was tested, and the operating parameters of each threshing cylinder were investigated. Results showed that detachment force decreased from the bottom to the top of the rice panicle. Optimal harvesting time was identified at moisture content of 29.69%, and the best operating parameters combination was cylinder speed of 600, 650 and 700 rpm, and concave clearances of 40, 35 and 40 mm. Combine harvester of transverse multi-cylinder device test results showed an un-threshed grain ratio of 0.64%, un-separated grain ratio of 0.35%, and broken grain ratio of 0.22%, at a feeding rate of 6 kg/s. This research can be used in the future to successfully design transverse multi-cylinders device for small and medium-sized rice combine harvesters.

Additional key words: detachment force; threshing and separation; agronomic characteristics; rice panicle; multi-cylinders.

Abbreviations used: I-TCy (I threshing cylinder); II-TCy (II threshing cylinder); III-TCy (III threshing cylinder); MOG (material other than grain).

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Introduction

When rice is harvested in the field, the moisture content of the grain and rice panicle differs (Cheng *et al.*, 2015). Different moisture content results in different attachment force between the grain and pedicel on the panicle, which thus require specialized threshing devices and operating parameters (Liu *et al.*, 2014). Rice harvesting results are significantly impacted by the crop characteristics and operating parameters of threshing devices. Accordingly, design of threshing devices should be based on the crop characteristics.

Over the past few years, many studies have attempted to determine the best threshing drum type, cylinder speed and feeding rate parameters, and grain/material other than grain (MOG) separation over the length of the threshing cylinder (Sudajan *et al.*, 2001; Golpira *et al.*, 2013). Several researchers (Singh *et al.*, 2008; Osueke, 2011; Bakhtiari *et al.*, 2013) concluded that variations in cylinder peripheral speed and effective concave clearance are the primary machine variables which influence threshing performance. Mansoori & Minaee (2003) explored the effect of cylinder speed and cylinder concave clearance on losses in the threshing unit to find that increase in cylinder concave clearance results in less grain breakage. Alizadeh & Khodabakhshipour (2010) investigated the effects of the threshing cylinder speed of an axial flow thresher at five levels, plus paddy moisture content at three levels, on rates of broken and cracked grains. Busato (2015) developed a simulation model to compare different practices of harvesting and operational parameter prediction. So far, there are many types of rice threshing devices (Tang *et al*., 2014). To obtain investigative and optimization basis for designing rice threshing devices, several researchers have explored the relationship between crop characteristics and threshing devices. Feiffer *et al*. (2001), for example, indicated that crop species, moisture, and biometrical indices that change during harvesting influence the threshing process. The grain losses observed at different threshing timings were in accordance with the findings of McCauley & Way (2002). Ntanos *et al.* (1996), in another relevant study, estimated total milling yield and grain breakage at six different harvest times. Kawamura *et al*. (2002) investigated the effect of tensile speed on detaching single grains of 20 different rice varieties, and indicated that detaching behavior was not affected by tensile speed, but instead was dependent on the water content of the stems and the specific type of rice. Inoue *et al*. (2003) evaluated strength distribution on the detachment force of paddy grains, conducting experiments for 49 days during the harvest season, and measured grain detachment force based on parallel and perpendicular forces. Yang *et al*. (2012) indicated that the detachment force of one rice panicle was different at different locations and different moisture content. Hosoi *et al*. (2008) studied seed threshability and shattering habits of weedy rice accessions collected from paddy fields. Azouma *et al*. (2009) measured grain shatter force for the design and development of throw-in type rice threshers for small-scale farmers. Moisture content (mature state) was determined to be a very effective criterion for the determination of optimum grain harvest time (Sun *et al*., 2013; Cheng *et al*., 2015). Design and development of threshing devices are highly dependent upon agronomic characteristics of crops.

Crop agronomic characteristics and machine operating parameter combinations are known to influence the performance of threshers (Singh *et al*., 2008; Dionysis *et al*., 2014). Combinations of operating parameters have been shown to influence threshing capability, as well. Srivastava *et al*. (1990) demonstrated that separation is very sensitive to variation in the physical properties of grain, straw, and chaff. The effects of inappropriate crop agronomic characteristics, in addition to their impact on energy requirements for threshing rice, extend also to high grain losses (Veselinov *et al*., 2014; Chen *et al*., 2015). Again, as demonstrated by the wealth of previous studies, the threshing capability of threshing devices is determined by the agronomic characteristics of crops. Rice should be threshed step-by-step with appropriate different threshing devices based on different operating parameters. There exists relatively little prior information regarding the threshing capability of multi-cylinder devices, or operating parameter combinations of transverse multi-cylinder devices on different agronomic characteristics of rice.

This study measured the attachment forces between the grain and pedicel on the panicle at different moisture contents, to obtain a distribution range of attachment forces, and to develop a transverse multi-cylinder test bench for threshing and separating rice step-by-step. A rice-threshing test bench experiment was also conducted to investigate the threshing and separating capability of each transverse cylinder under different operating parameter. Operating parameter combinations with differing moisture content were obtained by comparing threshing and separating performance detection indexes.

Material and methods

Transverse multi-cylinders device

Transverse multi-cylinders combination was the main body of threshing apparatus of combine harvester. In order to investigate the threshing and separating capability of transverse multi-cylinders, and to obtain the best operating parameters combination on different rice agronomic characteristics, a transverse multi-cylinders test bench was developed as shown in Fig. 1. The test bench was comprised of a conveying plat, feed auger, conveying chute, I threshing cylinder (I-TCy), II threshing cylinder (II-TCy), III threshing cylinder (III-TCy), and other parts shown in detail below. A group of reception boxes were fixed under the grid concave of the transverse multi-cylinder device to receive the grains and short stalks separated through the grid concave (Li *et al*., 2013). Operating parameters such as threshing cylinder speed and concave clearance are the most important factors that influence both the power consumption of the threshing apparatus and the grain loss ratio during the rice harvesting process. In this study, the cylinder speed and concave clearance combinations of three threshing cylinders were the primary operating parameters.

Diameters of the I-TCy, II-TCy, and III-TCy devices were 525, 515 and 450 mm, respectively; lengths were 548, 1280 and 1280 mm, respectively. The threshing teeth were spike teeth. A schematic diagram of the threshing cylinders is shown in Fig. 2. The three threshing cylinders were driven by the respective frequency

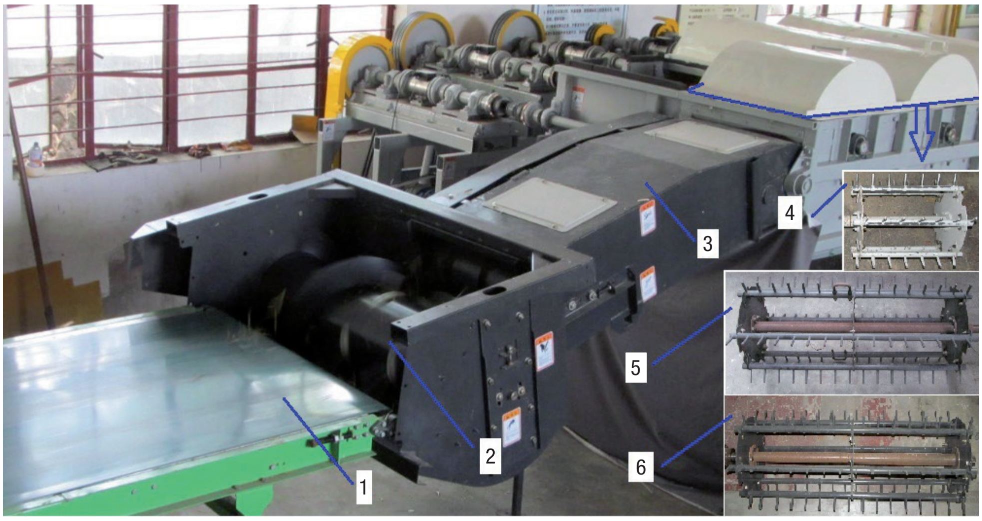

Figure 1. Schematic diagram of transverse multi-cylinder test bench: 1, conveying belt; 2, feed auger; 3, conveying chute; 4, first threshing cylinder (I-TCy); 5, second threshing cylinder (II-TCy); 6, third threshing cylinder (III-TCy).

conversion motors. During the threshing process, three HAD-CYB-803S torque sensors (Beijing Westzh M & E Technology Co., Ltd., China) measured the torque value and speed at measurement accuracy of 0.25% full scale and frequency response time of 100 µs. The rice straw was preliminarily threshed and separated by I-TCy, then moved to II-TCy, where any remaining un-threshed grain was re-threshed and re-separated. Finally, the un-separated grain was again separated by III-TCy.

In order to ensure the straw was fed smoothly into the threshing device, the distance between I-TCy and II-TCy (and between II-TCy and III-TCy) was very important. The most effective distance between the I-TCy axis and II-TCy axis was identified at 730 mm, the same as the distance between the II-TCy axis and III-TCy axis. The mutual positional relationship is shown in Fig. 3a. Once the rice was threshed and the grain was separated by I-TCy, II-TCy, and III-TCy, the straw was discharged through the discharge hole. To make sure the straw was discharged through the hole smoothly, the size of the discharge hole was optimized at 300 mm as shown in Fig. 3b.

Freshly-cut rice (72 kg) was placed on a 12 m × 1 m conveyer belt at a liner speed of 1 m/s (with constantly feeding rate of 6 kg/s). After the rice was threshed and the grain was separated through the grid concave (forming "collected grain") a few grains remained that were not threshed from the rice panicle (un-threshed grain) some that had not separated from

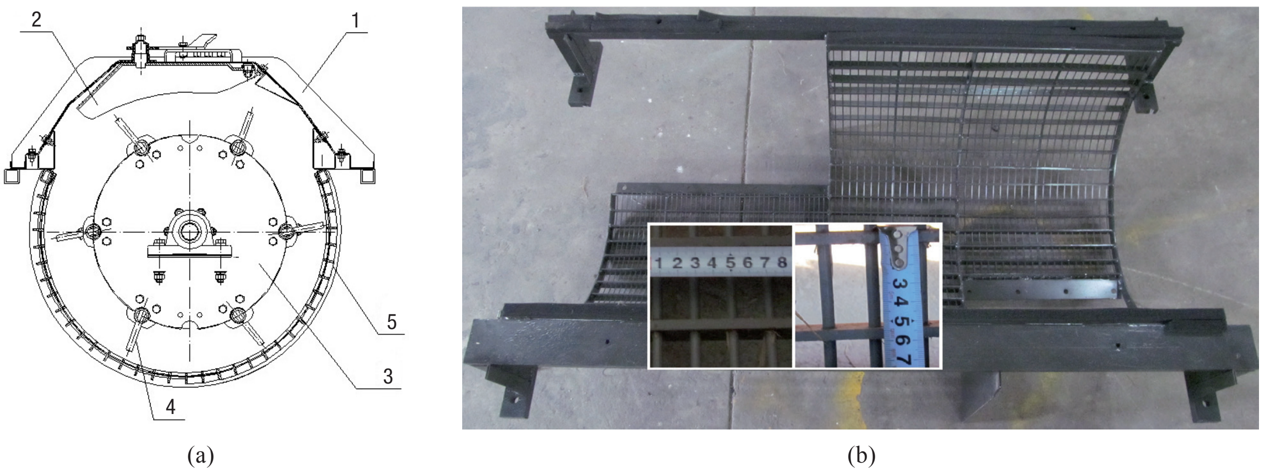

Figure 2. Schematic diagram of threshing cylinders: (a) assembly of threshing cylinders; 1, cylinder cover; 2, channel spiral plate; 3, threshing cylinder; 4, spike tooth; 5, grid concave; (b) diagram of grid concave. Note: distances shown in centimeters.

(a) (b)

Figure 3. Mutual positional relationship of three threshing cylinders (a) and discharge hole size of III-TCy (b). Note: distances shown in centimeters

the straw (un-separated grain), and some that were crushed by the spike tooth (broken grain); all of these grains combined grains formed the "total grain". The mass of the grains and the MOG were weighed on an electronic scale (JY60001, Shanghai Fangrui Instrument Co., Ltd.). The measurement accuracy of the electronic scale was ± 0.1 g, and its maximum range was 6 kg. The un-threshed grain ratio, un-separated grain ratio, and broken grain ratio were a mass percentage of the un-threshed grain, un-separated grain, and broken grain as they corresponded to the total grain. Three types of rice threshing test were conducted on the transverse multi-cylinders test bench. The first type was rice threshed only by I-TCy device, and the second was rice threshed by I-TCy and II-TCy devices (referred to as "I-TCy + II-TCy") . The third type was rice threshed by I-TCy, II-TCy and III-TCy devices (referred to as "I-TCy + II-TCy + III-TCy") .

Test rice material

The tested rice (*Oryza sativa* L. cv. Wujing15) was grown in Jiangsu Province, China. Its average characteristics are: moisture content of the stalks, 66.43%; grain moisture content, 25.02%; length of panicle, 100 mm; length of primary branch, 75 mm; number of primary branch, 12; number of grains in each primary branch, 12; and number of grains in each panicle, 150. Each branch, from the bottom of the panicle to the top, is marked as 1st, 2nd, ..., 12th part.

Detachment force of rice panicle

Rice panicles consist of grains, pedicels, primary branches, secondary branches, rachides, and stems. The attachment force of the grain and pedicel on the panicle reflect the threshing difficulty level and the shattering habit where the grain was threshed. A computerized, electronic universal testing machine, WDW30005 (Changchun New Test Instrument Co., Ltd., China), measured the specific detachment force of the grain and pedicel by vertical stretching method. Lots of freshly-cut rice panicles were used to measure the specific detachment force of the grain and pedicel. After detachment force was measured, the moisture contents of grain and pedicel were determined by XY-105MW Electronic Moisture Analyzer (Shanghai Hong Ji Equipment Co., Ltd.; the test range of moisture range was 0-100%; the moisture readability was 0.01%; the test mass range was 0-110 g). Results of the same moisture content were classified as one group of test and were used to statistical analysis. At least five samples with the same moisture content were used to analysis the detachment force of the grain and pedicel. The entire parameter estimation procedure and the results of each test were repeated five times, in order to reduce the impact of the random influence on choice of validation set. The panicle attachment was connected to the holding clip of the force gauge in two bending positions: perpendicular to the front of the grain, and perpendicular to the side of the grain. The threshing force value, in tension, was significantly higher than the any other loadings (Kronbergs, 2000).

Optimal parameter comparison

Optimal parameters were designed around the threshing and separating performance of the transverse multi-cylinders test bench. Detection indexes of threshing and separating performance were defined by power consumption and lost grain ratio-when power consumption and lost grain ratio were lowest, threshing and separating performance was best. The lost grain ratio contained un-separated grain ratio, un-threshed grain ratio, and broken grain ratio. The separated grain ratio (valid grain, as opposed to un-separated grain, un-threshed grain, or broken grain,) was the total grain ratio minus the total lost grain ratio.

The performance index of the I-TCy device can be described as follows:

$$\alpha = \frac{1-(r_1+t_1+s_1)}{\frac{P_1}{Q}} \qquad [1]$$

where α is the performance index of the I-TCy device; r_1 is the un-separated grain ratio, t_1 is the un-threshed grain ratio, s_1 is the breakage ratio, and P_1 is the power consumption of the device; Q is the total power of the transverse multi-cylinder test bench. The total power of all three frequency conversion motors Q=100 kW.

The performance index of I-TCy + II-TCy devices can be described as follows:

$$\beta = \frac{1-(r_2+t_2+s_2)}{\frac{P_1+P_2}{Q}} \qquad [2]$$

where β is the performance index of I-TCy+II-TCy devices; r_2 is the un-separated grain ratio, t_2 is the un-threshed grain ratio, and s_2 is the breakage ratio of the devices; P_2 is the power consumption of the II-TCy device.

The performance index of I-TCy + II-TCy + III-TCy devices can be described as follows:

$$\gamma = \frac{1-(r_3+t_3+s_3)}{\frac{P_1+P_2+P_3}{Q}} \qquad [3]$$

where γ is the performance index of I-TCy + II-TCy + I-TCy devices, r_3 is the un-separated grain ratio, t_3 is the un-threshed grain ratio, and s_3 is the breakage ratio of the devices; P_3 is the power consumption of the III-TCy device.

According to Eqs. [1], [2] and [3], when detection indexes α, β, and γ were bigger, the threshing and separating performance was better.

Statistical analysis

The complete parameter estimation procedure and the results of all tests were repeated five times to reduce the impact of random influence on choice of validation set. Means ± standard errors (SE) were calculated using the same variables (n=5). The mean data were analyzed statistically using a factorial design in SPSS software (v. 13.0, SPSS Inc., CA, USA), then mean results were compared by least significant difference (LSD) post-hoc test at the 5% significance level (p<0.05). The grain distribution rules were drawn using MATLAB 7.6 software.

Results and discussion

Detachment force of grain and pedicel

The grain moisture content of the rice panicles, shown in Table 1, was measured from one field. The attachment forces between grains and pedicels for each panicle at different moisture content were also meas-

Table 1. Detachment force of each part of the grains and pedicels with different moisture contents. Data are shown as means ± standard errors (SE) (n=5).

Shattering habit (part)	Moisture content (%)								
	40.98±0.25	**38.81±0.25**	**35.26±0.25**	**29.69±0.25**	**27.97±0.25**	**25.30±0.25**	**23.61±0.25**	**20.57±0.25**	**18.19±0.25**
1st	2.29 ± 0.58	1.93 ±0.24	2.16 ±0.31	1.86 ±0.46	1.92 ±0.43	1.94 ±0.42	2.06 ±0.27	2.01 ±0.22	2.30 ±0.45
2nd	2.18 ± 0.67	1.90 ±0.17	2.05 ±0.42	1.72 ±0.38	1.81 ±0.56	1.89 ±0.36	2.02 ±0.21	1.98 ±0.36	2.28 ±0.39
3rd	2.06 ± 0.60	1.88 ±0.33	1.76 ±0.43	1.69 ±0.46	1.78 ±0.56	1.82 ±0.25	2.00 ±0.34	1.96 ±0.25	2.29 ±0.40
4th	1.95 ± 0.61	1.78 ±0.40	1.81 ±0.61	1.65 ±0.46	1.72 ±0.49	1.85 ±0.37	1.97 ±0.56	1.95 ±0.17	2.21 ±0.38
5th	1.82 ± 0.56	1.72 ±0.55	1.64 ±0.66	1.58 ±0.47	1.65 ±0.52	1.81 ±0.25	1.96 ±0.44	1.93 ±0.25	2.25 ±0.41
6th	1.78 ±0.49	1.63 ±0.53	1.42 ±0.60	1.42 ±0.61	1.62 ±0.34	1.80 ±0.26	1.91 ±0.56	1.91 ±0.26	2.26 ±0.39
7th	1.73 ±0.50	1.62 ±0.50	1.38 ±0.50	1.46 ±0.52	1.59 ±0.16	1.76 ±0.36	1.86 ±0.36	1.88 ±0.36	2.19 ±0.59
8th	1.65 ±0.45	1.59 ±0.64	1.34 ±0.69	1.41 ±0.64	1.52 ±0.23	1.73 ±0.39	1.82 ±0.69	1.89 ±0.39	2.18 ±0.67
9th	1.59 ±0.51	1.54 ±0.39	1.28 ±0.62	1.38 ±0.53	1.49 ±0.27	1.68 ±0.47	1.81 ±0.58	1.85 ±0.47	2.15 ±0.52
10th	1.61 ± 0.26	1.58 ±0.73	1.31 ±0.66	1.37 ±0.42	1.50 ±0.31	1.62 ±0.30	1.79 ±0.27	1.82 ±0.24	2.13 ±0.54
11th	1.54 ± 0.38	1.56 ±0.58	1.24 ±0.48	1.32 ±0.40	1.45 ±0.30	1.57 ±0.42	1.72 ±0.52	1.79 ±0.25	2.09 ±0.40
12th	1.48 ± 0.57	1.56 ±0.44	1.19 ±0.64	1.36 ±0.31	1.42 ±0.28	1.52 ±0.25	1.68 ±0.32	1.81 ±0.34	2.04 ±0.45
Average value	1.81	1.69	1.55	1.52	1.62	1.75	1.88	1.90	2.20

ured. All results are shown in Table 1. According to the experiment results, detachment force decreased from the 1st part to the 12th part. This phenomenon was caused by differing moisture content, which was lower at 12th part than other parts. Diameter was also lower at the 12th part than other parts. These findings are in accordance with earlier reports by Ichikawa *et al*. (1990), Kawamura *et al*. (2002), Inoue *et al*. (2003) and Yang *et al*. (2012). As a general observation, the detachment force was different throughout any rice panicle. All grains threshed from a rice panicle must be threshed up to three times to deduce broken grain.

Fig. 4 shows the relationship between average detachment force and moisture content deduced from the results shown in Table 1. Moisture content was different for each field. The difference between maximum and minimum moisture content was 22.79% (Fig. 4). The detachment force differed alongside moisture content. When the moisture content was 29.69%, the average detachment force was at its minimum. Optimal harvesting time, to this effect, is when moisture content is at 29.69%. This is in agreement with earlier reports by McCauley & Way (2002). But De Toro *et al*. (2012) indicated that in order to complete harvesting operations in most years, it was necessary to operate at a moisture ceiling of 17-24% (w.b.). This difference results could be due to the differing characteristics and variables of rice and different geographical and climatic conditions (Zhou *et al*., 2014).

Fig. 5 shows the distribution proportion of detachment force (according to results shown in Table 1), where detachment force distributions were observed within three different ranges. The first range, 1.0-1.7 N, was 39.81%, and the second, 1.7-2.0 N, was 40.74%. Due to differences in detachment force distribution, these grains should be threshed by different threshing devices. The third detachment force distribution, 2.0-2.3 N, showed the lowest threshing value at 19.44%.

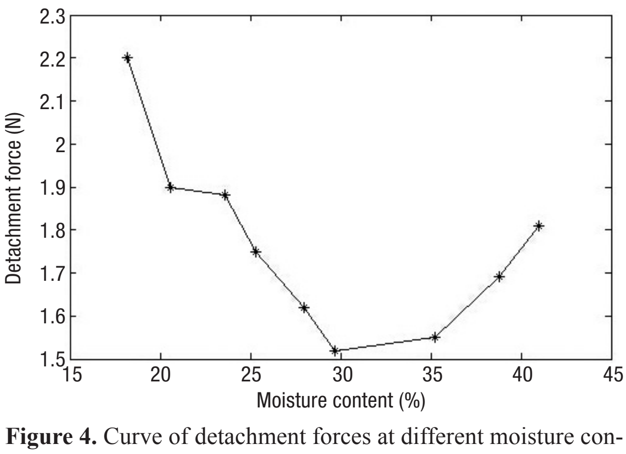

Figure 4. Curve of detachment forces at different moisture contents.

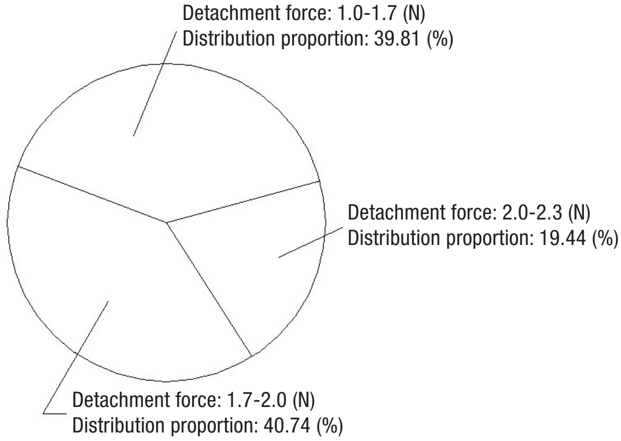

Figure 5. Distribution proportion of average detachment force.

Different device operating parameters must be applied to the rice in accordance with different attachment force values.

Threshing capability of transverse multi-cylinders

Power consumption of threshing and separation

During the rice threshing and separation process, the cylinder rotation speed of the I-TCy, II-TCy, and III-TCy devices were tested and recorded by HAD-CYB-803S torque sensors. The curves of cylinder rotation speed are shown in Fig. 6a. The torque signals of I-TCy, II-TCy, and III-TCy are shown in Fig. 6b.

As shown in Fig. 6a, the rotation speed of the I-TCy device was 550 rpm. I-TCy threshed rice at a rotation speed of only 545 rpm. Rotation speed was fluctuated within the range of ±3 rpm. The rotation speed of the II-TCy device was 600 rpm, the value of which was reduced during the threshing process to 10 rpm, fluctuating in a range of ± 5 rpm. The rotation speed of the III-TCy was 650 rpm. This value reduced during the threshing process to 32 rpm, in a fluctuation range of ± 8 rpm. A similar decrease in rotation speed was observed by Alizadeh & Khodabakhshipour (2010). The rice threshing process itself was the cause of decrease in rotation speed and load of rice threshing.

The torque value curves fluctuated, as well, caused by instability in the threshing process. When the rice stems were in the threshing device, interaction between the grid concave and threshing bars changed. The rice stem density was uniform throughout the entire threshing device. According to the results shown in Fig. 6b, the average torque value of I-TCy was 90 N.m, in a fluctuation range of ±70 N.m. The average torque value of II-TCy was 280 N.m, and fluctuation range

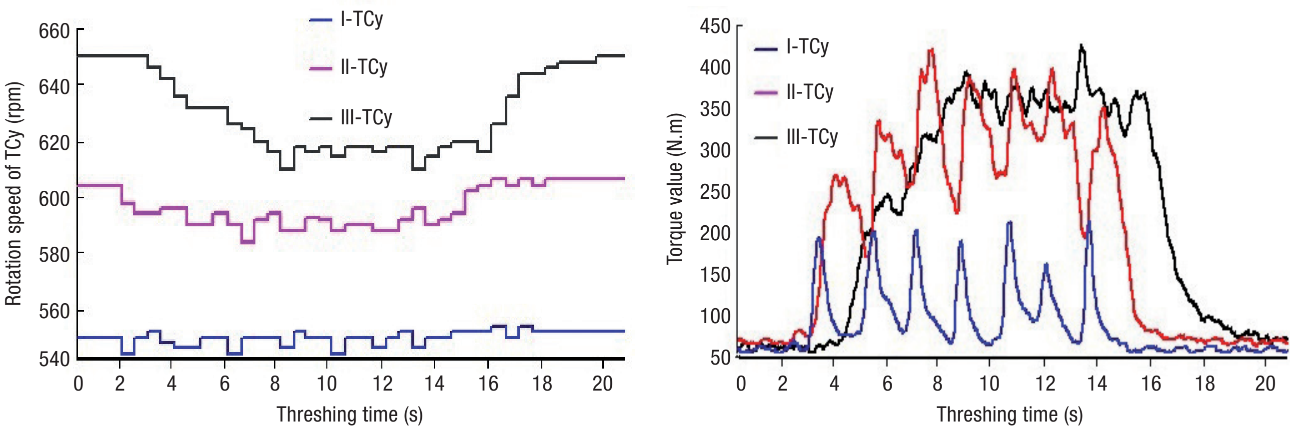

Figure 6. Rotation speed curve (a) and torque signal curves (b) of transverse multi-cylinders in rice threshing and separation process.

was ±60 N.m. The average torque value of the III-TCy was 320 N.m, in a fluctuation range of ±30 N.m. The first, second and third rising curves indicate torque values of I-TCy, II-TCy, and III -TCy, respectively. These rising curves suggest that the rice was first threshed and separated by I-TCy, then re-threshed and re-separated by II-TCy, then threshed and separated once more by III-TCy. Similar results were obtained in an experiment by Jin *et al.* (2015) performed on a paddy thresher.

Operating parameter combinations

In order to test the threshing performance under different cylinder speed combinations, rice threshing performance experiments were conducted at a feeding rate of 6 kg/s and concave clearance of 40 mm for each cylinder. Detailed programs and test results are shown in Table 2. The preliminary threshing capability of I-TCy was 45.32-47.83% and the preliminary separating capability of I-TCy was 12.26-14.08%. This demonstrates the strong threshing and separating ability of the I-TCy device. The average moisture content of grains threshed and separated by I-TCy was 28.34%. Separated grain ratio, breakage, and power consumption all increased with increasing cylinder speed. As shown in Table 2, when the rotation speed of I-TCy was 600 rpm, its threshed grain ratio was 47.83%. The separated grain ratio and power consumption of I-TCy was 14.08% and 3.82 kW, respectively.

At different cylinder speeds, the threshing and separating performance detection indexes α, β, and γ of the transverse multi-cylinder device were calculated using Eqs. [1], [2], and [3], respectively. The calculated results are shown in Table 3. The biggest threshing and separating performance index α was 3.69, which were said that the optimal rotation speed of I-TCy was 600 rpm. According to Table 2, the separated grain ratio and threshed grain ratio of I-TCy was 14.08% and 47.83% (un-threshed grain ratio was 52.17%). The power consumption of I-TCy was 3.82 kW. The biggest threshing and separating performance index β was 2.98 in Table 3. That indicated the optimal rotation speed of II-TCy was 650, with the rotation speed 600 rpm of I-TCy.

Table 2. Threshing and separation results of the transverse multi-cylinder device. The data are shown as means ± standard errors (SE) (n=5).

No.	Rotation speed (rpm)			Separated grain ratio (%)	Un-separated grain ratio (%)	Un-threshed grain ratio (%)	Crushing breakage ratio (%)	Power consumption (kW)
	I-TCy	II-TCy	III-TCy					
1	500			12.26 ±2.14	38.89±4.01	54.68±4.25	0.06±0.01	3.51±0.86
2	550			13.28±2.46	39.55±4.25	53.63±4.86	0.10±0.03	3.69±0.92
3	600			14.08±2.89	42.42±4.33	52.17±4.72	0.16±0.05	3.82±0.84
4	600	600		71.93±3.38	18.65±3.24	9.42±1.26	0.36±0.06	22.44±2.25
5	600	650		71.57±3.26	18.42±3.08	10.01±1.24	0.32±0.05	20.35±2.41
6	600	700		72.04±3.62	19.32±3.65	8.64±1.18	0.41±0.08	25.69±2.26
7	600	650	650	97.42±2.24	0.89±0.12	1.23±0.03	0.46±0.04	12.53±1.24
8	600	650	700	98.02±1.16	1.31±0.06	0.24±0.02	0.43±0.03	12.46±1.06
9	600	650	750	97.62±2.28	1.12±0.09	0.75±0.05	0.51±0.03	12.59±1.10

Table 3. Threshing and separating performance index of the transverse multi-cylinder device. The detection index α was calculated using Eq. [1], β by Eq. [2], and γ by Eq. [3].

No.	Rotation speed (rpm)			α	β	γ
	I-TCy	II-TCy	III-TCy			
1	500			3.49		
2	550			3.60		
3	600			3.69		
4	600	600			2.77	
5	600	650			2.98	
6	600	700			2.44	
7	600	650	650			2.55
8	600	650	700			2.66
9	600	650	750			2.32

According to Table 2, when the rotation speed of I-TCy was 600 rpm and the rotation speed of II-TCy was 650 rpm, the threshed grain ratio of II-TCy was 42.16% (because the un-threshed grain ratio of I-TCy+II-TCy was 10.01%). The separated grain rate of II-TCy was 57.49% (because the total separated grain rate of I-TCy+II-TCy was 71.57%), and its power consumption was 20.35 kW. According to Table 3, the biggest threshing and separating performance index γ was 2.66, which mean the optimal rotation speed combinations of I-TCy, II-TCy, and III-TCy was 600, 650, 700 rpm. According to Table 2, the transverse multi-cylinder test bench un-separated grain ratio was 1.31%, un-threshed grain was 0.24%, and breakage was 0.43%. The total power consumption of the transverse multi-cylinder test bench was 36.63 kW.

Rice threshing and separating tests on the transverse multi-cylinders were performed at cylinder speeds of 600 rpm (I-TCy), 650 rpm (II-TCy), and 700 rpm (III-TCy) and concave clearances of 35 mm (I-TCy), 40 mm (II-TCy), and 45 mm (III-TCy), at a feeding rate of 6 kg/s. The programs and test results are shown in Table 4.

At different concave clearances, the threshing and separating performance detection indexes α, β, and γ of the transverse multi-cylinder device were calculated by Eqs. [1], [2], and [3], respectively. Calculation results are shown in Table 5. By comparing the threshing and separating performance detection indexes (Table 3) of the transverse multi-cylinder device, it becomes clear that the most favorable cylinder rotation combination was 600 rpm (I-TCy), 650 rpm (II-TCy), 700 rpm (III-TCy). Results showed that grains with lower moisture content were threshed and separated first by I-TCy. Grains with higher moisture content were threshed and separated secondly by II-TCy. Grains with power detachment force were threshed and separated by III-TCy. According to Table 4, the separated grain ratios of I-TCy, II-TCy, and III-TCy all decreased with increase of concave clearance. Table 5 shows that when the concave clearance of I-TCy was 40 mm, its highest threshing and separating performance index α was at 3.69. The most effective concave clearance combination of multi-cylinders devices was 40 mm (I-TCy), 35 mm (II-TCy), 40 mm (III-TCy), determined by comparing the

Table 4. Threshing test of transverse multi-cylinders with different concave clearances. Data are shown as means ± standard errors (SE) (n=5).

No.	Concave clearance (mm)			Separated grain and power consumption of:					
				I-TCy device		II-TCy area		III-TCy area	
	I-TCy	II-TCy	III-TCy	Grain (%)	Power (kW)	Grain (%)	Power(kW)	Grain (%)	Power(kW)
1	35			14.45±1.56	4.12±0.64				
2	40			14.08±1.89	3.82±0.84				
3	45			11.09±1.36	3.65±0.72				
4	40	30		14.08±1.89	3.82±0.84	58.64±2.41	22.26±2.82		
5	40	35		14.08±1.89	3.82±0.84	58.01±2.24	21.18±2.96		
6	40	40		14.08±1.89	3.82±0.84	57.09±2.01	20.35±2.41		
7	40	35	35	14.08±1.89	3.82±0.84	58.01±2.24	21.18±2.96	25.66±1.02	13.68±1.42
8	40	35	40	14.08±1.89	3.82±0.84	58.01±2.24	21.18±2.96	25.28±1.03	13.04±1.56
9	40	35	45	14.08±1.89	3.82±0.84	58.01±2.24	21.18±2.96	24.96±1.12	12.46±1.64

Table 5. Threshing and separating performance index of the transverse multi-cylinder device. The detection index α was calculated by Eq. [1], β using Eq. [2], and γ by Eq. [3].

No.	Concave clearance (mm)			α	β	γ
	I-TCy	II-TCy	III-TCy			
1	35			3.51		
2	40			3.69		
3	45			3.04		
4	40	30			2.77	
5	40	35			2.88	
6	40	40			2.84	
7	40	35	35			2.47
8	40	35	40			2.56
9	40	35	45			2.55

threshing and separating performance detection indexes. The observed operating parameter combination for transverse multi-cylinders in this study is similar to a previous study by Sun (2014).

Distribution of separated material

In order to obtain the distribution rule of the transverse multi-cylinder test bench, a combination of operating parameters of cylinder speed (600, 650 and 700 rpm) and concave clearance (40, 35 and 40 mm) were tested at a feeding rate of 6 kg/s. After the rice was threshed and separated, the mixed material (grains and material other than grain) separated from the grid concave were collected in boxes. The separated grain and MOG are shown in Fig. 7. Grains were threshed and separated through transverse multi-cylinder griddle concaves, then dropped into the boxes. The percentages of grains in each material box are shown in Table 8.

Fig. 8 shows three-dimensional distribution of percentages of grain in boxes drawn by Matlab software, based on information found in Table 6. I-TCy separated relatively little grain, instead, most of the grain was threshed and separated by II-TCy. Rice was threshed mainly in the I-TCy device, and grain was separated mainly in the II-TCy device. Grains which were particularly difficult to thresh were mainly threshed and separated in the III-TCy device.

Application of structures and parameters

Structure and operating parameters for transverse multi-cylinders were applied to a rice combine harvester (Zhejiang Liulin Agricultural Machinery Co.,

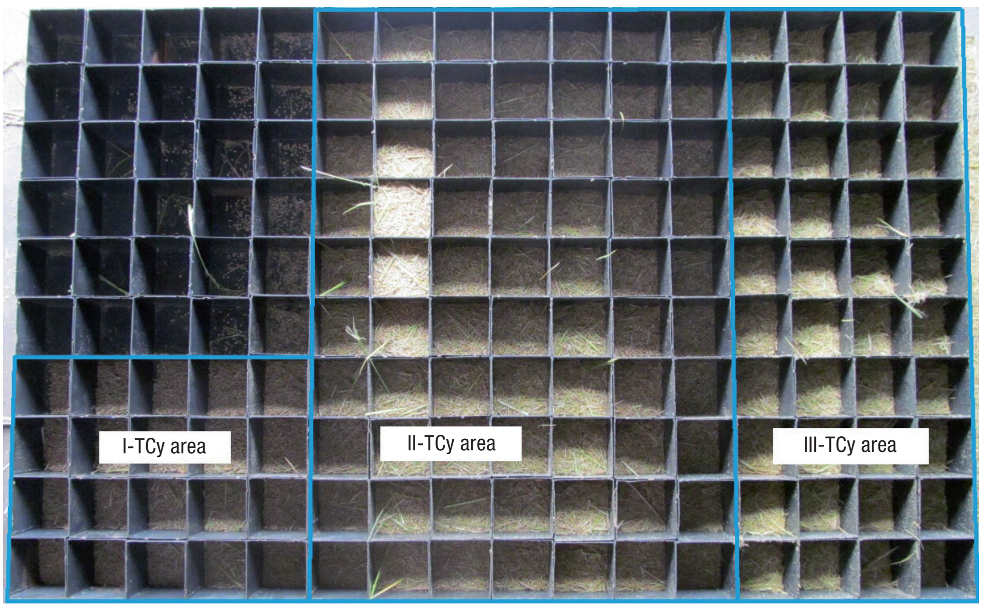

Figure 7. Mixed material and rice straw threshed by transverse multi-cylinders.

Table 6. Grain distribution percentages for each transverse multi-cylinder's box. The entire parameter estimation procedure and the results of each test were repeated five times to reduce the impact of random influence on choice of validation set.

Tangential No.	Axial No.									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	0.572	0.596	0.613	0.721						
2	0.555	0.588	0.687	0.795						
3	0.431	0.472	0.563	0.563						
4	0.398	0.422	0.497	0.530						
5	0.497	0.596	0.679	0.853						
6	0.878	0.944	0.895	1.102	0.787	0.903	0.820	1.019	0.779	0.265
7	0.928	0.977	1.027	1.524	2.270	2.709	2.485	2.559	2.460	1.342
8	0.729	0.803	0.886	1.143	1.483	1.756	1.367	0.977	0.861	0.638
9	0.770	0.994	1.168	1.135	0.845	0.820	0.687	0.547	0.431	0.315
10	0.994	1.392	1.607	1.474	1.044	0.895	0.953	0.572	0.315	0.224
11	0.638	0.795	0.754	0.828	0.754	0.621	0.572	0.422	0.232	0.141
12	0.630	0.572	0.737	0.803	0.795	0.646	0.679	0.588	0.439	0.323
13	0.828	0.944	1.184	1.441	1.383	1.060	0.779	0.671	0.497	0.348
14	0.315	0.422	0.613	0.762	0.779	0.621	0.472	0.406	0.356	0.257
15	0.149	0.157	0.232	0.315	0.331	0.340	0.323	0.340	0.389	0.364
16	0.058	0.099	0.224	0.273	0.340	0.398	0.439	0.456	0.580	0.514

Ltd., China). A structural diagram of the transverse multi-cylinder combine harvester is shown in Fig. 9. When rotation speed and operating parameters were applied to the combine harvester at cylinder speeds of 600 rpm (I-TCy), 650 rpm (II-TCy) and 700 rpm (III-TCy) and concave clearances of 40 mm (I-TCy), 35 mm (II-TCy), 40 mm (III-TCy), at a feeding rate of 6 kg/s, results showed an un-threshed grain ratio of 0.64%, un-separated grain ratio of 0.35%, and broken grain ratio of 0.22%. So, the structure of transverse multi-cylinders, plus specific operating parameter combinations, was proved to be effective for rice harvesting.

In summary, moisture content differed in each field, which results in different attachment force between the grain and pedicel on the panicle. Detachment force decreased from the 1st part to the 12th part of each branch. The first range, 1.0-1.7 N, showed 39.81% moisture content. The second range, 1.7-2.0N, showed 40.74%. The third range, 2.0-2.3 N, showed 19.44%. The most effective harvesting time was identified at moisture content of 29.69%. Different moisture content requires specialized threshing devices and operating parameters. Grains with lower moisture content were threshed and separated first by the I-TCy device, grains with higher moisture content were threshed and separated second by the II-TCy device, and grains with power detachment force were threshed and separated by the III-TCy device. The optimal operating parameter combination was cylinder speeds of 600 rpm (I-

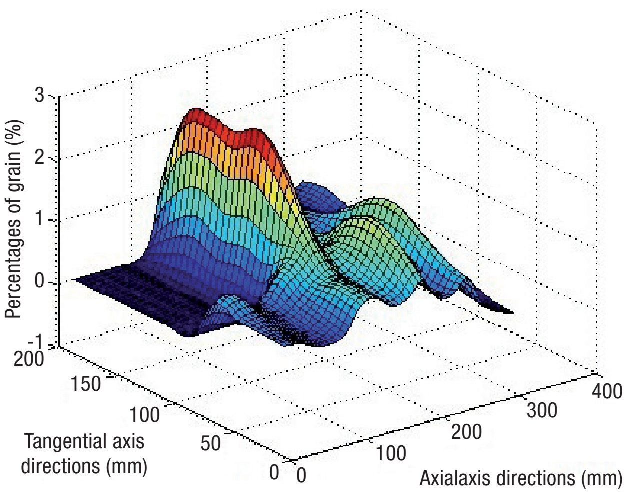

Figure 8. Distribution rules of grain in each transverse multi-cylinder box.

Figure 9. Structural diagram of a transverse multi-cylinder combine harvester.

TCy), 650 rpm (II-TCy), 700 rpm (III-TCy), and concave clearance of 40 mm (I-TCy), 35 mm (II-TCy), 40 mm (III-TCy), which showed an un-threshed grain ratio of 0.64%, un-separated grain ratio of 0.35%, and broken grain ratio of 0.22% at a feeding rate of 6 kg/s. The results of this research can be used to design successful, efficient transverse multi-cylinder rice combine harvesters.

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