Development and performance evaluation of the electric-hydraulic concave clearance control system based on maize feed rate monitoring

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Abstract: Complex field environments, diverse crop conditions, and varying feed rate fluctuations commonly result in a decline in the threshing performance and the clogging of the threshing cylinder for maize harvesters. In order to overcome these problems, an electric-hydraulic concave clearance automatic control system for the threshing unit was developed based on the maize feed rate monitoring, which can automatically realize the best match between the concave clearance and diverse feed rates during harvesting. The threshing performance of the electric-hydraulic control system was evaluated for varying and uneven maize feed rate fluctuations, such as the feed rate increased (6-8-10 kg/s), the feed rate decreased after an increase (6-10-8 kg/s, 8-10-6 kg/s), the feed rate increased after a decrease (8-6-10 kg/s, 10-6-8 kg/s), and the feed rate decreased (10-8-6 kg/s). In particular, the threshing rotor shaft peak torque, the range of threshing rotor shaft torque, the rate of broken grains (BGR), and the rate of unthreshed grains (UGR) with and without the electric-hydraulic control system were tested. Treatments with the electric-hydraulic control system were adjustable concave clearance with the value of 45 mm, 50 mm, and 55 mm. Treatments without the electric-hydraulic control system were constant concave clearance (50 mm). Results demonstrate that the threshing unit with the electric-hydraulic control system outperformed the one without the electric-hydraulic control system, with threshing rotor peak torque, the range of threshing rotor axis torque, the BGR, and the UGR decreasing by 18.38%, 38.27%, 2.08%, and 0.10%, respectively. Moreover, the rate of broken grains was lower than 5.00%, better than the national standard. Thus, the feed rate fluctuations and timely adjustment of the concave clearance were able to avoid blocking the rotor and improve the threshing performance compared to the constant concave clearance.

Keywords: maize harvester, threshing cylinder, feed rate, concave clearance, electro-hydraulic control system
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1 Introduction

Maize is an important crop and can be processed into various food and industrial products, including starch, sweeteners, oil, beverages, glue, industrial alcohol, and fuel ethanol[1]. With about 36.8 million hm^2 of the maize-growing area[2], China is the leader in producing and consuming maize in Asia[3]. Maize harvesting is usually carried out when the moisture content of the grain is within the range of 20%-35%, after a long time of drying, then threshed by a small thresher after moisture content is reduced to about 15%[4]. This method has some disadvantages, such as a prolonged treatment cycle, high labor intensity, and operating costs, which cannot meet the requirements of modern maize production operations. Therefore, the maize harvesting operations in China that have gradually changed to directly harvested grain are significant in shortening harvest cycles, saving production costs, improving operational efficiency, and promoting overall agricultural mechanization[5].

The threshing unit, a crucial component for the direct harvest of maize grains, separates the maize grains from the maize cobs by hitting, colliding, and kneading the ears as they enter the threshing chamber[6]. Therefore, the threshing unit has an essential impact on the rate of broken grains (BGR), the rate of unthreshed grains (UGR), and other performance indicators during the direct harvesting of the grains[7]. In particular, the feed rate and concave clearance are critical parameters for the threshing unit[8,9]. Current combine harvesters are affected by complex field conditions and various crop properties during the harvesting process, making it challenging to maintain a stable feed rate[10,11]. Furthermore, concave clearance is determined before the threshing operation, and the farmers will not make any adjustments during the actual threshing operation. That is, a traditional constant concave clearance cannot be adjusted with fluctuations in the feed rate during direct grain harvesting. That can subsequently cause problems, such as a high rate of broken grains and the clogging of the threshing rotor[12].

Numerous studies explore monitoring the feed rate during harvesting[13,14], with the majority focusing on three aspects. 1) Auger torque measurements[15,16] exhibit the best real-time performance, yet this method requires a customized sensor, and the

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costs are high; 2) Inclined conveyor measurements[17] generally monitor the driving shaft torque or the crop pressure on the inclined conveyor. This method is exact in an ideal environment, yet it does not solve the errors caused by variations in the inclined conveyor angle originating from the working land conditions and the cutting stubble height; 3) Measurements of the driving shaft torque within the threshing represent the feed rate[18], directly reflecting the threshing rotor load. Based on the aforementioned measurement types, researchers generally adopt the method of controlling the forward speed to regulate the feed rate to prevent clogging[19]. However, during the operation, the feed rate of the crop material being inserted into the threshing unit of the combine harvester is highly variable, which is influenced by operator selections (such as ground speed) and feed variations due to changes in the crop density and the presence of weeds[20]. For such cases, the threshing cylinder load can be stabilized by increasing the concave clearance[21]. Ronald et al.[22] designed a rotating concave grain threshing system based on the material characteristics and the torque induced on the concave. The controller compared the current torque with the ideal value and adjusted the concave speed to match the ideal state. Moreover, the Combine Advisor system of the John Deere (USA) S700 series harvester[23], the CLAAS (Germany) LEXION combine equipped with the CEMOS AUTOMATIC system[24], and the New Holland (Italy) CR9000 harvester with the IntelliSense™ system[25] can realize automatic driving and intelligent control of combine harvester during harvest, allowing for an efficient and high-quality harvest.

In China, current combine harvester monitoring and control system technology is still at the monitoring level, with limited control system applications[26]. Furthermore, maize grain direct harvesters control systems are presently unavailable for commercial use in China, and imported high-performance intelligent harvest equipment is expensive, making its large-scale adoption difficult in China. And maize planting plots in China are generally relatively small and scattered, large-scale combined harvesters do not adapt to the actual national conditions of China. Therefore, developing a low-cost maize grain direct harvesters control system and related equipment in China is of great significance[27]. To this end, basic research has been conducted. Zhang et al.[28] designed a feed rate monitoring system based on the header drive shaft torque and established a feed prediction model. Zhang et al.[29] theoretically analyzed the relationship between the tensioning force of the threshing cylinder driving chain and the feed rate of the combine harvester, then subsequently characterized the threshing cylinder load via the tensioning force of the driving chain. The linear relationship between the transmission chain tension and the feed rate was obtained via field experiments, and the corresponding fuzzy controller was designed to automatically adjust the concave clearance of the combine harvester. Liang et al.[30] investigated the relationship between the feed rate, grain flow rate, and the longitudinal-axial drum torque, and designed a framework for the indirect monitoring of the feed rate. Chen et al.[31] designed a reference fuzzy adaptive control system based on the forward speed model of the combine harvester and realized the adaptive control of the combine harvester forward speed via an adaptive control reference approach and multi-variable control rules. Li et al.[32] designed a threshing cylinder load monitoring and concave clearance adjustment device consisting of a concave clearance adjustment system and an oil pressure collection system behind the concave screen. This system can directly measure the feed rate to adjust the concave clearance, thus effectively avoiding blocking the threshing cylinder and improving the threshing efficiency. However, the majority of the combined harvester monitoring and control systems focus on rice, wheat, and other grains, while research on the intelligent control system of maize threshing, particularly for high-moisture maize threshing operations, is lacking. Furthermore, the movement of high-moisture maize inside the threshing unit differs from that of wheat and rice, and these grains' feed rate is lower than the maize, which severely limits the harvesting efficiency[33,34]. Hence, to avoid an undesired threshing performance index and reduce the threshing cylinder axis torque for low power consumption, threshing unit designs should include an adjustable concave clearance based on the feed rate.

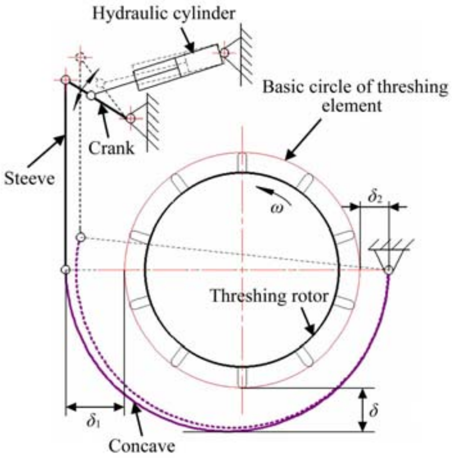
This study developed an electro-hydraulic concave clearance automatic control system for the maize threshing unit to avoid undesired mechanical damage and harvesting loss resulting from feed rate fluctuations during threshing. The operating performance of the electro-hydraulic concave clearance automatic control system was evaluated for diverse concave clearance and feed rates by comparing it with the constant concave clearance system. For the comparison, the operational performance after threshing, particularly the threshing rotor axle peak torque, the range of threshing cylinder axis torque, the BGR, and the UGR, were explored.

2 Materials and methods

2.1 Adjustment mode of the concave clearance

The researchers have implemented research in large quantities to investigate the method to change the concave clearance. There are two primary adjustment methods, one of which is employing changing the position of the concave clearance. The adjustment mechanism for the concave is installed at the bottom or outside of the thresher unit. The concave clearance can be adjusted in real-time during the operation of the combine harvester[35,36]. Another adjustment method is to adjust the concave clearance by changing the diameter of the rotor. Because the rotor keeps rotating during the operation of the combine harvester, the rotor diameter can only be adjusted by stopping the combine harvester first. This type of adjustment is complex and time-consuming. Moreover, the rotor diameter can only be adjusted to several fixed values, and no step-less adjustment is available, making it unsuitable for real-time adjustment during field operation[37].

Based on the above analysis, changing the concave position was adopted to realize the adjustment of the concave clearance in this study. In this study, one end of the concave is hinged with the frame, and the other end is hinged with the concave clearance regulating mechanism in the longitudinal axial flow threshing system. The hydraulic cylinder drives the cranks to rotate, and then the cranks drive the steeve to move up or down to adjust the concave clearance, as shown in Figure 1. The concave clearance refers to the clearance (δ) formed between the threshing element of the rotor and the concave. In order to realize the “grasping” and “accelerating” of the threshing components on the ears, the concave axis and the roller axis adopt eccentric and non-parallel design[38]. The concave clearance at the inlet end of maize ears (δ_1) was larger than the concave clearance at the outlet end of maize ears (δ_2). In order to conveniently describe the concave clearance, the distance (δ) from the bottom end of the basic circle to the concave at the middle position of the rotor in Figure 1 was defined as the concave clearance[39].



Note: δ is the clearance formed between the threshing element of the rotor and the concave; δ_1 is the concave clearance at the inlet end of maize ears; δ_2 is the concave clearance at the outlet end of maize ears; ω is the angular velocity of threshing rotor, rad/s.

Figure 1 Schematic of adjustment mode of the concave clearance

2.2 Electric-hydraulic control system design

The electro-hydraulic control system consists of a controller (HYDAC, HY-TTC 32, Germany), human-machine interface (HYDAC, HY-eVision2 7.0, Germany), a proportional directional valve (Duplomatic, DSE3-C04, Italy) combined with a valve amplifier (Duplomatic, EDC-112/10E0, Italy), a three-phase asynchronous motor (DEDONG, YE2-315S-4, China), a dynamic torque sensor (Brand, DYN-201, China), and a displacement sensor (ACCURACY, KTC150, China) (Figure 2). The dynamic torque sensor can measure from 0 to 2000 N·m with an accuracy of ±0.5% Full-Scale (FS), while the displacement sensor performs measurements within the range of 0 to 150 mm, with the repeated accuracy of 0.01 mm. The hydraulic cylinder designed for the threshing unit has inner and outer diameters of 50 mm and 36 mm, respectively, with an effective stroke of 120 mm and a maximum allowable working pressure reaching 20 MPa.

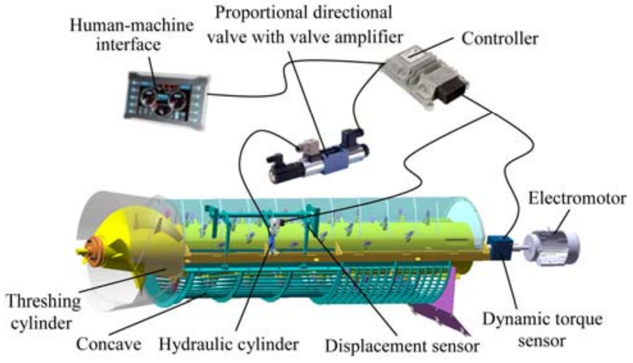


Figure 2 Components of the threshing unit equipped with the electric-hydraulic concave clearance control system

A 24 V power supply is employed for the hardware circuit of the control system. The controller communicates with the human-machine interface, dynamic torque sensor, and displacement sensor through a CAN (Controller Area Network) bus and AnalogIN analog signal interface, respectively (Figure 3). Moreover, the controller sends a digital signal to the valve amplifier via the VOUT (analog voltage output) module and controls the oil pressure output direction of the proportional directional valve. In order to control the proportional valve, the 0-10 V input volt signal of the valve amplifier is proportionately converted into an electric current signal of 0-860 mA. The voltage signals sent to the controller via the dynamic torque and displacement sensors lie within the ranges of 0-5 V and 0-10 V, respectively.

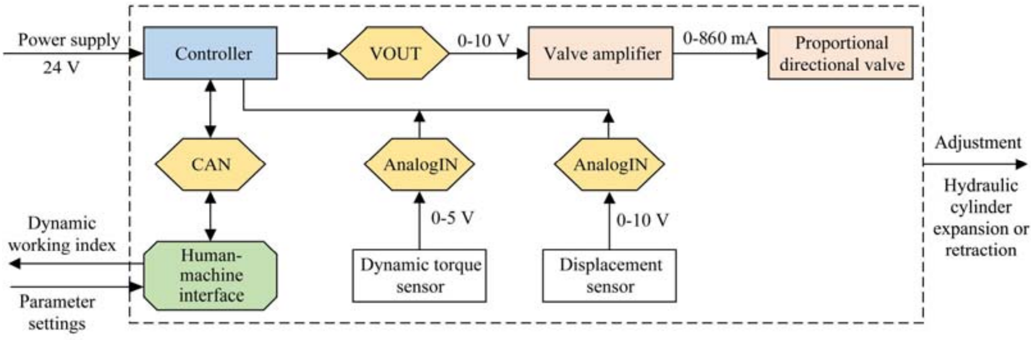


Figure 3 Hardware circuit of the electric-hydraulic control system

Figure 4 presents the algorithm flow chart of the electric-hydraulic control system. T_c is the current torque of the threshing cylinder, and H_c and H_0 are the current concave clearance and the optimal concave clearance, respectively. Once the power is supplied, the controller is initialized and receives the analog voltage output signals of the dynamic torque and the displacement sensors. The current feed rate and current concave clearance are then calculated in real-time. The corresponding relationship between the feed rate and torque of the threshing cylinder varies with the concave clearance conditions. The controller thus determines the feed rate corresponding to the real-time threshing cylinder axis torque and identifies the optimal concave clearance based on the current concave clearance. The error should not exceed ±1 mm. Following this, the difference between the current and optimum concave clearances is employed by the controller to adjust the expansion and contraction of the hydraulic cylinder via the proportional directional valve. Thus, the automatic adjustment of the concave clearance is realized based on the feed rate. The operational parameters (T_c, H_c, and H_0) are returned to the man-machine interface for display via CAN communication.

2.3 Calibration of the displacement sensor

During threshing, the actual expansion and contraction of the hydraulic cylinder are directly reflected according to the analog voltage value of the displacement sensor. The controller calculates the current concave clearance by the expansion and contraction of the hydraulic cylinder and automatically adjusts it to the optimal value. In order to perform this process, the linear relationship between the actual current concave clearance and the analog voltage output of the displacement sensor was obtained. The expansion and contraction of the hydraulic cylinder were adjusted manually via the proportional directional valve. For each concave clearance 5 mm increase, the voltage output of the displacement sensor was recorded using a multifunctional USB data acquisition card (MPS, MPS-010602, China). Each calibration test was repeated three times to eliminate any errors originating from the manual concave clearance measurements. Figure 5 depicts the relationship between the actual concave clearance and corresponding voltage output emitted from the sensor across the three replications. The R^2 of 0.9959 indicates the high accuracy of the function model obtained in the experiment.

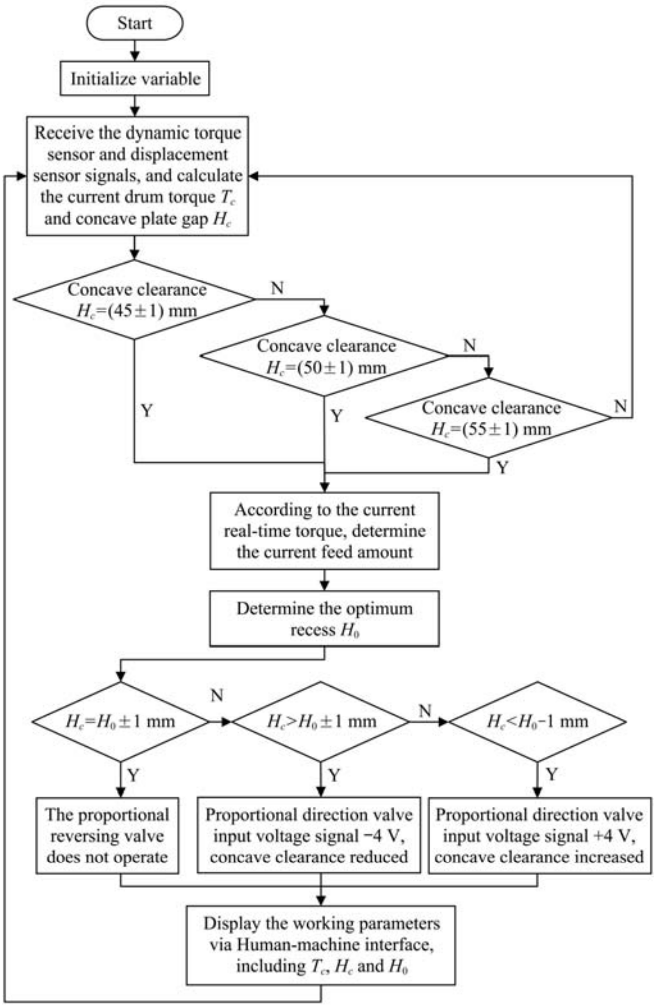


Figure 4 Algorithm flow chart of the electro-hydraulic system

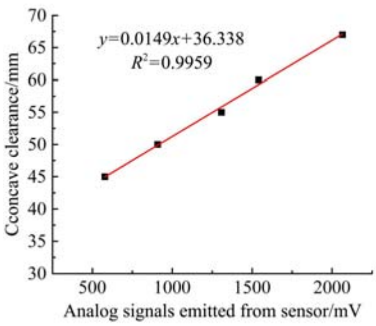


Figure 5 Relationship between measured concave clearance and corresponding sensor signals

2.4 Evaluation experiment

2.4.1 Characteristic of experimental maize

The moisture content of maize significantly impacts the rate of broken grains and the rate of the unthreshed grains of direct grain harvesting[40,41]. The test material was Zhengdan 958, picked manually to avoid mechanical damage, as shown in Figure 6. The size and quality of the ears were measured by Vernier caliper (Deli, DL3944, China, the measurement range is 0-150 mm, accuracy is 0.01 mm, measurement error is no more than ±0.03 mm) and a small electronic scale (Meilen, MTQ500, China, the measurement range is 0-500 g, accuracy is 0.001 g). The average length of the ears is 185 mm, the number of grain rows on the ear is about 15-18, the number of rows is 32-36, its grain size (long × width × thickness) is about 6.3 mm×3.4 mm× 5.6 mm with a half-horse toothed type, and the average weight of ear is 295 g. Ten maize ears were randomly selected from the test area for artificial threshing, then the moisture content of grains was measured by a moisture meter. Repeat the procedure three times and average it. The grain moisture meter (Kett, PM-8188-A, Japan, the measurement range is 6.0%-40.0%, accuracy is 0.1%, measurement error is no more than ±0.5%) was used to determine a maize seed average moisture content of 25.3%.

Figure 6 Zhengdan 958 maize samples used in this study

2.4.2 Experimental design

Bench tests were implemented in Handan City, Hebei Province, to evaluate the performance of this developed system by comparing it with that of the constant concave clearance and simultaneously exploring the impacts that the concave clearance and feed rate played on the operational performance of the threshing unit for maize. The test bench of the threshing unit, which China Agricultural University independently developed, can perform the conveying, feeding, threshing, and separating of maize ears (Figure 7). The concave clearance can be adjusted both automatically and manually by expanding the hydraulic cylinder, while the chain conveyor speed (simulate the forward speed) can be employed to adjust the feed rate. The hydraulic base station provides a maximum oil pressure of 20 MPa for the whole system.

1. Reducer and dynamic torque sensor 2. Hydraulic cylinder and displacement sensor 3. Hydraulic station 4. Controller 5. Human-machine interface 6. Chain conveyor 7. Feeding device 8. Threshing device

Figure 7 Test bench of the threshing device

Prior to the experiment, the maize ears with bracts were evenly and orderly laid on a conveyer unit with a length, test area, and acceleration zone of 15 m, 9 m, and 4 m, respectively (Figure 8). Following the feed rate requirements, maize ears of 30 kg, 40 kg, and 50 kg were randomly placed within the test area at 3 m intervals to simulate feed rate random fluctuations during the actual operation. Furthermore, feeding time in each area was 5 s. That is, the feed rates were 6 kg/s, 8 kg/s, and 10 kg/s, respectively. Feed rate fluctuations were as follows: the feed rate increased (6-8-10 kg/s), the feed rate decreased after an increase (6-10-8, 8-10-6 kg/s), the feed rate increased after a decrease (8-6-10, 10-6-8 kg/s), and the feed rate decreased (10-8-6 kg/s). The rotor speed was constant at 300 r/min (typical speed). Ears were fed to the threshing cylinder through a chain conveyor, and the separated grain fell onto the collecting plate under the rotor as the threshing process residues such as mandrel and bract leaves were discharged out of the device.

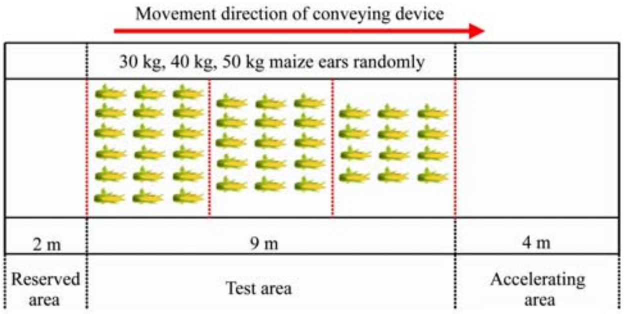


Figure 8 Conveying device with the test area, accelerating area, and reserved area

After the experiment, the test data was determined according to GB/T 21961-2008 "Test methods for maize combine harvester" and GB/T 5982-2017 "Thresher test method"[42,43]. The evaluation indexes were threshing rotor peak torque, the range of threshing cylinder axis torque, the rate of broken grains (BGR), and the rate of unthreshed grains (UGR). The samples of grains were randomly taken from the collecting plate, the broken grains were weighed, and the Z_s (BGR) was calculated by Equation (1). The grains remaining on the maize cobs in the mixture and all the grains in the test area were weighed, respectively. Furthermore, the S_w (UGR) was calculated by Equation (2). This work was repeated three times to calculate the average values.

$$Z_s = \frac{W_s}{W_i} \times 100\% \tag{1}$$

$$S_w = \frac{W_w}{W_z} \times 100\% \tag{2}$$

where, Z_s is the BGR; W_s and W_i are the weight of the broken grains in the sample and the weight of the sampled grains, respectively, g; S_w is the UGR; W_w and W_Z are the weight of the unthreshed grains and all the grains in the test region, respectively, g.

2.4.3 Statistical analysis

ANOVA was conducted using statistical software (IBM SPASS Statistics 21, IBM, USA) to examine the effects of the experimental factor (the concave clearance adjustment mode and feeding order) on the rate of broken grains and the rate of unthreshed grains. Means of measured variables were compared using the Least Significant Difference (LSD). Statistical significance was evaluated at $p<0.05$.

3 Results and discussion

3.1 Calibration experiment of dynamic torque sensor

Under the same concave clearance, different feed rates correspond to different torque ranges of the threshing rotor. The threshing rotor torque range corresponding to the same feed rate is different when the concave clearance is different. So it is necessary to conduct torque calibration tests for feed rates (6 kg/s, 8 kg/s, and 10 kg/s) under the three conditions of 45 mm, 50 mm, and 55 mm concave clearances, respectively, to determine the range of roller torque corresponding to each feed rate under different concave clearances. Due to differences in mechanical vibration and ears biology during threshing, the dynamic torque sensor outputs simulated voltage fluctuations even at a constant feed rate. Equation (3) describes the relationship between the analog voltage output value of the dynamic torque sensor and the measured torque value.

$$T=0.2U_t \tag{3}$$

where, T is the torque of the threshing cylinder axis, N·m; U_t is the voltage output of the dynamic torque sensor, mV.

According to Reference [34], the general maize feed rate during harvest in China is 6-10 kg/s. Furthermore, the range of concave clearance is 45-55mm. In order to facilitate the study, the feed rates were selected as 6 kg/s, 8 kg/s, and 10 kg/s. Furthermore, the concave clearances were 45 mm, 50 mm, and 55 mm, respectively. It was observed that under the concave clearances of 45 mm, 50 mm, and 55 mm, the dynamic torque sensor was able to detect the threshing cylinder axis torque range feed rates of 6 kg/s, 8 kg/s, and 10 kg/s, respectively (Figure 9). The torque range of the threshing cylinder axis corresponding to each feed rate was continuously reduced as the concave clearance increased. For small concave clearances, the impact of the threshing unit on the ear was high, and the reaction torque of the material layer on the threshing cylinder increased, thus amplifying the fluctuation range. In contrast, the reaction torque of the material layer to the threshing cylinder decreased for sizeable concave clearance values, and the fluctuation range was reduced. These observations are in agreement with similar experiments[44]. Therefore, the threshing cylinder axis torque decreases as the concave clearance increases under the constant feed rate, and the control model conforms to the objective law of actual production operations.

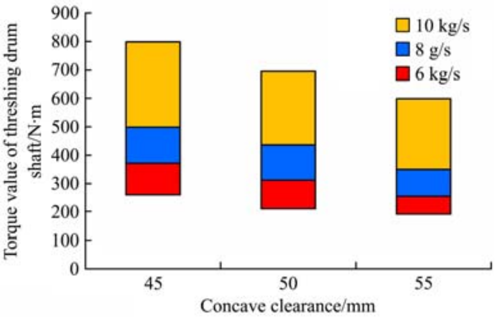


Figure 9 Relationship between the feed rate (6 kg/s, 8 kg/s, and 10 kg/s) under each concave clearance and the corresponding torque range of the threshing cylinder

3.2 Experiments on determining optimal combination parameters of concave clearance control model based on feed rate

The concave clearance is a crucial operational parameter for the threshing unit and significantly influences the rate of broken grains (BGR) and the rate of unthreshed grains (UGR)[45,46]. In order to determine the best match between the concave clearance and diverse feed rates, three typical levels of feed rate and concave clearance are selected respectively in the preliminary test; that is, a single-factor test was performed on the concave clearance (45 mm, 50 mm, 55 mm) under the constant feed rate (6 kg/s, 8 kg/s, 10 kg/s) to determine the best match between the feed rate and the concave clearance[34]. Analysis of variance (ANOVA) was conducted using statistical software (IBM SPASS Statistics 21, IBM, USA) to examine the effects of the experimental factor (concave clearance) on the rates of broken grains and unthreshed grains. Means of measured variables were compared using the Least Significant Difference (LSD). Statistical significance was evaluated at $p<0.05$. This provides a theoretical basis for the concave clearance control system and the optimal working parameters under the constant concave clearance.

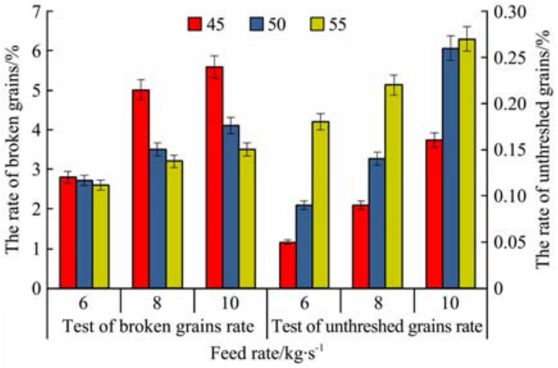


Figure 10 Threshing performance under different treatments

Table 1 reports the ANOVA results used to evaluate the significant influence of varying concave clearance values on the BGR and UGR. Results demonstrate the significant influence of the concave clearance on the rates of broken grains and unthreshed grains, agreeing with previous work[47]. The rate of unthreshed grains directly affects the threshing efficiency, which has an essential impact on production benefits. Therefore, selecting the optimal concave clearance for each feed rate depends on the rate of broken grains, and the rate of unthreshed grains. The 6 kg/s feed rate corresponded to a concave clearance of 55 mm, with a BGR of 0.20% and 0.12% lower than those of the 45 mm and 50 mm two concave clearances, respectively (Figure 10). Furthermore, the reduction rates were 7.69% and 4.62%, respectively. However, the UGR of the 55 mm concave clearance was significantly higher than that of the other two concave clearances. When the concave clearance increased from 45 to 50 mm, the BGR decreased from 2.80% to 2.72%, and the reduction rate was 2.86%. The UGR rose from 0.05% to 0.09%, and the increase rate was 80%. Thus, for a feed rate of 6 kg/s, the optimal concave clearance was 45 mm. At the 8 kg/s feed rate, the concave clearance was 45 mm, and the BGR was significantly higher than those of the other treatments, failing to meet the requirement of less than 5% of the national standard. For the concave clearances of 50 and 55 mm, the BGR decreased from 3.50% to 3.20%, and reduce rate was 8.57%, while the UGR increased from 0.14% to 0.22%, and the increase rate was 57.14%. Hence, the optimal concave plate clearance for the 8 kg/s feed rate was determined as 50 mm. A BGR of 5.59% was observed for the 10 kg/s feed rate and 45 mm concave clearance. This value also failed to meet the requirement of being lower than the national standard of 5.00%. At the 50 mm concave clearance, the UGR decreased by 0.01% compared to the 55 mm value, and reduce rate was 3.70%; yet the BGR increased by 0.6%, and the increase rate was 17.14%. Thus, the optimal concave clearance for the feed rate of 10 kg/s was determined as 55 mm. Based on the above studies, the optimal combination parameters can be obtained: When the feed rates were 6 kg/s, 8 kg/s, and 10 kg/s, the optimal concave clearances were 45 mm, 50 mm, and 55 mm, respectively.

Table 1 ANOVA results representing the contribution rate of the concave clearances on target indices

Test index/%	Quadratic sum	df	Mean square	*F*-value	*p*-value	Significance
BGR	8.778	2	4.389	5.869	0.008	**
UGR	0.068	2	0.034	10.143	0.001	***

Note: ***: $p \leq 0.001$; **: $p \leq 0.010$. BGR is the rate of broken grains; UGR is the rate of unthreshed grains; df is the degree of freedom.

In order to improve the factual accuracy of the verification, the threshing performance of the concave clearance automatic adjustment system was compared with the optimal working performance under a constant concave clearance. Therefore, an optimal concave clearance needs to be determined with the feed rate change for the threshing unit with constant concave clearance. The BGR did not meet the national standard requirements for the concave clearance and feed rates of 45 mm and 10 kg/s. When the concave clearance was 55 mm and the feed rates were 6 kg/s and 8 kg/s, the UGR was higher. When the concave clearance was 50 mm, fluctuations in the BGR and the UGR were more minor for all three feed rates, and the operational performance was relatively stable compared to the other concave clearances. Therefore, the threshing unit with constant concave clearance matched the feed rates of 6 kg/s, 8 kg/s, and 10 kg/s with the optimal concave clearance of 50 mm.

3.3 Contrast verification test of control system

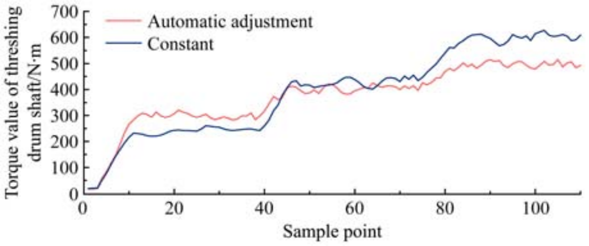
The electric-hydraulic control system was evaluated for the feed rates of 6 kg/s, 8 kg/s, and 10 kg/s via the threshing performance with and without the electric-hydraulic concave clearance control system (Table 2). The control system automatically matched the optimal concave clearances of 45 mm, 50 mm, and 55 mm based on the three feed rate levels (6 kg/s, 8 kg/s, and 10 kg/s), allowing for the automatic adjustment of the concave clearance. The concave clearance was maintained at 50 mm for the constant concave clearance mode based on the three feed rate levels. Furthermore, every treatment was performed three times to reduce errors and find out if interactive effects were significant.

Table 2 Comparison test factor level of threshing performance

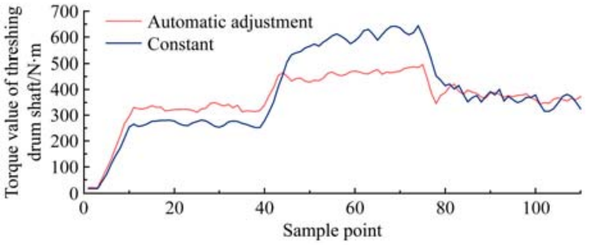
Levels	1	2	3	4
Feed rate/kg·s^{-1}	6	8	10	
Concave clearance/mm	45	50	55	Constant (50 mm)

3.3.1 Detection of threshing cylinder axis torque

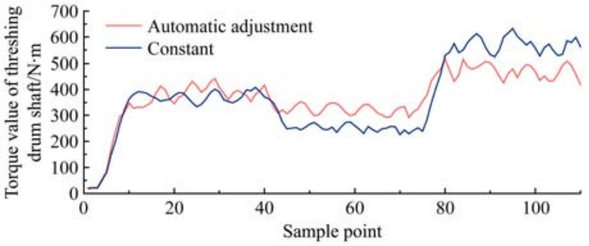
As shown in Figure 11, the torque fluctuation range of the threshing cylinder axle under constant concave clearance was observed to be larger for the varying feed rates (193-653 N·m). Moreover, the fluctuation was more prominent as the feed rate increased. The threshing unit with a control system can adjust the concave clearance according to feed rate. Furthermore, the squeezing effect between the material and the concave was relatively low. The threshing rotor exhibited a minimal friction resistance moment, and the torque fluctuation range of the threshing cylinder was observed within 249-533 N·m during the feeding of the ears. The threshing rotor axle peak torque and torque fluctuation range of the threshing cylinder were reduced by 18.38% and 38.26%, respectively, compared to the constant concave clearance, effectively avoiding excessive instantaneous load and exhibiting strong control stability. In addition, a blockage of the threshing rotor induced by the thick material layer resulted in an excessive friction resistance torque of the threshing cylinder. The threshing rotor was unable to provide such an ample torque, which reduced the speed and prevented the smooth transportation of the material. This resulted in the continuous accumulation of the material in the threshing chamber, thus blocking the threshing rotor[48]. Therefore, huge short-term feed rates increase the load of the threshing rotor. Thus, the load of the threshing rotor can be reduced by increasing the concave clearance promptly to prevent clogging. The test results demonstrate the critical role of the electric-hydraulic concave clearance control system in improving the threshing performance and reducing the operation failure rate.



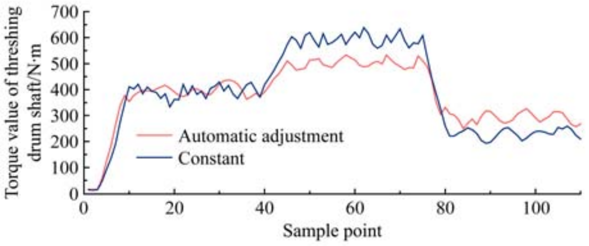
a. 6-8-10 kg/s



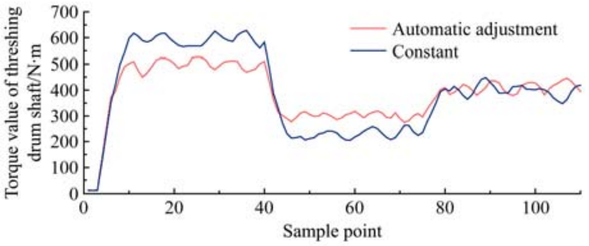
b. 6-10-8 kg/s



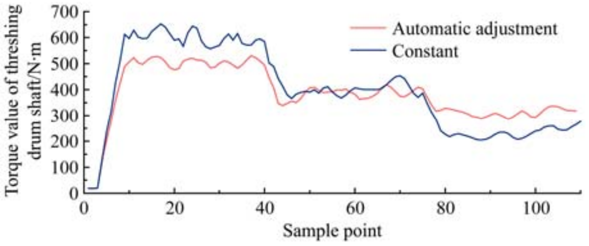
c. 8-6-10 kg/s



d. 8-10-6 kg/s



e. 10-6-8 kg/s



f. 10-8-6 kg/s

Figure 11 Torque variation of the threshing cylinder shaft for varying order of feed rate

3.3.2 Variance analysis of test factors

Table 3 reports the ANOVA results used to determine the influence of the adjustment technique and fluctuating feed rate on threshing performance, whereby the main effects of the two experimental factors (adjustment methods and feeding order) were compared. The adjustment mode and feeding order had significant effects on the BGR and UGR. Furthermore, the interaction between the adjustment mode and feeding order significantly affected the BGR and UGR. This implies that the timely adjustment of the concave clearance with the feed rate fluctuation was able to improve the threshing performance. The field conditions are complicated in actual harvesting operations, and the feed rate fluctuation is not easy to control. The adaptive adjustment of the concave clearance based on the threshing unit feed rate is crucial for performance improvements. The rate of broken grains and the rate of unthreshed grains were used as evaluation indexes. Then the adaptability and working performance of threshing units with and without the control system were analyzed under the condition of feed rate fluctuation.

Table 3 ANOVA results revealing the contribution rate of each factor and target index interactions

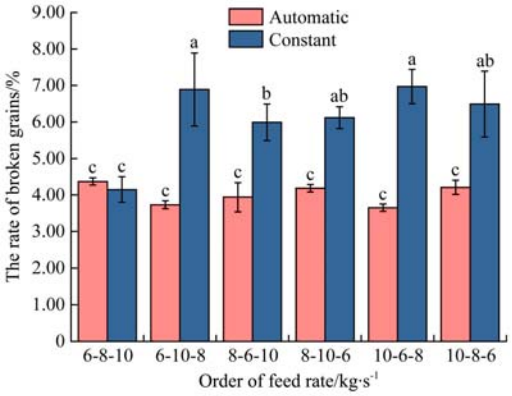
Dependent variable	BGR		UGR	
	p-value	Significance	*p*-value	Significance
X_1	0.000	***	0.000	***
X_2	0.006	**	0.002	**
X_1X_2	0.000	***	0.000	***

Note: ***: $p\leq0.001$; **: $p\leq0.010$; X_1 and X_2 represent the concave clearance adjustment mode (automatically adjusted and constant) and feeding order respectively.

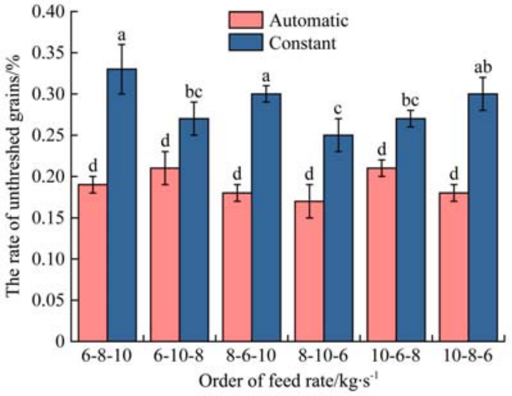
3.3.3 Threshing performance

The threshing unit with the electric-hydraulic control system designed in this research had an excellent working performance through experimental tests. Table 4 reports the statistical analysis results of the BGR and UGR with different treatments. As shown in Figure 12, the threshing unit with and without the electric-hydraulic control system on the BGR and UGR was a significant difference. As shown in Figure 12a, the average BGR of the concave clearance control system was 4.02%, and all of them were less than 5.00% of the national standard requirements. The average BGR of the constant concave clearance was 6.10%, and most of them exceeded 5.00% of the national standards. In particular, there was a 2.08% average reduction in the BGR of the concave clearance control system compared with that of the constant concave clearance. When the feed rate increased (6-8-10 kg/s), there was no significant difference in the BGR between the concave clearance control system and the constant concave clearance. Because the feed rate fluctuated less (fluctuation interval was 2 kg/s), the ear was squeezed and impacted less in the threshing process, and the BGR decreased accordingly. When the feed rate decreased after an increase (6-10-8, 8-10-6 kg/s), and the feed rate increased after a decrease (8-6-10, 10-6-8 kg/s), there was a significant difference in the BGR between the control system and the constant concave clearance. The former has a better threshing performance than the latter. Because the feed rate fluctuated wildly (the fluctuation interval was 4 kg/s), the ears were heavily impacted and rubbed by the threshing element and the concave, increasing the BGR. When the feed rate decreased (10-8-6 kg/s), the fluctuation interval of feed rate was smaller (2 kg/s), but the BGR between the control system and the constant concave was also significantly different. Because when the concave clearance was constant, the initial feed rate was large (10 kg/s), the material density increased, then the ear was struck by the threshing element and concave greatly, and the BGR increased.

The threshing unit with the electric-hydraulic control system could automatically adjust the concave clearance according to the feed rate so that the load on the ear is relatively uniform and the BGR is relatively small[45,49].



a. BGR



b. UGR

Note: BGR is the rate of broken grains; UGR is the rate of unthreshed grains. Columns labeled with different letters are significantly different at the 95% confidence interval.

Figure 12 Variations in BGR and UGR under different treatments

Table 4 Data statistics of the bench test

Feeding order/kg·s^{-1}	Adjustment Mode	Concave clearance/mm	BGR/%	UGR/%
6-8-10	Automatic	45-50-55	4.37	0.19
	Constant	50	4.15	0.33
6-10-8	Automatic	45-55-50	3.73	0.21
	Constant	50	6.89	0.27
8-6-10	Automatic	50-45-55	3.94	0.18
	Constant	50	5.99	0.30
8-10-6	Automatic	50-55-45	4.19	0.17
	Constant	50	6.12	0.25
10-6-8	Automatic	55-45-50	3.65	0.21
	Constant	50	6.97	0.27
10-8-6	Automatic	55-50-45	4.21	0.18
	Constant	50	6.49	0.30

As shown in Figure 12b, there was a significant difference between the UGR of the automatically adjusted and constant concave clearances, with the former (the average UGR was 0.19%) exhibiting a 0.10% average lower UGR compared to the latter (the average UGR was 0.29%); the reduced rate is 34%. Moreover, the any UGR of the concave clearance control system was lower than that of constant concave clearance. When the feed rate increased (6-8-10 kg/s), the feed rate decreased after an increase (6-10-8 kg/s, 8-10-6 kg/s), the feed rate increased after a decrease (8-6-10 kg/s, 10-6-8 kg/s), and the feed rate decreased (10-8-6 kg/s), the constant concave clearance would make the material easy to accumulate and increase the density. That resulted in a rise in the threshing ratio done by the force between the ears. The force between the ears was smaller than the impact and rubbing force of the threshing element and the concave on the ears, with a weak threshing force and an elevated UGR[50]. The automatic control system adjusted the concave clearance according to the feed rate, stabilizing the ear force and reducing the UGR. Thus, the electric-hydraulic concave clearance control system exhibits improved adaptability and threshing performance under the fluctuating feed rate than the threshing system with constant concave clearance.

4 Conclusions

This study developed an electric-hydraulic control system that avoids high BGR and UGR by automatically adjusting the concave clearance with the fluctuations in the feed rate promptly. Experiments were performed to evaluate the operational performance of the control system by comparing the proposed system in this study with that of constant concave clearance. The key conclusions are as follows:

1) The torque of the threshing cylinder axle varies with the feed rate, thus effectively representing the load of the threshing cylinder. For a fluctuating feed rate, the torque range of the threshing cylinder axis under the automatic adjustment of the concave clearance ranged within 249-533 N·m, which was 38.27% lower than that of the constant concave clearance (193-653 N·m). Furthermore, the peak torque of the threshing cylinder was reduced by 18.38% compared to that of constant concave clearance. The threshing unit with the electric-hydraulic concave clearance control system reduced the peak torque and the load fluctuation range of the threshing cylinder to avoid blockages.

2) The threshing unit with the electric-hydraulic concave clearance automatic adjustment system exhibited a better threshing performance due to the lower BGR and UGR. The BGR decreased by 2.08% on average, and the UGR decreased by 0.10% (34% of the reduced rate). Moreover, the concave clearance adjustment mode, feed rate fluctuation, and their interaction significantly affected the BGR and the UGR. Thus, the adaptive adjustment of concave clearance based on diverse feed rates is crucial for threshing performance improvements.

Acknowledgements

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