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Research Article

Optimal Design of Harvesting Speed and Forward Speed of Harvester Based on Adaptive Control System

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The working efficiency of the combine harvester is still very low. It is an important way to realize mechanization to optimize the cutting speed of the harvester and the forward speed of the cutter without increasing economic input. In view of this, the present study briefly summarized the current structure of combine harvester systems. A new type of adaptive control system of combine harvesters was designed from the angle of cutting speed and forward speed of cutter. The sugarcane test base was taken as the test field, and the best matching speed was obtained with the goal of high efficiency of combine harvester and minimum sugarcane damage rate. In the test of cutting speed and forward speed of combine harvester, the optimal cutting speed under different forward speed conditions was recorded. The test results showed that the designed adaptive control system of the combine harvester could control the cutting speed and forward speed of the cutter well. The cutting speed and forward speed adaptive control system can realize the response to the input parameters and meet the design requirements of the harvester. This study can improve the economic benefits of the combine harvester and the quality of the harvested crops.

1. Introduction

Since 2020, the mechanization rate of crop cultivation and harvesting in China has reached 71%, of which the comprehensive mechanization rate of wheat, rice, and corn harvesting has stabilized at 95%, 85%, and 90% [1, 2]. As one of the most commonly used crop cultivation and harvesting machinery, grain combine harvester has the characteristics of complex mechanical structure, complex workflow, and so on [3, 4]. The cutter is the main component of the combine harvester. It starts the whole harvesting process by cutting crops. The cutting frequency of the cutter has an important impact on the quality and power consumption of the cutting process, and its performance is related to the forward speed of the vehicle [5, 6]. However, the working efficiency of the combine harvester is still very low. It is an important way to realize mechanization to optimize the cutting speed of the harvester and the forward speed of the cutter without increasing economic input [7, 8]. Therefore, the research on the cutting speed of harvesting machinery and the forward speed of cutting machine is of great significance to realize the comprehensive mechanization of harvesting.

At present, great achievements have been made in the research on combine harvesters at home and abroad, especially in the cutting rate and the forward speed of the cutter. If the cutting rate of the cutter bar is higher than the optimal cutting rate, it will increase the possibility of repeated cutting of the cutter bar, thus increasing energy consumption and machine vibration. However, if the cutting rate is lower than the optimal cutting rate, it may lead to missed cutting and increase the harvest loss [9–11]. For example, Yin et al. [12] established the optimal cutting frequency model based on cutting mode, and established the relationship model between cutting energy and cutting frequency. Finally, the mechanical cutting frequency and the forward speed of the wheat harvester are determined. Shamilah et al. [13] studied the impact of field speed of combine harvester on paddy fields in Malaysia to obtain appropriate field operation speed. Liu [14] and Lu [15] explored the adaptive control system for the forward speed of the crawler combine and put forward a set of adaptive control system model and theory. Chen et al. [16] also studied the forward speed adaptive control system of combine harvester. Taking the cutting longitudinal flow combine as the research object, a fuzzy control rule integrating multiple variables was designed, and an adaptive control reference model was established. In order to alleviate the situation that the harvester cannot meet the first harvesting efficiency requirements of the harvesting season, the study analyzed a variety of factors affecting harvester scheduling, and established a combine harvester scheduling mathematical mode [17, 18]. When the combine harvester performs cutting operations in the field, various working subsystems need to cooperate with each other in a reasonable speed ratio to adapt to the changes in the complex working conditions of the field [19–21]. If the working subsystems are not properly matched, the crop loss rate and impurity rate will increase, and even the transportation and logistics channels of the crops will be blocked, which will affect the efficiency of the combine harvester and the economic benefits of farmers. The current adaptive control system for cutting speed and forward speed of combine harvesters has a certain research basis. Unfortunately, this system is only a mechanical speed tracking and feedback control system, which cannot achieve self-adaptation, and the response frequency is low [22, 23].

Therefore, on the basis of the current situation of combine system, this paper deeply studies the adaptive control system of cutting speed and forward speed. In this experiment, the sugarcane test base was taken as the test field, and the best matching speed was obtained with the goal of high efficiency of combine harvester and minimum sugarcane damage rate. In the test of cutting speed and forward speed of combine harvester, the optimal cutting speed under different forward speed conditions was recorded. The purpose of this paper is to solve the dilemma that the traditional combine harvester can not achieve the maximum harvest benefit, and to provide theory for relevant scholars to design and select the harvester control system in the future, and this research is of great significance for the realization of comprehensive mechanization of harvesting in agriculture.

2. The System Structure of the Combine Harvester

The combine harvester used by farmers at this stage usually consists of the following four systems, which are remote monitoring system, operation system, conveying system, and walking system. The specific combine harvester system structure is shown in Figure 1.

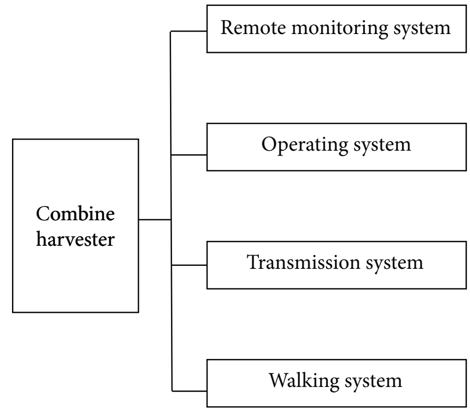

Figure 1: System structure diagram of the combine harvester.

In this paper, according to the relevant parameters of crop planting density, cutting width and cutting resistance in the field, the dual-speed closed-loop control of the cutting device of the combine harvester and the walking system is adopted, which can keep the speed of the walking system changing in a small range. Effectively ensure operation quality and efficiency. If the cutting rate of the cutter bar in the combine is higher than the optimal cutting rate, it will increase the possibility of repeated cutting of the cutter bar, thus increasing energy consumption and machine vibration. However, if the harvest rate is lower than the optimal harvest rate, it may lead to missed cutting and increase the harvest loss. Through sensor data transmission, compare the crop damage rate and mechanical work efficiency, constantly adjust the cutting speed and forward speed of the combine, and finally achieve the best matching speed with the goal of high efficiency and minimum crop damage rate of the combine.

2.1. Remote Control System. The remote control system, as its name implies, is a system capable of remotely controlling the combine harvester. The system collects relevant data by setting up corresponding sensors during the operation of the combine harvester's operating system, transmission system, and walking system, and transmit the data to the remote control system data processing center in real time. The remote control system collects a lot of data, including parameters such as cutter cutting speed, driving speed, and crop quality. When the system data processing center receives the data feedback, it will display the received data on the monitor for postprocessing and timely feedback the postprocessing to the relevant system to prompt the system to adjust in time. At this point, the remote control has realized a complete closed loop, completing the remote intelligent control of the combine harvester.

2.2. Operating System. The operating system application process is the actual crop cutting process of the combine harvester, which is the external presentation of the specific operations of all systems. The composition of the operating system includes all the hardware and software used for cutting activities, such as the granary, cleaning, drum, cutting table, threshing drum device, cleaning device, etc. Among them, the cutting table is used to receive the crops cut by the cutting knife in time, so that the crops can fall into the conveyor belt and enter the granary along with the conveyor belt. The threshing drum device is used to thresh crops such as corn on the conveyor belt and separate the corn cobs (threshed) from the corn kernels. The threshing drum on the threshing drum device has a nail-tooth axial flow structure, which can continuously hit and knead crops to achieve the purpose of complete threshing of crop particles. The cleaning device is a screening tool that can use a sieve to automatically separate crops and sundries.

2.3. Transmission System. The transmission system is equipped with a transmission device, which mainly rotates the conveyor belt through the energy generated by the internal combustion engine of the gearbox. Among them, the continuous variable transmission is the speed control device of the transmission system, which mainly transmits the engine energy by controlling the linkage of the traveling clutch and the output shaft of the engine. After that, the continuously variable transmission uses the intermediate shaft to distribute the energy of the engine. The energy distribution is as follows: part of the energy is distributed to the drum and intermediate shaft, and then transferred from the drum and intermediate shaft to the grain conveying auger and fan; the other part of the energy is distributed to the header, and then transferred from the header of the header to the header drive shaft, mixing wheel, etc.

2.4. Walking System. The walking system is mainly composed of stepper motor, Hall sensor, continuous variable transmission, internal combustion engine, walking wheel, and stepper motor. The Hall sensor is mainly used to monitor the driving speed of the harvester in real time. When the Hall sensor receives the feedback of the speed-related parameters of the harvester, it is responsible for transmitting the information to the remote monitoring system for information processing in time. After the remote monitoring system processes the information, it will feedback the processing results to the walking system to prompt the walking system to adjust the driving speed in time. Information forms a closed loop between the walking system and the remote monitoring system. The internal combustion engine is responsible for providing energy. In the process of walking, the combine harvester will face various resistances, such as the resistance caused by the slope of the ground, the friction of the ground, the resistance during acceleration or deceleration, and the friction resistance of the harvester's own system. Therefore, the combine harvester needs the energy required by the internal combustion engine during the traveling process to overcome the many obstacles that it may face. The continuous variable transmission is responsible for speed adjustment, and its operating mechanism is similar to that of the transmission system. The stepper motor is used in conjunction with the control lever of the continuously variable transmission to adjust the driving speed of the combine harvester.

3. Design of Adaptive Control System for Cutting Speed and Forward Speed

The speed control system of the adaptive control system of the cutting speed and forward speed of the combine harvester mainly includes the regulation and control of the cutting speed and the walking forward speed. In order to ensure that the combine harvester has sufficient response speed, this paper adopts the double closed loop method of load and vehicle speed to jointly control the operation and walking system. The details are shown in Figure 2.

In Figure 2, l is the speed of the combine harvester cutter device, v' is the total feedback and the required optimal speed input, and G_L is the load controller. The adaptive control system of the combine harvester initially takes the optimal driving speed as the output value, which is output by the load controller. At the same time, the adaptive control system of the combine harvester imports the optimal driving speed v' and the actual driving speed v to the vehicle speed controller G_v together. At this point, the control information of the cutting speed of the cutter and the forward speed of the harvester begins to circulate in the system. The control command starts as an output result from the load controller, and is transmitted to the vehicle speed controller G_v, and then from the vehicle speed controller G_v to the walking system G_1. Finally, the walking system G_1 transmits the relevant information of the crop and the driving speed to the operating system G_2. The feed q of the control device for the cutting speed of the cutter is transmitted to the cutter as an input value to obtain the total feedback value of the cutter cutting device.

3.1. Cutting Speed Control. The dynamic model of cutter cutting speed is:

$$\omega' = \frac{1}{J}\left[\frac{PR}{v} - \left(m + n\omega^2\right) - \frac{q\omega R^2}{2(1-f)}\frac{\gamma + v_1}{1+\gamma}\right]. \quad (1)$$

In the formula, w is the angular velocity of the cutter of the cutting device, rad/s; w' is the acceleration of the cutter of the cutting device, m^2/s; P is the cutting force, N; R is the cutting slip, m; r is the cutting angle; n is the crank speed, rad/s; v is the walking speed, m/s; $v1$ is the feed speed, kg/s; J is the inertia parameter of the cutter; f is the damping coefficient of the cutter; m is the harvester mass, kg.

$$q = dpv. \quad (2)$$

In the formula, q is the amount of feed per unit time, kg/s; d is the cutting width, kg/m^2; and v is the walking speed of the combine harvester, m/s.

3.2. Forward Speed Control. The main purpose of controlling the forward speed is to reduce the influence of external factors on the speed, so as to control the actual forward speed to be consistent with the initial set speed. In the process of moving forward, the speed of the combined cutting machine will not only be affected by the slope change of the ground, but also be affected by many factors, such as the change of oil quantity, the hydraulic fluctuation of CVT caused by the loading and unloading process of crops, and the viscosity change of hydraulic oil in the process of cutting crops. In order to ensure that the forward speed of the combined cutting machine is not affected and the forward speed can get the fastest response, this paper selects the PID controller with less calculation to control the forward speed. PID controller has the advantages of strong self-learning ability, easy adjustment, and simple structure, which is suitable for

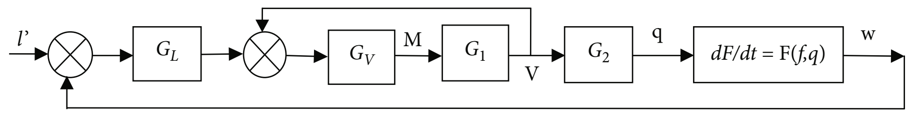

Figure 2: Schematic diagram of adaptive control of cutting speed and forward speed of harvester. Note: l is the speed of the combine harvester cutter device, m/s; l' is the acceleration of the set cutting device, m^2/snn; G_L is the transfer function of the load control device of the combine harvester; G_V is the transfer function of the speed control device of the walking system of the combine harvester, M is the signal output of the speed control device of the combine harvester; G_1 is the speed transfer function of the walking system of the combine harvester, which includes the relevant parameters such as field crop planting density and cutting width; V is the measured speed of the walking system of the combine harvester, m/s; G_2 is the transfer function of the feeding quantity of the combine harvester; q is the feeding quantity kg/s; f is the friction coefficient of the cutting device; $F(f, q)$ is the mathematical expression of the correlation between the feeding quantity and the parameters of the cutting device; w is the measured acceleration of the cutting device, m^2/s.

controlling and adjusting the forward speed. The specific operation path of PID controller is as follows:

First, when adjusting the vehicle speed, input

$$v = [e(t), e(t) - e(t-1), e(t) - 2e(t-1) + e(t-2)]. \quad (3)$$

In the formula, $e(t)$ is the t-time deviation between the set walking speed and the measured walking speed, which is equivalent to the integral part of the incremental PID; $e(t) - e(t-1)$ is the rate of deviation change, which is equivalent to the proportional link of the incremental PID; and $e(t) - 2e(t-1) + e(t-2)$ is the differential link of the incremental PID.

$$e(t) = v'(t) - v(t). \quad (4)$$

In the formula, v' is the set walking speed of combine harvester, m/s; v is the measured walking speed of combine harvester, m/s.

$$c(t) = k \sum_{i=1}^{3} \omega_i(t) v_i(t). \quad (5)$$

In the formula, $c(t)$ is the algebra of the walking speed i moment; k is the proportional coefficient of the walking device controller; $w_i(t)$ input data weight; $vi(t)$ is the i moment walking speed, m/s.

Secondly, use Hebb to adjust the output value appropriately.

$$\omega_i(t+1) = (1-p)\omega_i(t) + \eta e(t) c(t) v_i(t). \quad (6)$$

In the formula, $w_i(t+1)$ is the i input data weight of the Hebb rule at the time of $t+1$; $w_i(t)$ is the i input data weight of the Hebb rule at the time of t; p is the forgetting factor of Hebb rule,η is the learning efficiency factor of Hebb rule, $e(t)$ is the teacher signal of Hebb rule, $c(t)$ is the neuron input signal of Hebb rule, $v'(t)$ is the control signal of Hebb rule.

The p is the forgetting factor. η represents learning efficiency.

Finally, the PID controller can calculate the result as the evaluation standard, namely

$$J' = \frac{1}{2}\left[v'^{(t)} - v(t+1)\right]^2. \quad (7)$$

In the formula, J' is the sum of squares of the deviation of walking speed.

When testing the automatic control of the operation speed control system, first increase the throttle to the maximum to make the working parts of the combine work at the maximum speed. After setting the data of each monitoring point as the rated parameters, make the combine switch to the automatic control state. If the operating handle is observed to swing forward, the combine will accelerate the harvest and advance. When it is accelerated to the maximum forward speed, the photoelectric sensor at the lower end works to keep the combine in a maintained state. By reducing the throttle, the rotating speed of each working part is reduced, and the working state of the combine in which the feeding amount is suddenly increased is simulated. It is observed that the operating handle swings backward. At this time, the combine slows down. When the speed is reduced to zero, the photoelectric sensor at the upper end works to stop the stepping motor, and the combine is in a maintained state. Adjust the throttle repeatedly to simulate the automatic operation of the combine harvester in the field. The control system adjusts the direction and rotation angle of the stepping motor to make the harvester have a suitable forward speed. After many times of debugging, the operation speed control system of the combine harvester can meet the needs of the forward speed adjustment for the change of the field feeding amount, and the system can carry out the fault alarm work. The whole control system can meet the requirements of the field test.

4. Field Test Verification and Result Analysis

4.1. Test Parameters. According to the above description, a system model is built. The test parameters are set according to the actual parameters of the hydraulic components on the crop combine harvester (Table 1). Set the communication interval to 0.001 s and the simulation time to 80 s.

4.2. Test Equipment and Materials. Set up the combined harvesting advance according to the above parameters, and prepare the equipment and materials. The specific preparation content is shown in Table 2. A sugarcane planting experimental base was selected as the experimental site.

4.3. Combination Matching Test and Result Analysis of Cutter Speed and Forward Speed. The forward speed of the

Table 1: Test parameters of adaptive control system.

Subsystem	Parameter	Value
Cutter head system	Relief valve opening pressure MPa	17
	Displacement of cutter head motor mL/r	84.6
	Displacement of cutter head pump mL/r	60
	Rotation speed of cutter head pump r/min	2400
Walking system	Flushing valve overflow valve opening pressure MPa	1.7
	Opening pressure of charge pump relief valve MPa	3.0
	Opening pressure of main relief valve MPa	25
	Displacement of travel charge pump mL/r	15
	Displacement of walking motor mL/r	1690
	Displacement of walking main pump mL/r	70
	Engine speed r/min	2400

Table 2: Test equipment and materials.

Name of test equipment or material	Model	Quantity
Sugarcane combine harvester	Medium cut	1
Proportional valve	PVG-32-1-PVEM	1
Proximity speed sensor	—	2
Pressure sensor	GSEE-TECH	3
Expansion module	EM235	1
Expansion module	S7-1214CPLC	1
Touch screen	SAMKOONAK-070MG	1
Vehicle DC power supply	24 V	1
Laptop	—	1
Tape measure	10 m	1

Table 3: Optimal matching combination of forward speed and cutter speed.

Forward speed Km/h	Cutting speed r/min	Breakage rate %
1	570	7.01
2	620	6.70
3	660	6.20

Table 4: Field test results.

Test group	Total number of sugarcane plants	Number of broken heads strains	Broken head rate%
a	40	6	6.67
b	44	6	7.33
c	37	5	7.40
d	41	7	5.86
e	39	7	5.57
f	46	7	6.57

combine harvester in the working process changes according to changes in terrain, weather, crop growth, and variety, and the tracking and matching of the cutting speed to the forward speed significantly affects the cutting quality of the harvested crop. Therefore, the final goal of this experiment is to find a reasonable matching relationship between the forward speed and the cutter speed, and the field experiment will be carried out. Only by finding a reasonable matching relationship between the forward speed and the cutting speed of the cutter can the rate of crop breakage be effectively reduced, the harvesting efficiency of the harvester can be ensured, and the cutting quality of the crop can be improved.

In this experiment, the sugarcane test base was used as the test site, and the sugarcane breakage rate was calculated as an indicator. During the single factor test of the forward speed of the combine harvester, the best cutter speed under different forward speed conditions was recorded. At the same time, when the forward speed of sugarcane combine is 1 km/h, 2 km/h, and 3 km/h, the cutter speed is set to 540 R/min, 570 R/min, 620 R/min, and 660 R/min, respectively, and the breakage rate of sugarcane with different cutter speeds under the unified forward speed is counted. When the breakage rate value has the lowest value, it is the optimal matching speed. In order to reduce the experimental error, the experiment was repeated twice.

The test results show that when the forward speed is 1 km/h and 2 km/h, the breakage rate of the crops to be harvested shows a wave dynamic trend with the increase of the cutter speed, and the specific performance is that it first decreases and then increases. It may be that when the cutting machine speed is low, the sugarcane root is easy to cut many times, resulting in an increase in the breakage rate. It may also be that when the speed of the cutter increases, the forward speed does not match it, resulting in repeated cutting of sugarcane. When the forward speed is 3 km/h, the damage rate of crops to be harvested will decrease with the increase of cutter speed. The best matching combination of forward speed and cutting speed is shown in Table 3.

Under the conditions of the three sets of optimal matching combinations, the average broken rate of sugarcane by the combine harvester is 6.63%, which meets the requirements of the adaptive control system.

4.4. Test and Result Analysis of Adaptive Control System for Cutting Speed and Forward Speed. Based on the above-mentioned optimal matching combination of forward speed and cutter speed, the adaptive control system of cutting speed and forward speed is tested.

The test results show that the cutter speed of the adaptive control system designed in this paper can follow the change of the forward speed according to the best matching value. During normal harvesting, the cutting speed of the combine harvester used in the test will be 10-20 r/min lower than the precontrolled speed. It is consistent with the conclusion of Yin et al. [12] that the field cutting frequency is usually lower than the standard setting. This may be because the combine harvester is working with load during the test. The joint cutting opportunity of load work causes the system pressure to increase. When the combine harvester is under high pressure, the pressure difference between the two ends of the proportional valve will increase, which will lead to the increase of the flow and diversion through both ends of the proportional valve. Therefore, the cutter speed is lower than that under no load. According to calculations, the maximum error of the cutter speed used in this test is 3.51%. This shows that the adaptive control system designed in this paper can meet the requirements of coordinated linkage control of the cutting speed and forward speed of the combine harvester. The conclusion is consistent with the adaptive control reference model proposed by Lu [15] to optimize the forward speed of the harvester, which improves the work efficiency. When the forward speed is changed, 7-12 MPa is the most suitable cutter pressure, and 5-8 MPa is the most suitable cutting pressure. When the cutter pressure and the cutting pressure are set to the above values, the combined cutting machine will be in the optimal working pressure range. According to the results of field test in Table 4, the broken rate of sugarcane is between 5.50% and 7.50%, and the average breaking rate is 6.54%, which is basically consistent with the average breaking rate of 6.63% under the optimal combination of cutter speed and forward speed. This shows that the cutting speed and forward speed adaptive control system can realize the response to the input parameters and meet the design requirements of the harvester.

5. Conclusion

In this experiment, the sugarcane test base was taken as the test field, and the best matching speed was obtained with the goal of high efficiency of combine harvester and minimum sugarcane damage rate.

(1) The cutting speed and forward speed adaptive control system of combine cutter designed in this paper adopts the load adaptive control and speed ratio point control algorithm to improve the cutting speed and forward speed control system of traditional combine cutting equipment

(2) By maintaining the constant output speed of the engine and inputting the corresponding parameters in the manual control operation equipment, the system can match the stepless speed regulation device to ensure the optimal matching between the cutting speed of the cutter and the forward speed

(3) The cutting speed and forward speed adaptive control system can realize the response to the input parameters and meet the design requirements of the harvester

This study can improve the economic benefits of the combine harvester and the quality of the harvested crops.

Data Availability

All data, models, and code generated or used during the study appear in the submitted article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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