STUDY ON THE LOSS CONTROL SYSTEM OF WHEAT COMBINE HARVESTER
/
小麦联合收获机损失控制系统研究

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***Keywords:** Feeding quantity; drum speed; harvest loss; walking speed; automatic control system*

ABSTRACT

In order to reduce the harvest loss and optimize and improve the comprehensive performance of the combine harvester, the relationship between the feeding quantity, drum torque, drum speed, harvest loss, and other factors of the wheat combine harvester is studied, and the functional relationship between the loss, feeding quantity and speed is determined. According to the test data, the relationship model between the feeding quantity of the harvester and the drum torque is a quadratic function. For the land with uniform growth, the size of feeding quantity is mainly affected by the forward speed of the harvester. In this way, this paper indirectly achieves the purpose of controlling the feeding quantity by controlling the speed of the harvesting machinery. The control system designed in this paper uses the compensated fuzzy PID to control the walking speed of the vehicle through real-time detection of the drum torque, drum speed and loss of the harvester, so as to comprehensively control the working speed of the harvester and effectively control the harvest loss. The test results show that the control system can effectively reduce the harvest loss and improve the harvest efficiency compared with the manual harvest of the wheat.

摘要

为减少小麦联合收获机收获过程中的收获损失，优化提升联合收获机工作综合性能，本文对小麦联合收获机的喂入量、滚筒转矩、滚筒转速、收获损失等因素间的相互关系进行研究，并确定了损失与喂入量、车速等之间的函数关系。根据试验数据分析得到收获机的喂入量与滚筒转矩呈一次函数关系模型；喂入量与收获损失呈二次函数关系模型。由分析数据模型可知，通过改变收获机械喂入量，可实现低损失控制；喂入量的大小对于长势均匀的地块而言，其主要受收获机械前进速度影响，因此本文通过控制收获机械的车速间接达到控制喂入量的目的。本文所设计的控制系统，通过实时检测收获机的滚筒转矩和滚筒转速及损失等数据，使用补偿式模糊 PID 控制车辆的行走速度，实现综合控制收获机械的工作速度进而达到有效控制收获损失。试验结果表明，该控制系统与人工操作收割小麦相比，有效降低了收获损失，提高了收获效率。

INTRODUCTION

During the working process of the combine harvester, there will be different harvest losses due to the influence of harvesting time and harvesting method, among which the harvest losses mainly include pre-harvest losses, header losses and harvest process losses *(Cujbescu et al., 2021)*. Pre-harvest loss refers to the loss of grain falling caused by natural factors such as wind, rain and maturity before harvest. This loss is natural loss and is affected by uncontrollable factors of natural attributes. The header loss is mainly composed of missed cutting, grain falling and ear loss, which is affected by grain maturity, operation route, and the reel position and rotation speed *(Vlăduț et al., 2022)*. In addition to the natural properties of grains, the harvest loss is also mainly affected by the harvest parameters such as the feeding quantity, and the ratio of grass to grain. This loss directly affects the efficiency and operation quality of the harvester *(Sessiz and Ulger, 2003; Bhardwaj et al., 2021; Ivan et al., 2015)*. The losses in harvesting process mainly include threshing loss, separation loss and cleaning loss, which are caused by threshing, separation and cleaning devices of the combine harvester respectively.

To reduce the harvest loss of the combine harvester, many scholars have conducted a lot of researches on the factors related to the harvest loss and structural control. According to detecting the load of the inclined conveying feeding roller, *Coers and Burke, (2004),* indirectly measured the feed in quantity of the harvester and controlled the speed of the harvester according to the feeding quantity, so as to improve the efficiency.

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Staiert and Krukow (1982) designed a control structure for the feeding roller and tried to achieve the purpose of uniform grain feeding by changing the speed of the feeding roller. Through analyzing the relevant structure of the harvester and the relationship between the feeding quantity and the threshing drum, *Budzich(1964)* designed a measurement system to detect the feeding quantity of the measurement system by detecting the torque of the threshing drum, so as to realize the control of the working speed. Based on the experiments of 3 models, *Chen et al. (2011)* studied the relationship between the feeding quantity and harvest loss. A relationship model based on power function, exponential function and quadratic function was established, in which the quadratic function model had high accuracy *(Chen et al., 2020)*. According to the detection of the feeding quantity through the pressure sensor installed on the tilt conveyor, many tests were carried out. Finally, a feeding quantity model based on the pressure of grains on the bottom plate of the tilt conveyor was established for the feedback of the working speed and the control of the feeding quantity *(Chen et al., 2020)*.

Most scholars obtain the feeding information by detecting different parts of the harvester to control the speed and improve the efficiency of the vehicle, but ignore the harvest loss *(Wang et al., 2018; Mu et al., 2018; Marjanović et al., 2018; Madhusudana et al., 2018; Chai et al., 2020; Galluzzi et al., 2018)*. It is necessary to reduce harvest loss while improving the efficiency. Based on the feeding quantity, the harvest loss of the combine harvester is studied and a compensation fuzzy PID automatic walking control system based on the drum torque and drum speed is proposed.

MATERIALS AND METHODS

Sample acquisition

The RevoGushen GE80-H wheeled grain combine harvester (rated feeding quantity 8.0 kg/s, cutting range 2.65 m, productivity 0.6-1.3 hm2/h) was used as the test prototype, as shown in Fig.1. A field harvesting experiment of wheat was carried out in Jimo District, Qingdao, Shandong Province to obtain a large amount of experimental data. The test field was divided into small plots with a width of 2.75m and a length of 26m, and 24 small plots in all. For each small plot, the four-point sampling method was used to collect four corners of the plot as test samples. The side length of the collected sample was 0.5m, and the area was 0.25m^2. The average value of the four groups of data was calculated to obtain the wheat planting density, the ratio of grain to grass and other information of the test plot. After removing 0.5m from both ends of the small plot, the remaining plot will be used as the plot for harvest test. In the test, the plots were harvested at different speeds. GPS was used to record the real-time track information and speed information to obtain the working condition of the drum torque and drum speed of the combine harvester under different feeding quantities.

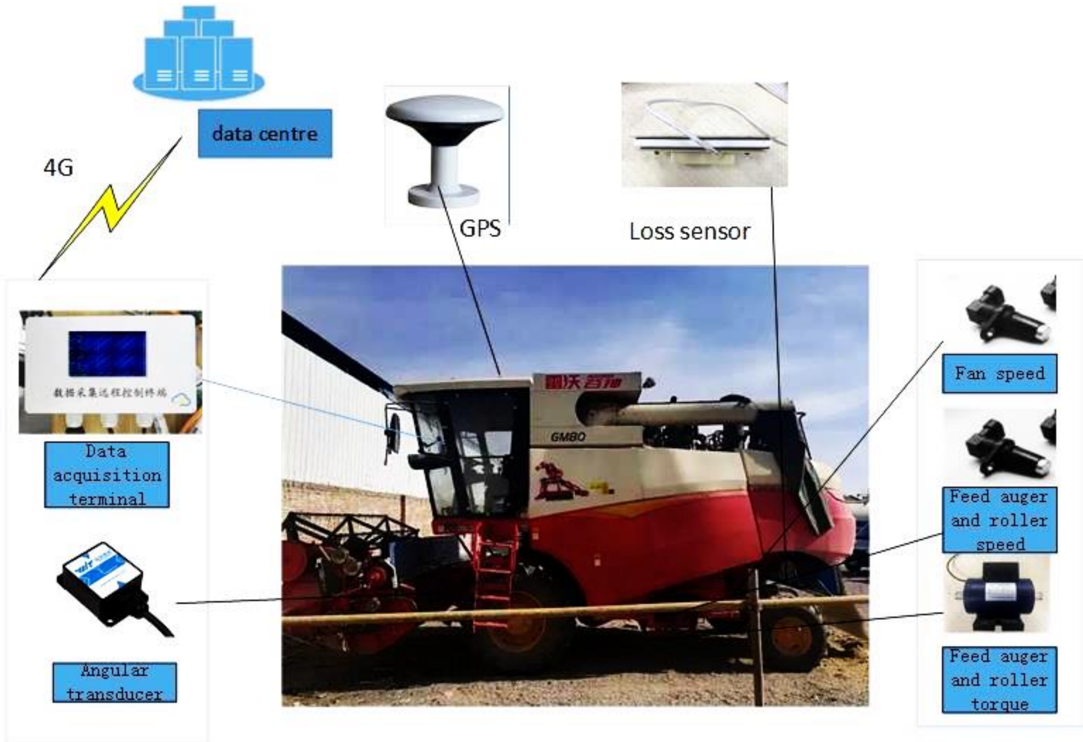


Fig. 1-Test prototype

Test principle

In addition to being related to the structure of the vehicle, the harvest loss generated in the harvesting process of the combine harvester will also be greatly related to the feeding quantity *(Pokojski et al., 2019)*. Among them, the influencing factors of the feeding quantity q_i per unit time of the header mainly includes the cutting width B, the working speed v, the grain density W and the grain-grass ratio γ. The mathematical relationship model of the feeding quantity per unit time of the header is as follows:

$$q_i = \frac{B\,v\,W}{10000}\left(1+\frac{1}{\gamma}\right) \tag{1}$$

For a specific combine harvester, the cutting width B is a constant. During the harvesting, the header height of the combine harvester is almost constant, and the grain-straw ratio γ isalmost unchanged. The grain density W fluctuates greatly in the field, which is not only related to the number of plants per unit area and growth potential, but also related to the moisture content of straw *(Li et al., 2019)*. The operation speed v is the working speed of the vehicle, which will vary due to the influence of the ground and the driver. When the working speed increases, the feeding quantity will also increase *(Reddy and Rangadu, 2018*). To this end, it is necessary to control the operating speed v of the harvester to control the feeding quantity of the harvester.

The crop is transported from the header to the threshing drum through the conveyor. The feeding quantity of the conveyor is the same as the harvest of the header at unit time. The feeding quantity flowing into the threshing drum can be obtained as follows:

$$q_r = q_i * \delta(t - t_s) \tag{2}$$

where:

q_r is the feeding quantity of the threshing drum; *t* is the feeding time, and t_s is the transfer delay time from the header to the threshing drum.

In addition to providing no-load load moment and inertia moment for itself, the threshing drum also needs to provide kinetic energy moment for the input grain. When the drum is unloaded, it is necessary to overcome the mechanical friction resistance during rotation and the blowing resistance of the drum. According to the drum theory, the no-load torque of the threshing drum can be obtained as follows:

$$\mathrm{M_{rk}} = \mathrm{A} + \mathrm{B}\omega^2 \tag{3}$$

where”

ω is the angular velocity of the threshing drum; A is the torque generated by mechanical friction, and B is the blower torque coefficient of the drum. The moment of inertia of the threshing drum is as follows:

$$\mathrm{M_{rg}} = \mathrm{J}\frac{\mathrm{d}\omega}{\mathrm{dt}} \tag{4}$$

where:

J is the moment of inertia of the threshing drum, and ω is the angular velocity of the threshing drum.

During the harvesting, the grain fed into the drum is set to be evenly feeding and the threshing space is constantly flowing, then the overall power consumption of the threshing drum is as follows:

$$\mathrm{P_c} = \zeta\frac{\mathrm{q_r}}{1-\mathrm{f}}\mathrm{R}^2\omega^2 \tag{5}$$

Where:

ζ is the correction coefficient;f is the comprehensive kneading friction coefficient when the grain passes through the threshing drum gap, and R is the drum radius.

The torque $\mathrm{M_{rc}}$of the drum threshing at this time is as follows:

$$\mathrm{M_{rc}} = \zeta\frac{\mathrm{q_r}}{1-\mathrm{f}}\mathrm{R}^2\omega \tag{6}$$

The total torque of the threshing drum is as follows:

$$\mathrm{M} = (\mathrm{A} + \mathrm{B}\omega^2) + \mathrm{J}\frac{\mathrm{d}\omega}{\mathrm{dt}} + \zeta\frac{\mathrm{q_r}}{1-\mathrm{f}}\mathrm{R}^2\omega^2 \tag{7}$$

From the above, when the threshing drum rotates at a constant speed (ω is a fixed value), the torque and the feeding quantity of the threshing drum are a function relationship, which can better reflect the size of the feeding quantity.

In the actual harvesting process, when the feeding quantity of the threshing drum of the combine harvester is too small, the kneading between the threshing drum and the grain is not sufficient, resulting in unclean threshing and increasing losses. If the feeding quantity of the threshing drum is too high, the separation and cleaning system will not be able to fully separate and clean the threshed materials, resulting in an increase in the loss rate of the harvest. To reduce the loss rate of the harvester, it is necessary to effectively control the feed rate of the harvester.

Scheme design of the speed control system

The aim of the control system of the combine harvester is to reduce the harvest loss. A complementary PID control system scheme is thus designed to control the walking speed of the harvester, and then indirectly control the feeding quantity to reduce the harvest loss. The sensors used in the system include torque sensor, speed sensor and GPS. The torque sensor installing on the rotating shaft of the threshing drum is used to detect the torque of the threshing drum, so as to detect and obtain the feeding information of the vehicle. The speed sensor is installed on the axis of the threshing drum to detect the speed of the threshing drum. GPS is used to detect the driving track and speed of the vehicle.

PID control is a widely used control method for control system, and its control system expression is as follows:

$$\mathrm{u}(t) = \mathrm{K_p} e(t) + \mathrm{K_i} \int_0^{\mathrm{k}} e(k) + \mathrm{K_d} \frac{\mathrm{de(t)}}{\mathrm{dt}} \tag{8}$$

In practical applications, signal acquisition is generally discrete, and the discrete PID is used commonly. Its discrete PID control expression is as follows:

$$\mathrm{u}(k) = \mathrm{K_p} e(k) + \mathrm{K_i} \sum e(k) + \mathrm{K_d}(e(k) - e(k-1) \tag{9}$$

In order to reduce the impact of cumulative error, the incremental PID can be used for control, and its formula is as follows:

$$\Delta\mathrm{u}(k) = \mathrm{u}(k) - \mathrm{u}(k-1) = \mathrm{K_p}(e(k) - e(k-1)) + \mathrm{K_i} e(k) + \mathrm{K_d}(e(k) - 2e(k-1) + e(k-2) \tag{10}$$

In PID control, $\mathrm{K_p}$is the proportional control coefficient that is used to reflect the deviation signal of the control system proportionally and make the system immediately produce control effect to reduce the deviation.The output u(t)of the proportional controller is proportional to the input deviation e(t), which can quickly reflect the deviation to reduce the deviation, but cannot eliminate the static error. $\mathrm{K_i}$is the integral control coefficient, which is mainly used to eliminate the static error and improve the error-free degree of the system. However, if the integral coefficient is too large, the integral effect will be too strong, resulting in the increase of system overshoot and even the oscillation of the system.$\mathrm{K_d}$isa differential control coefficient that is used to reflect the change trend of the deviation signal *(Lopez and Rubio, 2018).* It can introduce an effective early correction signal into the system before the value of the deviation signal becomes too large, so as to speed up the action speed of the system and reduce the adjustment time. If the differential time constant is too large, it will make the system unstable and easy to introduce high-frequency noise.

To effectively control the system, the fuzzy PID control is introduced based on PID control. Through fuzzy reasoning, the three parameters Kp, Ki and Kd are effectively controlled, so that it can control and use different PID parameters under different deviations to quickly and stably achieve the control goal*(Sun et al., 2021)*.

This design uses the compensation fuzzy PID control algorithm. This algorithm uses the fuzzy PID to change the three parameters, Kp, Ki and Kd, of the incremental PID through the error $\mathrm{e_1}$ and the error variation$\mathrm{e_1}'$ to obtain the speed control. Its control diagram is shown in Fig. 2.To improve the response speed of the system when the feeding quantity is too large, the system will make fuzzy prediction to the drum speed error and amplify the output of fuzzy PID in different proportions *(Wu et al., 2018)*, so as to compensate the sensitivity of the fuzzy PID control for large feeding quantity, and finally obtain the vehicle speed to be controlled.The control process is shown in Fig. 2.*(Aulin et al., 2019).*

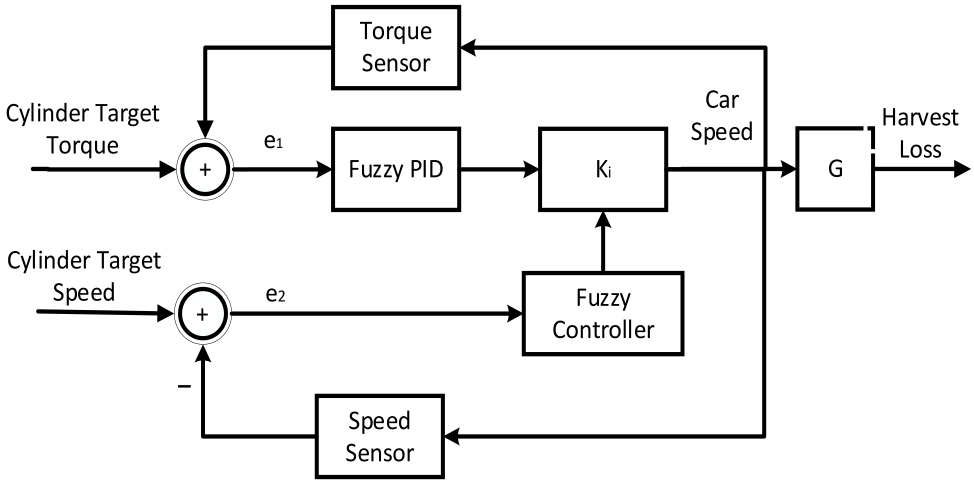


Fig. 2 - Flow of combine loss control system

RESULTS AND ANALYSIS

Data analysis

The data of 24 test plots obtained through the test are shown in Table 1.

Table 1

Data sheet of the test plot

Plot No.	Feeding quantity (kg/s)	Operating speed (m/s)	Drum torque (Nm)	Drum speed (r/min)	Loss rate (%)
0	0	0	28.63	1184	
1	1.46	0.76	55.32	1184	2.32
2	1.71	0.95	55.38	1183	2.43
3	1.74	1.02	53.8	1183	2.22
4	1.85	0.89	63.65	1182	1.77
5	2.16	0.99	78.6	1183	2.05
6	2.66	1.45	96.51	1182	1.59
7	3.06	1.43	100.09	1182	1.27
8	3.16	1.26	98.63	1180	1.20
9	3.52	1.33	109.35	1179	1.22
10	3.57	1.56	112.25	1180	1.24
11	3.59	1.85	118.23	1181	1.23
12	3.86	1.82	115.23	1178	1.32
13	3.91	1.71	121.65	1175	1.27
14	4.09	1.84	131.34	1169	1.32
15	4.56	1.86	132.65	1163	1.48
16	4.91	2.01	147.06	1168	1.89
17	5.15	2.05	156.21	1160	2.27
18	5.56	2.06	142.92	1157	2.38
19	5.66	2.05	163.51	1156	2.21
20	5.69	2.46	156.38	1158	2.24
21	5.85	2.16	166.85	1144	2.48
22	6.55	2.55	172.69	1139	2.68
23	6.56	2.90	160.84	1141	2.45
24	6.66	2.50	173.09	1138	2.72

Note: The plot with label 0 is the operating condition of the vehicle when the combine harvester runs without load.

According to the test data, the relationship curve between the feeding quantity and rotation speed is shown in Fig. 3.

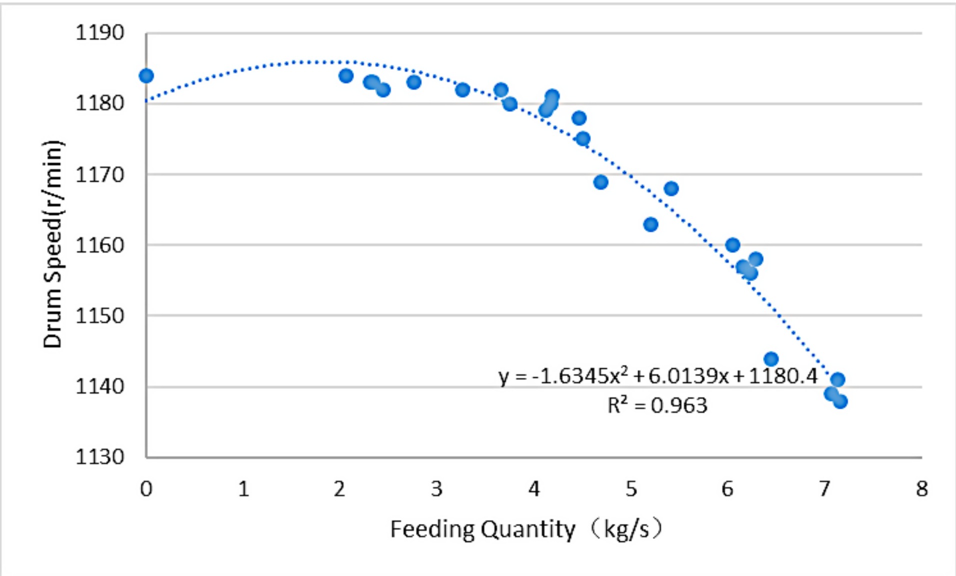


Fig. 3 - Relation curve between the feeding quantity and rotation speed

As shown in Fig. 3, when the feeding quantity is lower than 3.76kg/s, the rotation speed of the threshing drum is relatively stable and will not change with the feeding quantity. When the speed is greater than 3.76kg/s, the speed of the threshing drum will decrease with the increase of feeding quantity due to the large load. The numerical relationship between the feeding quantity and the drum torque obtained from the test is shown in Fig. 4.

According to Fig. 4, there is a functional relationship between the feeding quantity and torque of the combine harvester. R^2 is 0.9673, and the greater the feeding quantity, the greater the torque. The numerical relationship between the feeding quantity and the harvest loss obtained from the test is shown in Fig. 5.

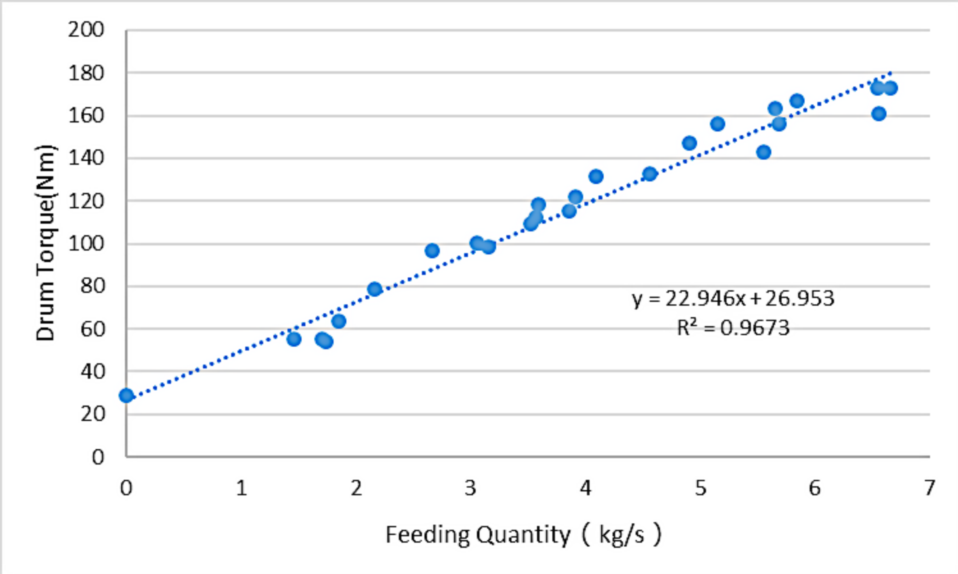


Fig. 4 - Relation curve between the feeding quantity and the drum torque

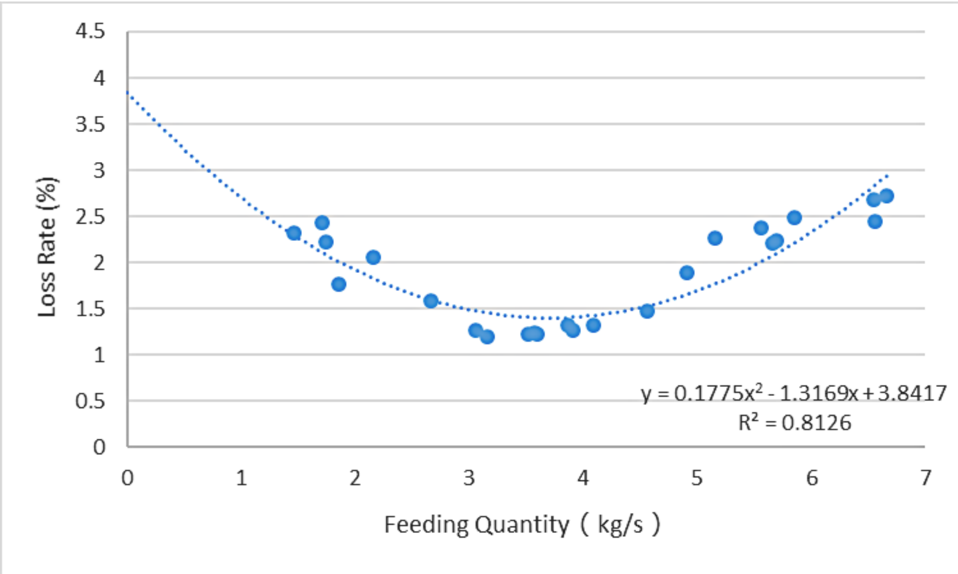


Fig. 5 - Relation between the feeding quantity and the harvest loss

According to the fitting curve between the feeding quantity and the harvest loss in Fig. 5, the quadratic function relationship model is higher than the primary function relationship and the power exponential relationship, which can better reflect the relationship between the two, and its R^2 is 0.8126.The relationship obtained from this model is as follows:

$$Y=0.1775X2-1.3943X+4.1224 \tag{11}$$

From this relationship curve, the lowest point is X=3.71kg/s. When the feeding quantity is 3.71kg/m, the harvest loss of the combine harvester can reach the minimum. In this way, taking this point as the target point of the feeding quantity of the control system can minimize the harvest loss. Since the feeding quantity is difficult to measure directly, it can be reflected by the drum torque and drum speed at this time. According to the above data model, it can be concluded that the drum torque corresponding to the feeding control target at this time is 112.08Nm and the drum speed is 1180r/min.

Control system result analysis

According to the above results, the torque error of the drum is set to [-20Nm, 20Nm] and is divided into 7 levels using the triangular membership algorithm; the change rate of the drum torque error is set to [-10Nm, 10Nm]and is divided into 7 levels using the triangular membership algorithm; the speed error of the drum is set to [-25r/min, 25r/min]and is divided into five levels using the triangular membership algorithm; the error change rate of the drum speed is set to [10r/min, 10r/min] and divided into five levels using the triangular membership algorithm. The fuzzy control rules and tables, and a complete combine harvester control system are designed.

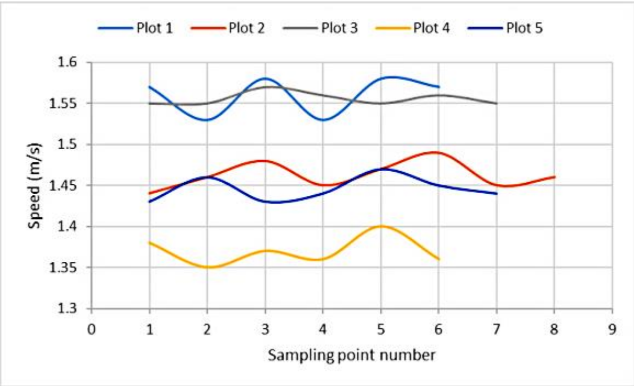
The actual harvest test was carried out on the designed control system, and the relevant verification test was carried out in Rizhao, Shandong Province. A total of 5 different plots were selected in the experiment, and the automatic control system was used to harvest wheat on the plots. During the harvesting process, GPS was used to obtain the real-time positioning and speed of the vehicle. During the walking process, the sampling points were randomly selected, each with a length of 10m and a width of 2.75m. The central axis was symmetrical with the track of the vehicle. The wheat harvest losses were collected manually, and the data after the test is shown in Table 2 as follows.

Table 2

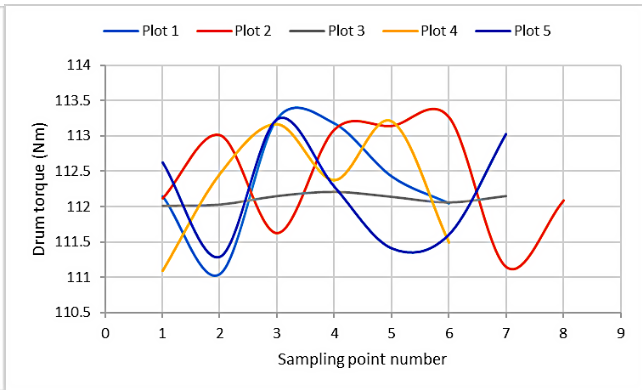
Experimental data of the control system

Plots	Sampling point label	Speed (m/s)	Drum torque (Nm)	Drum speed (r/min)	Loss rate (%)
Plot 1	1-1	1.57	112.15	1180	1.25
	1-2	1.53	111.05	1181	1.29
	1-3	1.58	113.25	1179	1.34
	1-4	1.53	113.18	1183	1.29
	1-5	1.58	112.43	1180	1.27
	1-6	1.57	112.05	1181	1.25
Plot 2	2-1	1.44	112.12	1181	1.25
	2-2	1.46	113.01	1181	1.26
	2-3	1.48	111.63	1180	1.27
	2-4	1.45	113.09	1182	1.27
	2-5	1.47	113.14	1180	1.29
	2-6	1.49	113.26	1179	1.33
	2-7	1.45	111.15	1180	1.27
	2-8	1.46	112.09	1181	1.26
Plot 3	3-1	1.55	112.01	1181	1.22
	3-2	1.55	112.03	1181	1.23
	3-3	1.57	112.15	1181	1.21
	3-4	1.56	112.21	1182	1.19
	3-5	1.55	112.14	1181	1.24
	3-6	1.56	112.06	1181	1.22
	3-7	1.55	112.15	1180	1.24
Plot 4	4-1	1.38	111.09	1181	1.26
	4-2	1.35	112.46	1181	1.26
	4-3	1.37	113.16	1180	1.29
	4-4	1.36	112.37	1182	1.26
	4-5	1.40	113.20	1180	1.32
	4-6	1.36	111.49	1180	1.30
Plot 5	5-1	1.43	112.62	1181	1.27
	5-2	1.46	111.29	1179	1.33
	5-3	1.43	113.23	1180	1.30
	5-4	1.44	112.28	1181	1.26
	5-5	1.47	111.41	1178	1.36
	5-6	1.45	111.60	1180	1.31
	5-7	1.44	113.02	1180	1.28

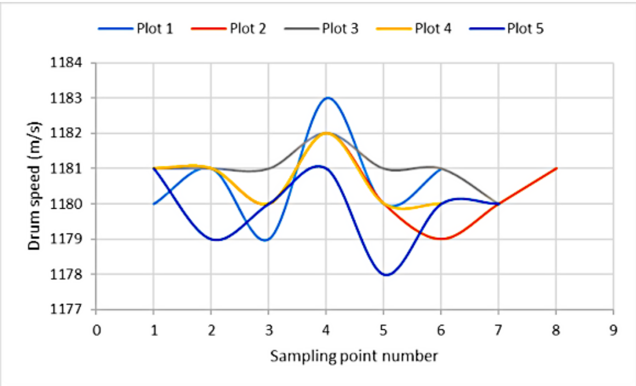
The curves of vehicle speed, drum torque, drum speed and loss rate of the five blocks are drawn respectively, as shown in Fig. 6.



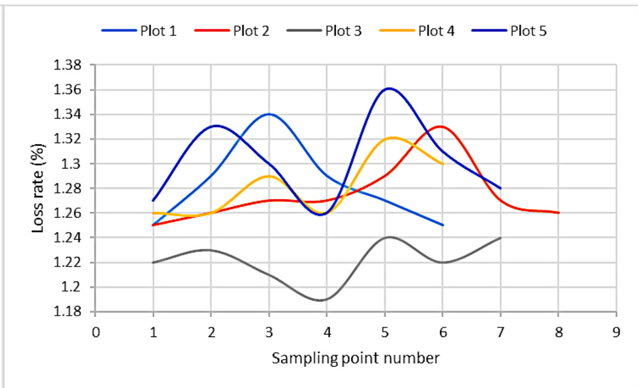
(a) Speed trend chart of five plots



(b) Drum torque trend chart of five plots



(c)Drum speed trend chart of five plots



(d) Loss rate trend chart of five plots

Fig. 6 - Trend chart of five-plot test data

According to the results, the drum torque harvested by the control system is relatively stable. The threshing drum torque can be controlled within 111r/min-113.5r/min, and the loss rate can be effectively controlled within 1.4%. The control system not only improves the working efficiency, but also achieves the effect of reducing the loss rate.

CONCLUSION

After field experiment and analysis of experimental data, the following conclusions are drawn:

(1) Analyzing the relationship between the feeding quantity of the harvester and the operating parameters and loss rate of its key working parts, it is found that the loss rate of the combine harvester is mainly affected by the feeding quantity. At the beginning, the combine harvester cannot reach the optimal working state due to the small feeding quantity, and its loss is large. As the feeding quantity increases, the minimum loss rate occurs when the feed rate is about 3.71kg/s, and the working state of the harvester reaches the optimum. Then the loss rate gradually increases with the increase of the feeding quantity.

(2) The control system uses the compensated fuzzy PID algorithm to combine the drum speed control and the drum torque control to jointly realize the speed control of the combine harvester, and then realize the effective control of the feeding quantity. According to the analysis of the verification test data, the control system designed in this paper can effectively reduce the harvest loss and improve the work efficiency.

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