A REVIEW OF THE FEED RATE DETECTION AND STABILITY CONTROL METHODS IN COMBINE HARVESTERS

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联合收割机喂入量检测与稳定控制方法研究现状与发展趋势

Xiaoyu YANG [1)], Panpan LI[1)], Zhihao ZHAO[1)], Chaoxu LEI [1)], Chengqian JIN [*,1,2)]

[1)] School of Agricultural Engineering and Food Science, Shandong University of Technology, Zibo, Shandong / China

[2)] Nanjing Institute of Agricultural Mechanization, Ministry of Agriculture and Rural Affairs, Nanjing, Jiangsu / China

Corresponding author: Chengqian JIN

Tel: +8615366092900; E-mail: 412114402@qq.com

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ABSTRACT

The feed rate is an important index for evaluating the performance of a combine harvester. Determining how to accurately reflect the feed rate during harvesting and establishing a reliable detection model is a major focus of current research and an important basis for the next step of feed rate stable control. This paper provides an overview of feed rate detection methods and stable control techniques for combine harvesters. It reviews methods that estimate the feed rate based on the inclined conveyor extrusion pressure, header power, and threshing unit energy consumption. Additionally, it introduces machine learning-based methods that incorporate multiple influencing factors to predict the feed rate. A comparison of different noise reduction techniques used in feed rate detection is also presented, analyzing their effectiveness. Furthermore, this study examines feed rate control methods in combine harvesters, discussing various control approaches with an emphasis on methods that stabilize the feed rate by adjusting header height and harvester forward speed. In response to the current issues of inadequate detection accuracy in feed rate monitoring, limited adaptability, and instability in control systems, it is pointed out that future research needs to innovate in developing advanced sensor technology, optimizing automatic control algorithms as well as data fusion and analytical methodologies.

摘要

喂入量是衡量联合收割机性能的重要指标，通过何种方式将收获时机的喂入量反应出来并建立可靠的检测模型是当前研究的重点，也是下一步稳定控制喂入量的重要依据。该文概述了联合收割机喂入量检测方法以及喂入量稳定控制方法的研究现状，综述了基于过桥挤压力、割台功率、脱粒元件功耗等反应收割机喂入量的方法，介绍了利用机器学习结合多种影响喂入量的因素预测喂入量的方法，并对比了喂入量检测中不同降噪方法的降噪效果的优劣，接着对联合收割机喂入量控制方法进行了梳理，探讨了不同控制策略，着重分析了通过调节喂入量高度、收割机前进速度使喂入量保持稳定的方法。结果表明现阶段喂入量检测方法均能在一定程度上反映出喂入量变化情况，但普遍存在稳定性差、检测精度不高等问题。通过控制喂入量有效减少了收获损失率，但控制误差易受田间环境影响、波动大。针对上述问题，指出今后研究需要在发展先进传感器技术、优化自动控制算法、数据融合与分析等方面开拓创新。

INTRODUCTION

A combine harvester is a field operation machinery that integrates cutting, threshing, separation, and cleaning functions. Its introduction has significantly reduced the labor intensity of farmers and enhanced production efficiency in agricultural settings (*Pingali, 2007*). As the crucial mechanical equipment in the grain harvesting process, the harvesting quality and efficiency of the combine harvester have always been the indicators of user’s concern, and also the focus of research by scholars. Crop feeding process is the front-end operation of combine harvester, affecting the machine threshing, cleaning and other subsequent operations. The feed rate has always been an important indicator for evaluating the performance of the harvester. Both excessive or insufficient feed rate can lead to a decrease in the efficiency of the harvester (*Fan et al., 2022*). Therefore, it is beneficial for the harvester to keep the best working condition by monitoring the real-time data of the feed rate and stabilizing feed rate during field harvesting (*Chen et al., 2011*).

At present, scholars at home and abroad have conducted a series of studies on the feed rate and its stable control methods, and have made some progress. Overseas research focuses on the height and density of feeding crops, estimating the feed rate indirectly by calculating the crop density in front of the harvester. Domestic research on feed rate detection methods mainly focuses on the following three aspects: estimating the feed rate by detecting grain flow rate; predicting the feed rate by measuring the squeezing force on inclined conveyor during crop feeding; establishing a feed rate detection model through analyzing the power consumption of major threshing components (*Tang et al., 2023; Zhang, 2019; Wang et al., 2019; Abdeen et al., 2022*).

In terms of feed rate control, mature feed rate control systems have been widely applied on large combine harvesters abroad, while most domestic research in China remains at the experimental stage, with a certain gap between research and practical application.

This review aims to present the research status of feed rate detection and stability control methods in combine harvesters. It summarizes common feed rate detection methods, feed rate signal denoising methods, feed rate stability control methods, highlights the problems and limitations of existing approaches, and proposes future research directions for improving feed rate detection and control methods.

RESEARCH PROGRESS ON FEED RATE DETECTION METHODS IN COMBINE HARVESTERS

The feed rate of the combine harvester refers to the total mass of all materials fed into the thresher body within a unit of time. It is closely related to header cutting width, operation speed, yield per mu, grain-straw ration, etc. Real-time monitoring and controlling the feed rate is crucial for the combine harvester to achieve optimal working efficiency (*Jie, 2009*).

Since the 1970s, many experts have conducted research on feed rate detection and have achieved certain results. In *Cao Chongwen, (1975),* many parameters that were considered as the basic for adjusting the feed rate were summarized, including the torque of several important transmission shafts such as cutter drive shaft and screw conveyor shaft, the speed of threshing cylinder and the pressure of concave plate, etc. (*Cao,1975*).

Jie Zhan et al. (1990) began researching quantitative measuring techniques for feed rate, using two methods of measuring pressure and displacement, and conducting a rice bench simulation experiment. By utilizing the principle that the sensor can convert the feed rate into electrical signals, the study explored the correlation between feed rate and electrical signals, and respectively summarized the fitting equations between pressure sensor voltage and feed rate, and displacement sensor voltage and feed rate. The error calculation results showed that the test accuracy of the pressure sensor is better than that of the displacement sensor. In order to improve the detection accuracy, the pressure sensor was calibrated. Firstly, the sensor was statically calibrated through weight loading, and after obtaining the static calibration regression equation, dynamic calibration was conducted through bench testing (*Jie et al., 1990*).

In 2009, a mathematical model for feed rate testing was established (*Jie et al., 2009*). The force-electric sensor was installed on the bottom plate of the inclined conveyor to conduct real-time analysis and processing of feed rate signals. The regression curves were established for the preset feed rate data group and the signal mean, as well as the signal change value. Due to random errors caused by factors such as the state of the feed-in material, placement factors and conveying factors, the repeatability of the feed rate data was poor. Although the stability and reliability of this system have been greatly improved, it still did not meet the technical requirements for telemetry of feed rate in field experiments.

Tang Zhong et al. (2012) analyzed the power consumption of the longitudinal flow threshing-separation process, and deduced the relationship between the feeding rate and the net threshing power consumption of the longitudinal-flow threshing cylinder in wheat harvesting. The field test results showed that the net threshing power consumption of the longitudinal-flow threshing cylinder could accurately predict the feed rate (*Tang et al., 2012*).

Lu Wentao et al. (2011) designed a hydraulic infinitely variable speed system for threshing cylinder of grain combine harvester and installed a pressure sensor in hydraulic to measure oil pressure. This oil pressure was used to represent the feed rate. By analyzing the data of oil pressure, threshing cylinder and engine speed under different feed rate, the fitting equation of oil pressure and feed rate was established. However, the feed rate model established by this method can be valid only when the combine harvester is operating stably, the physical properties of the crop are consistent and the feeding is uniform, which is an ideal condition (*Lu et al., 2011*).

Liang Xuexiu et al. (2013) analyzed the flow rate of grains, the torque and the speed of the threshing cylinder, corrected and calculated the formula for the feed rate, and designed a set of field online monitoring system for the feed rate (*Liang et al., 2013*).

Liu Yuanyuan et al. (2017) analyzed the power and dynamic model of the header auger conveyor, and designed a power consumption monitoring system for the auger conveyor. The location of the sensor is shown in Figure 1. This monitoring system was installed on the Guwang TB60 combine harvester for field experiments. Through linear fitting of the power of the header screw conveyor and the feed rate data, it was found that there is a linear relationship between the two, with a correlation coefficient R^2=0.9099, indicating that the method of predicting the feed rate based on monitoring the power of the auger conveyor is feasible (*Liu et al., 2017*).

Yin Yanxin et al. (2018) designed a chain wheel torque speed sensor based on the feeding auger structure characteristics, and constructed a multi-information acquisition system for combine harvester based on the distributed data collection, transmission and processing system of CAN bus (Fig 2). This system can synchronously obtain online parameter information such as the power output of the header lifting, auger conveyor, inclined conveyor, and threshing cylinder of the combine harvester, providing reliable data for predicting the feed rate and operation quality of the grain combine harvester (*Yin et al., 2018*).

Zhang Zhenqian et al. (2019a) designed a feed rate monitoring system, which obtains the header drive shaft torque signal through a wireless torque sensor, and measures the header drive shaft speed signal with a Hall sensor to predict the feed rate (*Zhang et al., 2019*).

Sun Yifan et al. (2020) selected the feed rate detection method based on the power of the header active shaft and the power of the inclined conveyor to design the text system, and compared the detection accuracy of the two methods. After processing and analyzing the field text data, the linear regression equations between the torque voltage signal of the header's driving shaft, the inclined conveyor's power shaft torque voltage signal and actual feed rate were respectively established by the least square method. Although this method simplifies the calculation process for the feed rate model, it cannot reflect the relationship between feed rate and power at different shaft speeds (*Sun et al., 2020*).

At present, the related research results of feed rate detection method based on traditional mathematical model are shown in Table 1.

Table 1

Research on the detection method of combine harvester feed rate

Detection method	Sensor type	Installation position	Grain type	Error
Inclined conveyor extrusion pressure	Force-electric sensor	Inclined conveyor bottom plate	Rice	Bench test error ≤8 %.
Power consumption of threshing element	Torque sensor	Threshing cylinder active shaft	Wheat	Bench test error ≤ 0.89 %
	Oil pressure sensor	Threshing cylinder hydraulic stepless variable speed system oil circuit	Rice	
Header power	Torque sensor	Header auger conveyor active shaft	Wheat	R^2=0.9099
	Torque sensor	Header active shaft	Wheat	R^2=0.8520
	Torque sensor	Header drive shaft	Wheat	R^2=0.8325
Combined type	Torque sensor; Pressure sensor	Between the threshing cylinder power source and the load; Between the grain elevator and the grain outlet	Rice	Error ≤ 5 %
	Chain wheel torque speed sensor	Header auger active shaft; Inclined conveyor drive shaft; Threshing cylinder active shaft	Rice	Error ≤ 2 %

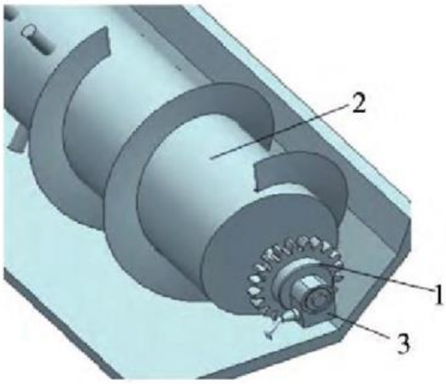

Fig. 1 - Installation diagram of torque sensor
(Liu Yuanyuan et al., 2017)
1.Torque sensor; 2. Header screw conveyer;
3.Signal convertor torque sensor

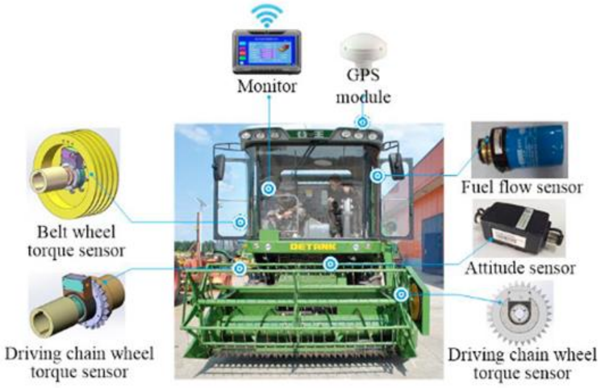

Fig. 2 - The scheme of the system layout and sensors installation sites of the system
(Yin Yanxin et al., 2018)

With the development of computer science, more and more scholars use machine learning models such as fuzzy neural networks and convolutional neural networks to predict the feed rate (*Dorokhov et al., 2019*). *Lu Wentao (2014)* considered that when the physical characteristics of the grain changed, the one-to-one correspondence between the feed rate and the oil pressure was not established. In this condition, it was difficult to obtain the accurate feed rate by using the theoretical equation, so they used a neural network to establish the model for the feed rate. Through the orthogonal test, it was concluded that the feed rate, material humidity and grain-straw ration had significant effects on the oil pressure, so the oil pressure, material humidity and grain-straw ration were taken as the three neurons of the input layer, and the feed rate was taken as the neuron of the output layer. A feed rate neural network model was established by processing and analyzing the experimental data. Comparing the training results of the network model with the multiple linear regression function, it was concluded that the network model is superior to the regression equation. This method can reduce the impact of the changes in physical characteristics of the feed material on the accuracy of the feed rate detection (*Lu et al., 2014*).

Sun Yifan (2022) used rice as the harvest object and designed a feeding monitoring system that could simultaneously monitor the header height, rice moisture content and the torque changes of the header's power shaft. In order to accurately calculate the feed rate, he established a three-layer BP neural network with 12 neurons in the hidden layer, with header height, grain moisture content and header's power shaft torque as input layers, and the feed rate as the output layer. The structure of the neural network is shown in Fig. 3. To prevent the neural network from getting stuck in local minima during the fitting process, the particle swarm optimization algorithm was introduced to optimize the initial value and threshold of BP network. The average absolute percentage error of the optimized feed rate model decreased from 8.42% to 7.62% (*Sun et al., 2022*). The neural network prediction method of feed rate is summarized as shown in table 2.

Table 2

Neural network prediction method of feed rate

Model	Input layer signal	Effect
Fuzzy neural network	Crop density deviation, Crop density deviation change rate	
BP neural network	Oil pressure, material humidity, grain-straw ration	SSE=0.769
	Header height, grain moisture content, header’s power shaft torque	MAE=7.69%
Convolutional neural network		Accuracy=86.7%

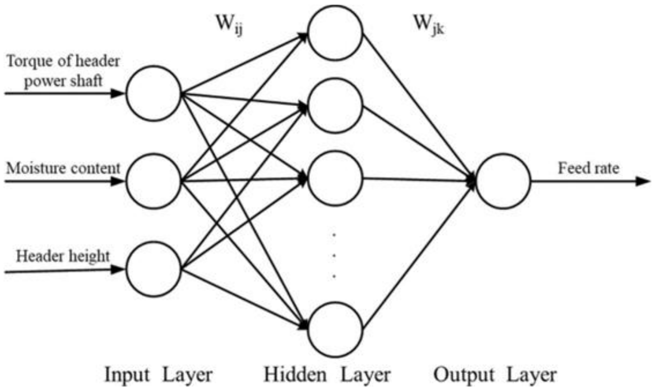

Fig. 3 - Structure of the BP neural network
(*Sun et al., 2022*)

In response to the issue of insufficient interpretability of processing results in machine learning prediction models, some scholars have begun to predict the feed rate model through grey relational analysis and association rule analysis. Grey relational analysis is an analytical method based on grey system theory, mainly used to deal with incomplete information or uncertainty. Compared to traditional machine learning methods, grey relational analysis places more emphasis on evaluating the degree of correlation and establishing correlation models. *Zhang Yawei et al (2018)* studied the factors affecting the feed rate of combine harvester based on the grey correlation analysis. The feed rate, crop attributes and harvesting conditions were regarded as a grey system with some information being clear and some unclear. Combined with the data of crop attributes and the feed rate, the grey relational analysis was used to find out the correlation between factors such as operating speed, crop density, torque and speed of the feeding auger and the inclined conveyor, torque and speed of threshing cylinder and the feed rate. It was concluded that in the actual field harvesting, the correlation degrees of operation speed and the feed rate were the highest, followed by the torque of the threshing cylinder. Based on this, a prediction model of feed rate detection error based on grey prediction was proposed, using the product of operating speed and crop density, feeding auger torque, inclined conveyor and threshing cylinder torque as inputs to establish the feed rate detection model (*Zhang et al., 2018*). *Liu Yehong et al (2023)* incorporated the torque and speed of the threshing cylinder, grain, grain augers and tailing augers into the feed rate monitoring. He proposed using association rules to explore the relationship between each parameter and the feed rate (*Liu et al., 2023*).

In addition to detecting the feed rate by measuring the power, pressure and other key components of the combine harvester during operation, many scholars have studied the crop growth status at the front end of the harvester, proving reference basis for subsequent feed rate detection and control. *Ji Binbin (2005)* designed a combine harvester feed rate prediction system based on fuzzy neural network. According to the crop density deviation and the change rate of crop density deviation measured by the combine harvester grain feeding amount sensor at time t, the actual crop density deviation of t + △t was predicted. Fuzzy neural networks combine the advantage of fuzzy logic and neural networks and can overcome the shortcomings of traditional neural networks in handling fuzzy and uncertain information. This combination can help in dealing with fuzzy inputs, outputs and rules, making the network more adaptable to problems involving fuzzy concepts (*Ji, 2005*).

Saeys et al. (2009) used two types of light detection and ranging sensor and different online processing methods to estimate the crop density in front of the combine harvester. They proposed a new method for estimating crop volume by fitting thin plate splines to ground and ear points to calculate the volume between ground profiles and crop profiles (*Saeys et al., 2009; Blanquart et al., 2020*).

Pan Jing et al (2010) used computer image processing technology to fit the 2R+G color feature value extracted by image processing with the actual measured feed density image, and established relevant model coefficients. The feed density of the combine harvester was obtained in real time to predict the feed rate of the harvester (*Pan et al., 2010*). *Zhang Shuqi (2021)* used machine vision to measure the height of rapeseed in the field, and built a convolutional neural network model to predict the density of rapeseed in the field, which was used as the basis for detecting the feed rate. Based on obtaining accurate feed rate detection results, an adaptive control strategy was used to achieve a scientific match between the forward speed and the rotation speed of the reel wheel (*Zhang, 2021*).

SIGNAL NOISE REDUCTION PROCESSING METHODS IN FEED RATE DETECTION

The working environment of the combine harvester is special. The terrain fluctuates in the field making it impossible to maintain a consistent flatness. The density and height of the harvested crops also vary. Moreover, the combine harvester itself has a complex system and harsh operation conditions. During operation, noise caused by the machine's vibrations and bumps inevitably interferes with sensor signals. In order to improve the accuracy of feed rate prediction, it is necessary to denoise the signal collected by the sensors.

Zhang Zhenqian (2019b) performed double threshold filtering on the torque signal of the header drive shaft collected by the sensor for edge detection and segmentation, and then used piecewise linear interpolation to obtain more detailed information to remove singular values. He made a comparison on the noise reduction effects of Butterworth low-pass filtering, FIR low-pass filtering, moving average filtering and adaptive filtering on the torque signal. After error analysis, it was found that the adaptive filtering had the best noise reduction effect (*Zhang et al., 2019*).

Sun Yifan et al. (2020) performed Fourier transform on the collected data, converting the data from the time domain to the frequency domain, providing clearer frequency domain information for filtering processing, and then using Butterworth band-pass filter to filter the torque signal (*Sun et al., 2020*). The denoising framework is shown in Figure 4.

In order to solve the signal noise issue in the feed rate monitoring system, *Tao Jiang et al. (2022)* first performed Fast Fourier Transform on the torque of the auger conveyor drive shaft during the no-load rotation of the harvester to obtain the noise frequency domain information. Since the signal during the harvester's loaded operation is a non-stationary process, Fourier transform has limitations in that it can only determine the frequency components contained in a segment of the signal overall, without knowledge of when each component appears. Therefore, it cannot determine the changes in signal frequency during feeding, nor can it filter out noise in the signal. In response to this situation, wavelet transform was applied to the torque signal obtained during the harvester loaded operation, followed by denoising using a fixed threshold estimation method to reduce errors in the relationship between torque and the feed rate (*Jiang et al., 2022*). The denoising framework is shown in Figure 5.

Fengzhu Wang et al. (2023) studied a feed rate detection method based on multi-component power monitoring, effective data automatic screening and multivariate data fusion regression. The Mann-Kendall algorithm was used to detect the boundary points of field harvest data. The Grubbs standard was used to validate the data, and outliers were rejected one by one at a confidence level of 0.05. The correlation of the established regression model was verified by Pearson algorithm, and multi-parameter calibration and fusion feeding amount detection were realized (*Wang et al., 2023*).

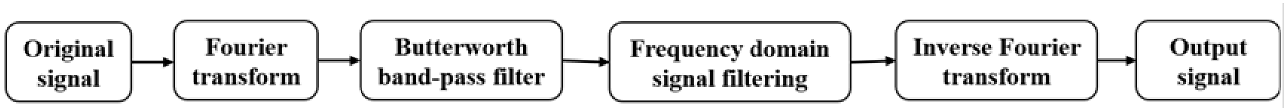

Fig. 4 - Fourier transform denoising framework (*Sun Yifan et al., 2020*)

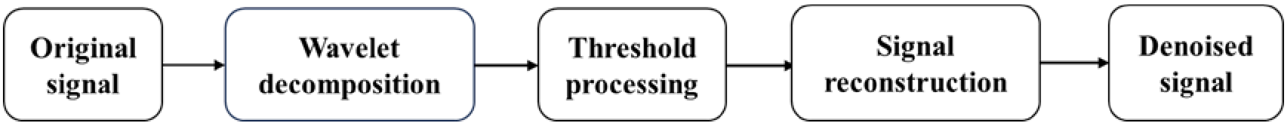

Fig. 5 - Wavelet method denoising framework (*Wang et al., 2023*)

RESEARCH PROGRESS ON THE FEED RATE CONTROL METHOD IN COMBINE HARVESTERS

The application of automatic control technology in agricultural machinery has a breakthrough impact on modern agricultural production, which is conducive to the intelligent and sustainable development of agricultural equipment in production operations. Currently, research on the automatic control of combine harvesters mainly focuses on controlling the rotational speed of the threshing drum, the concave screen clearance, the height of the header, the forward speed etc. (*Ivan et al., 2015*).

Alabushev et al. (2020) explored the factors influencing the binding force of winter wheat grains and ears and established a regression model to provide a basis for intelligent control of threshing process (*Alabushev et al., 2010*). *Xu Baoyan et al. (2020)* conducted experiments by setting different concave plate clearances and drum speeds, and derived the relationships among concave plate clearance, drum speed, and threshing quality. Based on a type - 2 fuzzy logic controller, they designed a threshing controller with a low loss rate (*Xu et al., 2020*). *Fan Chenglong et al. (2022)* designed a guide vane inclination adjustment mechanism with a hydraulic cylinder as the driving source under the monitoring of the feed rate (*Fan et al., 2022*). *Li Ying et al. (2021)* designed a frequency subsection regulation system for the combine harvester header cutter. By constructing the cutter trajectory equation, they analyzed the relationship between the forward speed of the harvester and the cutting frequency, as well as the impact on the cutting area, and determined the optimal cutting frequency range at different operating speeds (*Li et al., 2021*). In view of the shortcomings of current combine harvester research, such as the focus on single-device control, inaccurate feedback information, and poor adaptability of control models, *Li Yang et al. (2024)* regarded the threshing cylinder device as an integrated control object. They designed an electric adjustment mechanism for the main operating parameters of the threshing and cleaning devices. Based on the fusion method of particle swarm optimization and wavelet neural network, they conducted system identification on the state - space model and the NARMAX model to explore their applicability and obtain the optimal model. They adopted the model predictive control method to adjust the threshing and cleaning parameters and carried out the control process simulation in Simulink, achieving good results (*Li et al., 2022; Li et al., 2024*). *Yang Yu et al. (2024)* designed an electric control adjustment device for threshing clearance based on a crank - rocker mechanism, proposed a control method for threshing clearance based on a fuzzy neural network PID, and established relevant models and determined parameters (*Yang et al., 2024*).

Controlling the feed rate within a stable range during the operation of a combine harvester is beneficial for the machine to achieve optimal performance and reduce grain loss. The feed rate cannot be directly controlled. *Zhang Yawei et al. (2018)* found through grey relation analysis that the forward speed during harvesting has the highest correlation with the feed rate, followed by the correlation between the threshing cylinder torque and the feed rate (*Zhang et al., 2018*). At present, there are two main methods for controlling the feed rate: one is to control the forward speed of the harvester to control the feed rate, and the other is to achieve stable control of the feed rate by adjusting the height of the header (*Maertens and Baerdemaeker, 2004*).

The CR90.90 combine harvesters developed by Case New Holland Company use two ultrasonic sensor to detect the feed rate of threshing cylinder. When an excessive feed rate is detected, the machine's overload anti-spitting device can automatically adjust. The machine is equipped with the AFS advanced precision agriculture system, which effectively combines and analyzes data from several key stages of cultivation, providing users with personalized agricultural solutions (*Cheng et al., 2018; Wang, 2021*).

Huang Zhigen (2010) designed a multi-signal acquisition system for combine harvester, which can detect the rotation speed, feeding rate and grain loss signal during the operation. In order to obtain a stable feeding rate, he designed an automatic speed control mechanism for the combine harvester. The main control unit based on ARM was used to control the stepper motor and then control the angle of the hydraulic stepless transmission joystick to control the forward speed of the combine harvester. In addition, a load feedback automatic control system of the combine harvester was established, utilizing fuzzy control technology to create a multi-information fuzzy control model (*Huang, 2010*).

Fuzzy control system is a control method based on fuzzy logic theory, which simulates human thinking and decision-making process, and can deal with the problems of uncertainty and fuzziness.

Mahmoud Omid et al. (2010) designed a fuzzy logic control system combined with human expert knowledge, which integrates human expert knowledge into the learning process, and finds the best technical parameters of the harvester through continuous trial and error based on expert knowledge and relevant experience. It provided a reference for the design of combine harvester control system in the future (*Omid et al., 2010*). *You Huiyuan et al. (2015)* used PLC to establish a fuzzy control system for feed rate, and controlled the working speed of the combine harvester to keep the feed rate within a stable range. The actuator adopts an electronically controlled hydrostatic system, which changed the speed of the hydraulic motor by altering the current signal and the swashplate angle of the variable pump to adjust the travel speed (*You et al., 2015*).

Wang Li et al. (2021) designed an intelligent control test bench for combine harvesters. The designed double - closed - loop PD controller can effectively and dynamically adjust the control parameters according to the changes in the driving speed of the harvester. The motor module was utilized to simulate the rotational speeds of rotating components such as the combine drum, conveyor through, and header screw conveyor of the combine harvester, while the simulation module was used to simulate the feeding and loss processes. The intelligent control algorithm for the forward speed of the test bench was tested, achieving good results (*Wang et al., 2021*).

He Yongqiang et al. (2024) proposed a control algorithm that combines the Pose Vector Method (PVM) and the Support Vector Regression (SVR) model. They designed a research platform for traveling control adapted to different Paddy Ground Conditions (PGCs), and used the Real - Time Kinematic Global Navigation Satellite System (RTK - GNSS) to measure information such as the pose of the combine harvester. The PVM was proposed to determine the steering radius online, and the SVR model was used to predict the error - correction factor for the steering trajectory radius. A feedforward compensation control method was designed based on the steering control model. This study provided new ideas for enhancing the online perception of the motion state of crawler combine harvesters and improving the adaptive control performance (*He et al., 2024*).

Because the combine harvester is a complex system with nonlinear time-varying and time delay and has numerous and complex working components and changeable working environment, the traditional control theory was difficult to be applied to the harvester control system (*Pan et al. 1999*).

Fuzzy control considers fuzzy and imprecise input and output, making the system more adaptable to fuzzy, uncertain, or difficult to model situations. In the past two decades, it has been widely used in the design of combine harvester control system. However, fuzzy control has low interpretability, complex calculation, and lack of global optimization. Many scholars have begun to try to combine fuzzy control with some algorithms such as adaptive control to make the system more adaptable to complex environments and changes (*Wang et al., 2014.; Randal et al., 2005*).

Chen Jin et al. (2014) designed a fuzzy adaptive control system of forward speed for combine harvester based on model reference, as shown in Figure 6. Compared with the traditional fuzzy control, the adaptive fuzzy control system introduces self-adaptability. The system can dynamically adjust the reference fuzzy rules and member functions according to real-time feedback to adapt the changes of the system. The control system received input and loss signals collected by sensors, and then calculated the change of the forward speed of the combine harvester through the model reference fuzzy adaptive control algorithm, and outputted the control signal to drive the actuator to adjust the forward speed (*Chen et al., 2014*).

Ning Xiaobo et al. (2015) conducted a comprehensive dynamic analysis of the motion mechanism of the combine harvester, and designed a fuzzy logic controller, with the speed deviation of the threshing cylinder and the rate of change of the speed deviation as input variable, and the rotation angle of the stepping motor as the output variable. If the input variable exceeded the range of change, the controller would adjust the forward speed of the harvester by controlling the hydraulic infinite transmission based on the output variable (*Ning et al., 2015*).

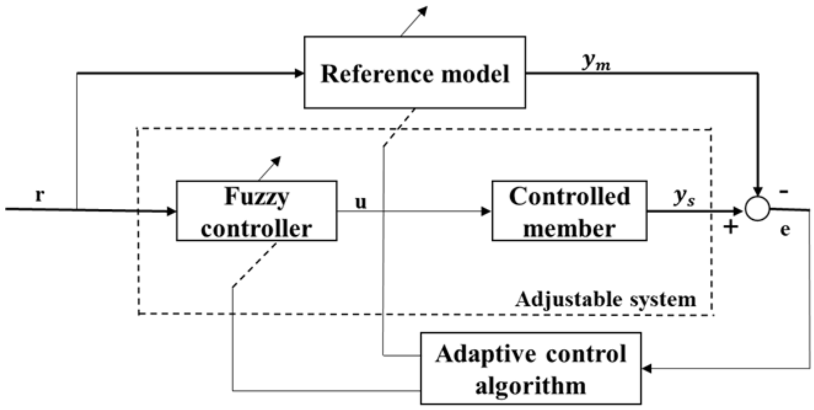

Fig. 6 - Structure diagram of model reference fuzzy adaptive control system (*Chen et al., 2014*)

Because fuzzy control requires more professional knowledge to model the system, and the design process is more complex and subjective, some scholars began to use optimization algorithms to help adjust the parameters of fuzzy controllers to improve system performance.

Ning Xiaobo (2015) further used a multi-objective genetic algorithm to optimize the influence factors of each parameter in the constructed multi-parameter fuzzy control system, such as the speed of the tangential cylinder. By comparing the simulation test with the model before optimization, it can be seen that the overall performance of the harvester is improved (*Ning, 2015*). In addition, *Ning Xiaobo*, *Chen Jin et al. (2016)* used association rule knowledge to evaluate the weight factor of association rules between each operating parameter of the harvester and the feed rate and loss rate, studied the principle of adaptive fuzzy control, constructed the adaptive control model of the whole domain operating speed of combine harvester and designed the adjustable factor fuzzy controller (*Ning et al., 2016*).

In 2017, *Chen Jin (2017)* proposed a multi-parameter fuzzy control strategy for the forward speed of the combine harvester based on Knowledge Discovery in Databases (KDD). She found the optimal trade-off point between the auger conveyor, the inclined conveyor and the threshing cylinder, and used MATLAB to establish a muti-parameter control model based on KDD (*Chen et al., 2017*).

Hou Ankang (2021) designed the control system of header module, threshing module, grain tank and travel module of combine harvester, and established the speed control model of each component of the combine harvester. The core idea was to control the feed rate to be constant, and this was achieved by controlling the flow rate of the hydraulic valve (*Hou, 2021*). *Li Xiaoyu et al. (2023)* designed the automatic control algorithm of corn grain harvester, with a travel system using closed-loop hydrostatic drive. They proposed an improved particle swarm optimization that combines the cuckoo search algorithm's local wandering strategy, and built a PSO-CS-Fuzzy PID control model based on MATLAB Simulink. This algorithm was beneficial for addressing the issue of traditional particle swarm algorithms easily getting stuck in local minima, and achieved good control effects in subsequent simulation experiments (*Li et al., 2023*).

Sun Yifan et al. (2023) established a model for detecting the change of feed rate during the operation of the combine harvester. The harvester operation speed was taken as the control object, and the stable control of feed rate was taken as the control target. The model prediction method was used to simulate and control the feed rate. The grey wolf optimization algorithm was used to optimize the weight matrix to reduce the control error of the output feed rate (*Sun et al., 2023*). Table 3 summarized the research on the stable control strategy of feed rate with the control target of controlling the forward speed of harvester.

Table 3

Research on the stable control strategy of feed rate

Control strategy	Optimistic algorithm	Advantage
Fuzzy control		The rules are intuitive in form, adaptable and flexible.
MSIFC		Control precision and robustness are improved.
AFC	Association rules analysis	The extraction of fuzzy rules is more accurate, and the control system is more interpretable.
FRAMFC		The system response speed and modeling accuracy are improved.
MPFC	MOGA	The global optimization ability is improved, and the multi-parameter coordinated optimization is improved.
	KDD	Parameter optimization is more targeted.
PID control	PSO-CS	Avoid falling into local optimal value
MPC	GWO	The convergence speed is faster and adapts to the multivariable complex system.

In addition to controlling the forward speed of the combine harvester, another effective way is to adjust the height if the header to control the feed rate. By raising or lowering the header, the cutting position of the crop can be changed, and this flexible control method can more finely adjust the feed rate (*Cheng et al., 2018; Tai et al., 2020; Wang et al., 2024*).

Chen Jin et al. (2018) designed a keys electric controlled adjustment device for header parameters with PLC as main controller, which can realize the keys electric controlled of header height, reel height and reel speed. The actuator of the header was controlled by hydraulic pressure, and the components were three-position four-way solenoid directional valve and proportional solenoid valve. The speed control model of the reel was established, and the fuzzy control and PID control were combined to realize the real-time control of the system. Effective header height control is helpful to improve the stability of feed rate and reduce the load fluctuation of each link of the whole machine (*Chen et al. 2018*).

Zhuang Xiaobo and Li Yaoming (2020) analyzed the dynamics of the header and established the model. According to the hydraulic motion equation, the state space model of the header height hydraulic system was established. They proposed a height control strategy of combine harvester header based on robust feedback linearization, which could make the header height follow the ground fluctuation. They designed a controller and compared it with the PID controller in experiments. The results showed that under the same simulation conditions, the error under the control of this method was smaller than that under the PID control (*Zhuang et al., 2020*).

Ni Youliang et al. (2021) developed a height adjustment system for soybean harvester header. They designed a profiling mechanism and a hydraulic drive system based on existing soybean harvesters, and designed a header height self-adaptive adjustment system, and established an evaluation index for the height adjustment system of the soybean harvester header (*Ni et al., 2021; Liu et al., 2023*).

Ji Kuizhou et al. (2022) proposed a multi-sensor data fusion technique based on a backpropagation (BP) neural network. This method integrates ultrasonic sensors for ground height detection, infrared sensors for monitoring crop lodging status, and pressure sensors for real-time measurement of header load. By adaptively adjusting the weighting of data from various sensors through the neural network, the system optimizes the self-adaptive regulation of header height in combine harvesters (*Ji et al., 2022*).

Ruan Mingjian et al. (2019) designed an automatic control system for the header height of a combine harvester. They established a relational model between the header height of the combine harvester and the sensor signals, and adopted the grey prediction PID algorithm to reduce the hysteresis of the header height control model. Good results were achieved in the field experiments (*Ruan et al., 2022*).

CONCLUSIONS AND RECOMMENDATIONS

In summary, at present, researchers have made a lot of achievement in the research of combine harvester feed rate detection and stability control methods. However, the existing methods still have certain limitations, and there is still a considerable gap in the application of combine harvester design. The main problems are as follows:

(1) The current feed rate detection method is difficult to adapt to the complex environmental changes during the operation of the harvester, and the detection accuracy is not high. The mainstream detection method is to establish the relationship between the feed rate and the power consumption of the main working components such as the header and the threshing cylinder during the harvester operation. However, it is difficult to avoid the fluctuation of land and the change of crop density when the harvester is working, which can lead to insufficient stability of sensors, and noise interference from driveline torsional vibration, bending moment, and engine vibration can affect the signals collected by the sensors. The filtering method is difficult to completely eliminate noise and can only reduce noise to a certain extent.

(2) The stability of the control system is low, and research on the speed control algorithms remains limited. Currently, widely used fuzzy rules mainly depend on expert experience. Some improved methods are also based on fuzzy rule control, making it difficult to dynamically adjust weight factors and other relevant parameters for different situations. Additionally, combine harvesters exhibit significant time delays during operation, yet current research rarely considers factors such as actuator delays, resulting in control effects that fail to meet expected performance levels.

In response to the current issues, the future research on the feed rate detection and stability control of combine harvester is supposed to focus on the following aspects:

(1) Advanced sensing technology. In view of the limitations of current sensors, research is being conducted on more advanced and stable sensor technology to improve detection accuracy in complex environments and adapt to changes in land topography and crop density.

(2) Data fusion and analysis. Introducing big data technology to conduct more comprehensive and real-time analysis on data collected by sensors. Utilizing data fusion technology, combined with machine learning algorithms, to establish more accurate feed rate models.

(3) Advanced control algorithms. By studying more advanced speed control algorithms, including model predictive control, adaptive control etc., it is possible to better cope with complex environments and time-delay characteristics and improve the stability of the control system.

(4) Delay compensation technology. The control algorithm considering the delay of the harvester actuator is studied to adapt to the time delay of the harvester.

The future development of combine harvesters will move towards the application of intelligent technology, modular design, and autonomous driving technology. By utilizing advanced sensors, machine learning, and artificial intelligence technology, the harvester will be able to better adapt to different field condition, and modular design will enhance the flexibility of machine applications. It is necessary to accelerate research and innovation in the detection and stable control of the feed rate of combine harvesters to align with the development trend.

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