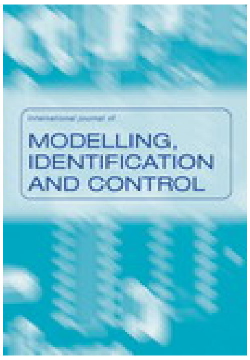


International Journal of Modelling, Identification and Control

ISSN online: 1746-6180 - ISSN print: 1746-6172
https://www.inderscience.com/ijmic

Variable frequency speed control method for wheeled grain harvester based on fuzzy control theory

Haiyan Hu, Chang Su

DOI: 10.1504/IJMIC.2025.10073125

Article History:

Received:	31 December 2024
Last revised:	16 June 2025
Accepted:	24 June 2025
Published online:	24 December 2025

Variable frequency speed control method for wheeled grain harvester based on fuzzy control theory

Haiyan Hu*

School of Engineering,
Jilin Business and Technology College,
Changchun, 130507, China
Email: huhaiyan@jlbtc.edu.cn
*Corresponding author

Chang Su

Information Center,
Changchun Eleventh High School,
Changchun, 130062, China
Email: 1146682054@qq.com

Abstract: With the advancement of agricultural mechanisation, higher requirements have been proposed for the work efficiency, automation level, and energy-saving performance of grain harvesters. Aiming to reduce the coefficient of variation of data and speed control overshoot, this paper designs a variable frequency speed control method for wheel grain harvesters based on fuzzy control theory. A frequency conversion mathematical model for wheeled grain harvesters was constructed, with motor speed online estimation achieved through adaptive disturbance rejection design and adaptive estimation model. Finally, fuzzy rules, feedforward compensation, and PID controller optimisation were utilised to enable dynamic parameter adjustment and precise speed control. Experimental results demonstrated that after applying this method, the speed data coefficient of variation decreased from 0.06 to 0.02, with maximum speed overshoot reaching only 2.97%.

Keywords: wheel grain harvester; variable frequency speed regulation; speed control; fuzzy control PID controller; feedforward compensation mechanism.

Reference to this paper should be made as follows: Hu, H. and Su, C. (2025) 'Variable frequency speed control method for wheeled grain harvester based on fuzzy control theory', *Int. J. Modelling, Identification and Control*, Vol. 46, No. 2, pp.82–90.

Biographical notes: Haiyan Hu received her Master's in Computer Application from Jilin University in 2013, and is studying for a Doctor's degree. She is currently a Professor in the School of Engineering of Jilin Business and Technology College. Her research interests include computer applications, large data processing and artificial intelligence. She is the Leader of Jilin Institute of Technology and Business Artificial Intelligence and Communication Engineering, the Director of Jilin Intelligent Agriculture Society, and a member of the Changchun Branch of China Computer Federation. She has won many personal titles such as 'Women's Meritorious Service', 'Excellent Teacher' and 'Model of Morality'.

Chang Su received his Master's in Computer Application from Northeast Normal University in 2014. He is currently an Engineer in the information Center of Changchun Eleventh High School. Her research interests include computer applications, large data processing and information security.

1 Introduction

With the advancement of modern agriculture, performance requirements for grain harvesters have become increasingly stringent, and the operational efficiency of wheeled grain harvesters plays a critical role. Grain harvesting quality is determined by multiple indicators, including cutting height and threshing cleanliness (Jia, 2023). However, fixed-speed harvesters struggle to adapt to complex operating conditions such as varying crop growth density, terrain, height, and humidity, making it difficult to maintain stable operational quality. Consequently, during wheeled grain harvester operation, speed adjustment must be flexible to accommodate different crop types, growth conditions, soil characteristics, and harvesting requirements (Gao et al., 2023; Dzhasau and Kalinouski, 2024). The variable frequency speed control method enables adaptive adjustment of harvester travel speed based on real-time operating conditions, thereby enhancing overall efficiency. Currently, variable frequency speed control has emerged as a key technology for advancing the intelligence of wheeled grain harvesters. By integrating sensors and control systems, harvesters can autonomously adjust speed according to factors such as crop yield distribution and terrain information, contributing to precision agriculture development (Wang et al., 2024). Thus, designing effective variable frequency speed control methods holds significant practical importance.

Zhao and Zhang (2024) proposed an automatic control method for variable frequency speed regulation based on CEEMDAN-wavelet threshold. The motor signal of the equipment was first collected and decomposed through CEEMDAN. Subsequently, wavelet thresholding was applied to eliminate high-frequency noise components from the signal. Finally, the variable frequency speed regulation was calculated, and a current-speed dual closed-loop PI controller was employed to regulate motor speed and load torque, achieving automatic control of variable frequency speed regulation. However, the effectiveness of wavelet threshold denoising depends on threshold selection and wavelet basis function matching. Inappropriate threshold selection or mismatched wavelet basis function may result in incomplete removal of high-frequency noise. Residual noise could intensify motor speed data fluctuations, increase the speed data coefficient of variation, and consequently affect control accuracy and system stability. Freitas et al. (2024) proposed a speed control method based on fuzzy predictive PID control. This method combines fuzzy PID control with a receding horizon controller through a single-loop strategy to design an integrated predictive controller, achieving DC speed regulation in dynamic environments while reducing the settling time. During operation in dynamic environments, the receding horizon controller requires prediction of future system states. However, the performance of such controllers depends on prediction accuracy, which is difficult to guarantee under complex and variable practical operating conditions. Significant deviations between predicted and actual states may cause the controller to make incorrect adjustments, potentially leading to increased speed overshoot and compromising both control accuracy and system stability. Chen et al. (2021) proposed a variable speed control strategy for harvesters based on the GA-SVR model. The strategy utilised loading pressure and speed signals collected from cutting, walking, chopping, and fan mechanisms as input variables, with stray and loss rates serving as output variables. A genetic algorithm-optimised support vector regression model was established to determine the optimal correlation between walking speed and harvester speed, achieving variable speed control. However, employing a single-loop control strategy makes it challenging to adequately account for the interactions and coupling effects in multivariable systems. This simplification prevents the model from accurately capturing system dynamics under complex operating conditions, resulting in elevated speed data variation coefficients that compromise both control precision and system stability.

During grain harvester operation, the load exhibits significant fluctuations due to variations in crop density, humidity, and terrain. These load variations cause motor speed instability, negatively impacting harvesting efficiency and crop quality. Conventional control methods struggle to adapt rapidly to these nonlinear and time-varying load changes, leading to unstable motor speed and increased coefficient of variation in speed data. Additionally, sensor-acquired motor speed and load signals often contain high-frequency noise, where inadequate denoising methods allow residual noise to exacerbate speed fluctuations and further raise the coefficient of variation. Furthermore, traditional control algorithms exhibit slow response in dynamic environments and are prone to overshoot, particularly during sudden load changes where delayed controller adjustments increase speed overshoot. To address these challenges, this study develops a variable-frequency speed control method for wheel grain harvesters based on fuzzy control theory. Fuzzy control theory eliminates the need for precise mathematical models and effectively handles nonlinear, time-varying, and uncertain systems, making it suitable for complex field conditions. By incorporating expert knowledge-based fuzzy rules, the fuzzy controller enables rapid response to load fluctuations, dynamically adjusting motor speed to maintain system stability. Moreover, fuzzy control demonstrates strong robustness against noise and disturbances, effectively reducing speed fluctuations and enhancing control accuracy. Its straightforward design and implementation reduce system complexity while improving harvester operational efficiency and reliability. The design concept of this method is as follows:

1 Mathematical model of variable frequency operation for wheeled grain harvester. A mathematical model for variable frequency operation of wheeled grain harvesters was established. By analysing the dynamic relationships among harvester components including the engine, transmission system, and harvesting system, transfer functions of the frequency converter, motor, and harvesting system were derived. These transfer functions incorporate physical parameters and system characteristics such as acceleration constant, motor torque, transmission shaft displacement, and harvesting efficiency, collectively forming the overall transfer function for harvester variable-frequency speed regulation. This model offers theoretical insights into equipment operation mechanisms and precise mathematical tools for developing subsequent variable-frequency speed control strategies, demonstrating an innovative integration of theory and practice in agricultural mechanisation.

2 Adaptive anti-interference design. Based on the mathematical model of variable frequency operation for wheeled grain harvesters, an adaptive disturbance rejection control mechanism was designed. This mechanism implements smooth transition tracking through a differentiator, expands the state observer for real-time disturbance estimation, and adjusts control inputs via nonlinear state error feedback. The approach effectively compensates for internal parameter variations and external disturbances, enhancing stability and accuracy in variable-frequency speed control while demonstrating the strategy's innovation and practical applicability.

3 Estimate the motor speed of the wheeled grain harvester. Online motor speed estimation for wheeled grain harvesters was implemented with construction of a motor rotor magnetic flux model based on voltage and current parameters. This model was incorporated into the adaptive law as an adjustable module to establish an adaptive estimation framework. Through processing motor operating parameters from both axes and generating real-time speed estimation outputs, the method delivers precise data support for variable-frequency speed control while demonstrating innovative and practical characteristics.

4 Variable frequency speed control. A variable-frequency speed controller for wheeled grain harvesters was developed based on fuzzy control theory. The system dynamically adjusts PID controller parameters through real-time motor speed estimation inputs, combined with feedforward compensation mechanisms and membership functions, effectively addressing nonlinear speed fluctuations. This approach enhances speed regulation stability and harvesting efficiency, demonstrating the innovative application of fuzzy control in complex agricultural machinery systems.

2 Variable frequency speed control method for wheeled grain harvester based on fuzzy control theory

2.1 *Mathematical model for variable frequency operation of wheel grain harvesters*

Establishing a mathematical model for variable-frequency operation of wheeled grain harvesters aims to quantitatively characterise dynamic relationships among the engine, transmission system, and harvesting system, providing theoretical foundations for developing efficient control strategies. Through derivation of transfer functions for the frequency converter, motor, and harvesting system, acceleration characteristics, torque-speed relationships, and harvesting efficiency correlations with engine speed were characterised, culminating in a comprehensive transfer function model. This model exhibits systematic and integrated advantages by accurately reflecting cooperative operational characteristics of all harvester components, thereby establishing theoretical foundations for control strategy optimisation. Mathematical modelling further transforms complex multi-link systems into quantifiable representations, offering efficient analytical tools for subsequent variable-frequency speed control research while contributing to enhanced harvester operational efficiency and stability.

Wheeled grain harvester operation requires coordinated functioning of the engine, transmission system, and harvesting system components (Bedeker et al., 2023). When establishing a mathematical model for harvester variable-frequency operation with time as the independent variable, the initial step involves deriving transfer functions for each operational component:

1 The transfer function of the frequency converter is as follows:

$$F_1 = \frac{\sigma_s}{0.1ts + 1} \tag{1}$$

In equation (1), σ represents the acceleration constant; s represents the working parameters after Laplace transform; t represents acceleration time.

2 The motor transfer function is derived by combining the motor output torque with the transmission shaft torsional displacement of the wheeled grain harvester, constructing the motor torque equation, and performing Laplace transformation:

$$F_2 = \frac{1}{Js^2 + Vs + HL\cos\theta} \tag{2}$$

In equation (2), J represents the output torque of the motor; V represents the viscous friction coefficient; H represents the elasticity coefficient; θ represents the torsion angle of the transmission shaft; L represents the displacement of the transmission shaft (Liu et al., 2023).

3 The harvesting system transfer function for wheeled grain harvesters describes the relationship between harvesting efficiency (grain flow rate) and engine speed. With first-order linear system characteristics assumed and harvesting efficiency considered as a function of motor speed, the harvesting system transfer function is expressed as:

$$F_3 = \frac{K}{tw} \tag{3}$$

In equation (3), K represents the gain of the harvesting system (the degree to which the harvesting system amplifies the input), and w represents the complex frequency variable.

Equations (1) through (3) establish the mathematical model for variable-frequency operation of wheeled grain harvesters:

$$\psi(t) = F_1 + F_2 + F_3 \tag{4}$$

In equation (4), $\psi(t)$ represents the total transfer function of the variable frequency speed regulation operation of the wheel grain harvester. The operating principle of the equipment is mathematically modelled to establish the foundation for subsequent variable-frequency speed control.

2.2 *Adaptive anti-interference design*

Following the construction of a mathematical model for variable-frequency operation of wheeled grain harvesters, this study incorporates an adaptive disturbance rejection control mechanism to address internal parameter variations and external disturbances, enabling effective variable-frequency speed control. The adaptive disturbance rejection control mechanism structure and design are presented as:

Step 1 Track differentiator processing.

The tracking differentiator design is determined by the harvester motor's dynamic characteristics, particularly response speed and stability (Kamilla et al., 2022; Zaman et al., 2021). Motor parameters (inductance, resistance) are used to adjust the tracking differentiator's speed factor and nonlinear factor, generating smoother position and velocity transitions while reducing control process overshoot and oscillation. The tracking differentiator processing procedure is presented as:

$$g_h = r \times \frac{\theta_n - \theta_{ref}}{\alpha \times j} \tag{5}$$

In equation (5), g_h represents the output of the tracking differentiator; h represents the integration step size; r represents the speed of the motor; α represents the nonlinear coefficient; j represents the filtering factor; θ_{ref} represents the reference input angle; θ_n represents the initial input angle.

Step 2 Expand the state observer for observation and analysis.

The extended state observer analyses feedback position and internal state information of harvester motors to estimate real-time operating conditions and system disturbances (Xiang et al., 2024). The extended state observer outputs are presented as:

$$s_k = \frac{\beta \times \left(\theta_k^* - \theta_k\right)}{\tau + 1} \tag{6}$$

In equation (6), s_k represents the k^{th} operation cycle of the extended state observer; θ_k represents the actual motor angle feedback value; θ_k^* represents the observed value of disturbance; β represents the observer coefficient; τ represents the feedback coefficient.

Step 3 Nonlinear state error feedback adjustment.

Error analysis is performed on outputs from steps 1 and 2, with identified harvester motor parameters used to adjust error function gain and nonlinear factors for precise control input calculation. The feedback adjustment results are presented as:

$$z_k = \frac{\alpha \times E\left(s_k + g_h\right) \times (w+1)}{k} \tag{7}$$

In equation (7), $E(\cdot)$ represents the error function; w represents the gain amount.

The control process begins with receiving reference inputs, proceeds through tracking differentiator processing, extended state observer monitoring, and nonlinear state error feedback adjustment, then outputs control commands to the frequency converter to maintain stability in the wheel grain harvester's variable frequency speed regulation process.

2.3 *Estimate the motor speed of the wheeled grain harvester*

Estimate the motor speed of the wheel grain harvester in a stable control environment.

Motor speed is the key factor affecting harvester operating speed, making variable frequency speed control essentially a continuous adjustment of motor speed (Mirzazadeh et al., 2022). Consequently, online motor speed estimation serves as an important foundation for variable frequency speed control.

In the process of speed estimation, this study first focuses on the motor rotor magnetic flux and constructs a voltage model as follows:

$$\begin{cases} \chi_{Au} = \dfrac{\varepsilon'}{\varepsilon}\left(\int (U_A - RI_A) - \varepsilon^* I_A\right) \\ \chi_{Bu} = \dfrac{\varepsilon'}{\varepsilon}\left(\int (U_B - RI_B) - \varepsilon^* I_B\right) \end{cases} \tag{8}$$

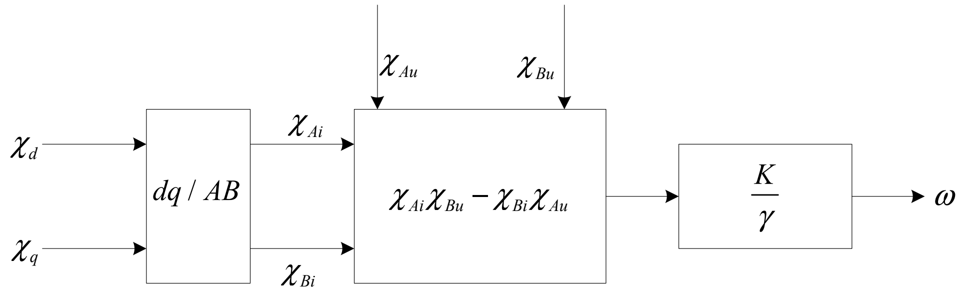
In equation (8), χ represents the calculated value of rotor magnetic flux; A and B represent two phases; u represents the rotor magnetic flux voltage model; ε represents the mutual inductance between the stator and rotor, and ε' represents the self-inductance of the stator; ε^* represents rotor self-inductance, U represents stator voltage, R represents stator resistance, and I represents stator current.

Similarly, the mathematical model of rotor magnetic flux current can be expressed in the following form:

$$\begin{cases} \chi_{Ai} = \dfrac{1}{1+\partial}\left(\varepsilon I_A - \chi_{Bi}\varphi\right) \\ \chi_{Bi} = \dfrac{1}{1+\partial}\left(\varepsilon I_B - \chi_{Ai}\varphi\right) \end{cases} \tag{9}$$

In equation (9), i represents the rotor magnetic flux current model; ∂ represents the differential factor; φ represents the stator speed (Liu and Zhang, 2024).

Figure 1 Principle structure diagram of adaptive estimation model



The two models presented in equations (8) and (9) serve as adjustable models. Adaptive laws are incorporated to establish the adaptive estimation model as follows:

$$\omega = \frac{K}{\gamma}\left(\chi_{Ai}\chi_{Bu} - \chi_{Bi}\chi_{Au}\right) \tag{10}$$

In equation (10), ω represents the estimated motor speed of the wheel grain harvester; K represents an adjustable coefficient; γ represents the adaptive coefficient (Du and Feng, 2022).

The principle structure of the adaptive estimation model is shown in Figure 1.

In Figure 1, d and q represent two axes, θ represents the orientation angle. Inputting the motor's two-axis operating parameters and performing adaptive estimation operations yields the motor speed estimation result.

2.4 Variable frequency speed control

Using the estimated motor speed of the wheeled grain harvester, fuzzy control theory is applied to achieve variable frequency speed control of the harvester motor.

A controller is designed for wheeled grain harvester variable frequency speed control using fuzzy control theory. Considering load change requirements, engine speed fluctuations, and harvesting efficiency demands, the controller regulates the frequency converter's output frequency to achieve adaptive control in the harvester's variable frequency speed regulation system, maintaining stable speed and ensuring harvesting efficiency.

The specific control process is as follows:

Step 1 In the stable control environment established in Section 1.2, use the estimated motor speed result ω as the input to the controller. The input quantity *Inp* of the controller is as follows:

$$Inp = \eta(\mu\omega) \tag{11}$$

In equation (11), η represents the quantisation factor; μ represents the weight coefficient.

Step 2 In the wheeled grain harvester's variable frequency speed control process, harvester motor dynamic operation causes instantaneous speed fluctuations with peak and valley values (Yi et al., 2022; Shi et al., 2024). This nonlinear variation presents significant challenges for traditional PID control algorithms. When establishing fuzzy control rules, comprehensive and accurate coverage of all potential speed changes proves difficult due to multiple interacting nonlinear factors. During frequent harvester operating condition changes, the PID controller often fails to maintain speed stability and harvesting efficiency effectively because of inadequate adaptive adjustment response speed.

In response to the above issues, this study introduces a feedforward compensation mechanism. This mechanism takes the difference between the estimated motor speed ω of the harvester and the set ideal speed value ω^* as the compensation value. Assuming the time series is $\{t_1, t_2, \cdots, t_Q\}$, the compensation value is:

$$e = t_Q\left(\omega - \omega^*\right) \tag{12}$$

Step 3 Set the quantised domain of the input variable *Inp* within the range of $[-V, V]$, and define the fuzzy set of the input variable based on the relationship between *Inp* and $\omega + e$. If $Inp < \omega + e$, it is a negative fuzzy set. If $Inp \geq \omega + e$, it is a positive fuzzy set. Based on this, a membership function is constructed, and the results are as follows:

1 For negative fuzzy sets, their membership functions are as follows:

$$f^-(Inp) = \begin{cases} \dfrac{Inp+V}{2m}, & \text{if: } -V \leq Inp < -m \\ 1, & \text{if: } -m \leq Inp < 0 \\ \dfrac{Inp}{2m}, & \text{if: } 0 \leq Inp < m \\ 0, & \text{if: } Inp \geq m \end{cases} \tag{13}$$

2 For a positive fuzzy set, its membership function is as follows:

$$f^+(Inp) = \begin{cases} 0, & \text{if: } Inp \le -m \\ \dfrac{Inp}{2m}, & \text{if}: -m < Inp \le 0 \\ 1, & \text{if}: 0 < Inp \le V \\ \dfrac{Inp}{2m}, & \text{if: } m < Inp \le V \\ 0, & \text{if}: Inp > V \end{cases} \tag{14}$$

In the equation, *m* represents a parameter between 0 and *V*, which is used to define the width of the transition zone of the membership function.

Step 4 Input the compensation value *e* obtained from equation (12) into the PID controller as a feedforward signal. By comparing *Inp* with $\omega + e$, use the membership function to adjust the control parameters in advance, so as to achieve effective compensation for control fluctuations (Zhao et al., 2024; Ge et al., 2024). The parameters of the PID controller are as follows:

$$\begin{cases} Y_P = \dfrac{\sum_{i=1}^{n}(Y_{Pi} \times f)}{n} \\ Y_I = \dfrac{\sum_{i=1}^{n}(Y_{Ii} \times f)}{n} \\ Y_D = \dfrac{\sum_{i=1}^{n}(Y_{Di} \times f)}{n} \end{cases} \tag{15}$$

In equation (15), *n* represents the number of fuzzy set elements; *f* represents the membership function, and the idea of this function participating in fuzzy rules is as follows:

1 For Y_P: When the input quantity belongs to a negative fuzzy set with high membership degree, the parameter value should be increased. Conversely, when the input quantity falls into a positive fuzzy set with high membership degree, the parameter value should also be increased. However, when the input quantity approaches zero, the parameter value must be reduced to prevent over-adjustment.

2 For Y_I: When the input quantity maintains a negative or positive state for an extended duration, increasing this parameter eliminates steady-state errors. Conversely, when the input approaches zero with system stability, reducing this parameter prevents integral saturation.

3 For Y_D: When the input quantity's rate of change is significant (indicating rapid deviation variation), increasing this parameter enables advance prediction and overshoot suppression. Conversely, when the rate of change is minimal, reducing the parameter decreases noise sensitivity.

Step 5 Based on the adjusted control parameters, obtain the final variable frequency speed control result *Outp* of the wheel grain harvester as follows:

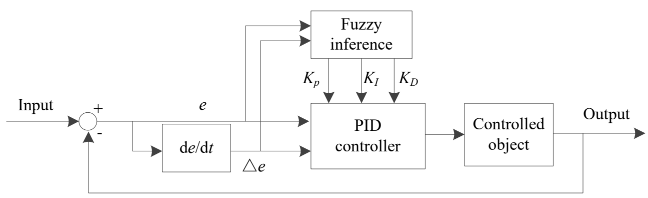
$$Outp = \omega_{PID} + (\omega + e) \times \delta \tag{16}$$

In equation (16), ω_{PID} represents the output value of the PID controller; δ represents the feedforward compensation gain coefficient, used to adjust the size of the feedforward compensation signal.

The structure of the variable frequency speed controller is shown in Figure 2.

Fuzzy controllers achieve dynamic responses to complex working conditions without requiring precise mathematical models by converting expert experience into fuzzy rules. Compared with traditional PI controllers, fuzzy controllers demonstrate faster response speeds and stronger robustness during severe load fluctuations, enabling rapid motor speed adjustment while reducing overshoot and steady-state errors. Additionally, fuzzy control exhibits strong tolerance for noise and interference, further enhancing system stability. This innovative design allows wheeled grain harvesters to maintain efficient and stable operation in complex and variable field conditions, providing reliable technical support for agricultural mechanisation.

Figure 2 Structure diagram of variable frequency speed controller



3 Experiment and results analysis

3.1 Experimental design

To validate the feasibility of implementing variable frequency speed control in wheeled grain harvesters using fuzzy control theory, a dedicated experiment was designed.

The wheeled grain harvester used in the experiment is shown in Figure 3.

The experimental equipment consists of a 9 kg/s (feeding capacity) self-propelled fully-fed grain combine harvester, model Weichai Lovol Gushen 4LZ-9E2 (G4), with relevant parameters detailed in Table 1.

Table 1 Relevant parameters of the harvester

Project	*Value/description*	*Project*	*Value/description*
The overall dimensions of the machine	6,800 × 3,020 × 3,440 mm	Feeding amount	9 kg/s
Quality of the whole machine	6,040 kg	Hourly productivity	7,000~14,000 m^2/h
Width of cutting table work	2,750 mm	Fuel consumption	0.0035kg/m^2
Minimum ground clearance	300 mm	The size of the main threshing drum	550 × 1,805 mm
Cutting blade type	II	Dimensions of the secondary threshing drum	500 × 900 mm

Figure 3 Physical picture of wheeled grain harvester (see online version for colours)

The harvester's accompanying motor model is WP4.6NG190E470A, with corresponding parameters listed in Table 2.

Install a fuzzy controller, frequency converter and sensor on the harvester's accompanying motor. Through system debugging, ensure the fuzzy control algorithm properly receives sensor data and outputs control signals.

To ensure experimental result reliability, the method in Zhao and Zhang (2024) and the method in Freitas et al. (2024) were compared and validated concurrently with the proposed method.

Table 2 Relevant parameters of the harvester matching motor

Project	*Value/description*
Structural type of supporting engine	Four stroke, inline, water spray, direct spray
The number of cylinders for the matching engine	4
Calibration power of matching engine	140 kW
Calibration speed of the matching engine	2,200 r/min

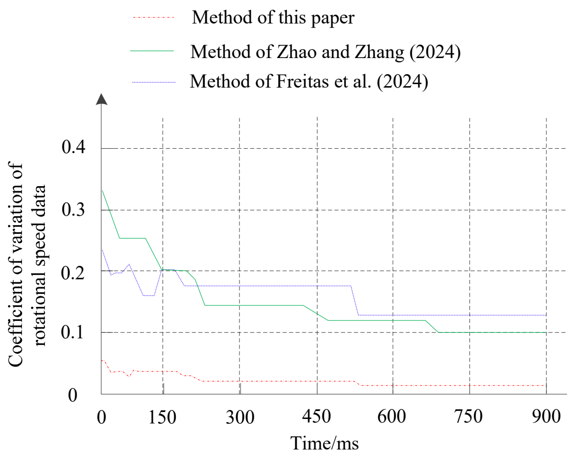
3.2 Result analysis

Motor speed data was collected over a 1-minute cycle, with control effectiveness evaluated based on the speed data's coefficient of variation. A smaller coefficient indicates higher speed stability and better control performance. Figure 4 presents the coefficient of variation results obtained using different methods.

Figure 4 demonstrates a decreasing trend in rotational speed coefficient of variation with increasing experimental time. The method from Zhao and Zhang (2024) reduced the coefficient from 0.33 to 0.10, while Freitas et al.'s (2024) method decreased it from 0.24 to 0.13. The proposed method showed the most significant improvement, reducing the coefficient from 0.06 to 0.02. These results numerically verify that the proposed method maintains the coefficient at substantially lower values, demonstrating superior rotational speed stability control in the wheel grain harvester.

Under identical experimental conditions, different methods were evaluated using motor speed overshoot as the performance metric. This metric represents the ratio between the maximum deviation exceeding steady-state value and the steady-state value during control response, indicating method stability and accuracy. Lower overshoot values correspond to better control performance. Table 3 displays the overshoot measurement results for different methods.

Figure 4 The coefficient of variation of speed data after applying different methods



In Table 3, condition 1 represents speed regulation under constant load while condition 2 shows speed regulation under variable load. The numerical results in Table 3 indicate that under condition 1, the overshoot of the proposed method remains relatively stable with minor fluctuations, ranging from 1.11% to 2.66%. Under condition 2, although the overshoot of the proposed method increases slightly, it maintains a relatively low level overall, reaching a maximum of only 2.97%, which demonstrates good control stability. While the two comparison methods exhibit certain control effects, their overshoot variations are more significant. Comparatively, the proposed method achieves better variable frequency speed control performance.

Table 3 Comparative analysis of overshoot of rotational speed (unit:%)

	Working condition	*Number of experiments*				
		1	*2*	*3*	*4*	*5*
Method of this paper	Working condition 1	1.24	2.66	1.11	2.46	1.31
	Working condition 2	1.88	2.97	0.90	2.08	1.67
Method of reference [5]	Working condition 1	2.44	3.22	2.57	3.35	2.46
	Working condition 2	3.22	3.75	3.33	2.79	2.99
Method of reference [6]	Working condition 1	2.75	4.54	2.88	3.46	2.63
	Working condition 2	4.11	6.22	4.99	5.32	4.45

Table 4 Steady state error results (unit: rpm)

	Working condition	*Number of experiments*				
		1	*2*	*3*	*4*	*5*
Method of this paper	Working condition 1	0.12	0.10	0.11	0.13	0.14
	Working condition 2	0.25	0.23	0.24	0.26	0.27
Method of reference [5]	Working condition 1	2.56	2.58	2.60	2.57	2.59
	Working condition 2	3.20	3.22	3.25	3.19	3.21
Method of reference [6]	Working condition 1	3.78	3.80	3.79	3.81	3.77
	Working condition 2	5.50	5.52	5.49	5.53	51.51

Steady-state error directly reflects the accuracy and performance of wheeled grain harvesters under variable frequency speed control. Testing evaluates whether the control system can accurately achieve target speed under different operating conditions, ensuring harvester stability and efficiency during field operations. Excessive steady-state error may reduce harvesting efficiency or cause equipment damage, while optimised control strategies to minimise steady-state error can enhance system response speed and robustness. Therefore, steady-state error testing is crucial for verifying control method effectiveness and optimising design. Table 4 presents the steady-state error comparison results of the three methods.

Table 4 shows the steady-state error data, indicating significant advantages of the proposed method under both operating conditions. Under constant load condition 1, the steady-state error range of the proposed method is 0.10–0.14 rpm, compared to 2.56–2.60 rpm for Zhao and Zhang (2024) and 3.77–3.81 rpm for Freitas et al. (2024). The error of the proposed method is approximately 1/20 that of comparative methods. Under variable load condition 2, the steady-state error range of the proposed method is 0.23–0.27 rpm, compared to 3.19–3.25 rpm for Zhao and Zhang (2024) and 5.49–5.53 rpm for Freitas et al. (2024). The error of the proposed method is approximately 1/15 that of comparative methods. These results demonstrate that the proposed method maintains high control accuracy under load fluctuations, significantly outperforming traditional methods. Furthermore, the error variation range of the proposed method remains minimal under both conditions (0.04 rpm), exhibiting superior stability and robustness, while comparative methods show larger variations (0.04 rpm and 0.06 rpm), further confirming the method's advantages in complex operating conditions.

Based on the above experimental results, the following discussion is made:

Figure 4 demonstrates significant improvement in speed stability control through the coefficient of variation analysis. The proposed method achieves a reduction in coefficient of variation from 0.06 to 0.02, substantially lower than the reference values of 0.10 (Zhao and Zhang, 2024) and 0.13 (Freitas et al., 2024). These results indicate superior capability in suppressing speed fluctuations and ensuring stable operation of wheel grain harvesters. The minimised coefficient of variation further confirms the method's high accuracy and robust dynamic adjustment performance.

Table 3 demonstrates superior control performance of the proposed method in both operating conditions based on speed overshoot analysis. Under constant load condition 1, the overshoot range measures 1.11%–2.66%, while under variable load condition 2, it maintains 0.90%–2.97%. These values contrast significantly with Zhao and Zhang (2024) and Freitas et al. (2024), particularly under variable load conditions where Freitas et al. (2024) exhibits overshoot up to 6.22%. The consistently low overshoot confirms the method's ability to maintain high stability and accuracy in complex operating environments.

Table 4 demonstrates superior steady-state error performance of the proposed method compared to reference methods under both operating conditions. Under constant load condition 1, the steady-state error range measures 0.10–0.14 rpm, representing approximately 1/20 of the values reported in Zhao and Zhang (2024) and Freitas et al. (2024). Under variable load condition 2, the steady-state error range of the proposed method maintains 0.23–0.27 rpm, equivalent to about 1/15 of comparative method values. The minimal error fluctuation range

(0.04 rpm) further confirms the method's high accuracy and robust performance during load variations.

4 Conclusions

This study explores a fuzzy control theory-based variable frequency speed control method for wheeled grain harvesters to improve their adaptability and operational efficiency in complex operating conditions. A mathematical model for harvester variable frequency operation was constructed with an adaptive disturbance rejection control mechanism to achieve precise motor speed estimation and effective control.

Experimental results demonstrate that the proposed method significantly reduces motor speed variation coefficient and overshoot compared to traditional methods, exhibiting superior stability and accuracy. These research findings provide novel approaches for intelligent control of wheeled grain harvesters and substantial support for upgrading modern agricultural equipment.

Acknowledgements

This work was supported by The Scientific Research Project of Jilin Provincial Department of Education 'Research on Monitoring and Warning Technology of Crop Diseases and Insect Pests' under grant no. JJKH20251231KJ .

Declarations

All authors declare that they have no conflicts of interest.

References

Bedeker, A.A., Zakharov, A.V. and Kashchenkov, A.V. (2023) 'Analysis of stator-winding circuits of electric-propulsion frequency-controlled motors', *Russian Electrical Engineering*, Vol. 94, No. 7, pp.449–454.

Chen, Y.L., Zhang, Y., Wang, X. and Sun, Y.J. (2021) 'A variable speed control strategy for impurity removal fan of sugarcane combine harvester based on GA-SVR model', *Sugar Tech*., Vol. 23, No. 5, pp.1–11.

Du, R.T. and Feng, Z.H. (2022) 'Design of variable frequency speed regulation control system for pillow packaging machine', *Packaging Engineering*, Vol. 43, No. 21, pp.260–265.

Dzhasau, D.V. and Kalinouski, A.A. (2024) 'The 1D simulation of the mechanism for steering in a transverse plane of the grain harvester adapter', *Tractors and Agricultural Machinery*, Vol. 91, No. 2, pp.207–215.

Freitas, J.B.S., Marquezan, L., Oliveira, E.P.J.D., Peñaloza, E.A.G. and Cely, M.M.H. (2024) 'A fuzzy-based Predictive PID for DC motor speed control', *International Journal of Dynamics and Control*, Vol. 12, No. 7, pp.2511–2521.

Gao, J.J., Liu, Z.Y., Gu, W., Zhang, F.F., Zhu, L.P. and Xu, J.X. (2023) 'Modal analysis and optimization of grain combine harvester undercarriage frame', *Machine Design And Research*, Vol. 39, No. 3, pp.199–205.

Ge, H.Y., Wang, T., Yang, M.Z. and Zhang, C.W. (2024) 'Research on variable universe adaptive fuzzy PID Vibration control system of mechanical meta-action unit driven by reliability', *Machinery Design & Manufacture*, Vol. 2024, No. 8, pp.191–196+201.

Jia, C.P. (2023) 'Research on efficiency optimization of crop harvester for intelligent manufacturing', *Journal of Agricultural Mechanization Research*, Vol. 45, No. 10, pp.126–129.

Kamilla, H.M., Heber, P.G., Juan, M.M.V. and Saulo, T.M.B. (2022) 'Performance of oversized pumps controlled by variable frequency drives in water supply systems', *Journal of Urban and Environmental Engineering*, Vol. 16, No. 2, pp.186–192.

Liu, J.G., Liu, W.Z., Wang, Y.Y., Zhang, G.L. and Chen, L.F. (2023) 'Research on high-frequency isolation type of dual-PWM variable frequency speed regulation', *Journal of Electrical Engineering & Technology*, Vol. 18, No. 4, pp.2929–2941.

Liu, S.Y. and Zhang, A.L. (2024) 'Solution on strong disturbance problem of variable frequency drive hydraulic control for rice and wheat combine harvester', *Hydraulics Pneumatics & Seals*, Vol. 44, No. 4, pp.87–92.

Mirzazadeh, A., Abdollahpour, S. and Hakimzadeh, M. (2022) 'Optimized mathematical model of a grain cleaning system functioning in a combine harvester using response surface methodology', *Acta Technologica Agriculturae*, Vol. 25, No. 1, pp.20–26.

Shi, Q.Y., Yang, F.B. and Zhang, J.H. (2024) 'Research on grey prediction fuzzy PID control of double cylinder hydraulic drive system', *Chinese Journal of Construction Machinery*, Vol. 22, No. 5, pp.572–576+587.

Wang, C.Z., Chen, M., Jin, C.Q., Mo, G.W., Zhang, G.Y. and Feng, Y.G. (2024) 'Design and experiment of digital test identification system for rice harvester field performance', *Journal of Agricultural Mechanization Research*, Vol. 46, No. 7, pp.170–177.

Xiang, B., Wen, T. and Wen, T. (2024) 'The speed control of PMLSM with discontinuous driving coils based on multi-loop DOB model', *ISA Transactions*, Vol. 146, No. 13, pp.366–379.

Yi, S., Lu, Z.G., Yuan, K.N., Wu, G.P. and Huang, S.D. (2022) 'The stability control of induction motor variable frequency speed regulation system injected with virtual reactance under low frequency and light load condition', *Transactions of China Electrotechnical Society*, Vol. 37, No. 8, pp.1959–1971.

Zaman, S.M.K., Liang, X.D. and Li, W.X. (2021) 'Fault diagnosis for variable frequency drive-fed induction motors using wavelet packet decomposition and greedy-gradient max-cut learning', *IEEE Access*, Vol. 9, No. 4, pp.65490–65502.

Zhao, D.D. and Zhang, X.D. (2024) 'Automatic control method of AC asynchronous motor variable frequency speed control based on CEEMDAN-wavelet threshold', *International Journal of Modelling, Identification and Control*, Vol. 45, Nos. 2–3, pp.100–109.

Zhao, X., Peng, Z.J., Liu, Y.B., Guo, Y.J. and Shi, Y.L. (2024) 'An improved fuzzy adaptive PID control algorithm based on quantization factor', *Ordnance Industry Automation*, Vol. 43, No. 6, pp.27–30+48.