



Article

Miss-Seeding Detection and Self-Compensation System for Air-Suction Soybean Seed-Metering Device Based on Suction-Hole Seed-Carrying State Recognition

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Abstract

In this study, a miss-seeding detection and self-compensation system based on suction-hole seed-carrying state recognition was developed to address miss-seeding and reduced seed-spacing uniformity caused by missed pickup at suction holes in air-suction soybean seed-metering devices. A through-beam photoelectric sensor was installed between the seed-cleaning and seed-discharge zones to detect the seed-carrying state of each suction hole in real time. With a programmable logic controller (PLC) as the control unit and an encoder for seed-metering disc speed acquisition, the system performed missed-pickup identification, compensation pulse output, and operating-state monitoring. When a suction hole without a seed was detected, the control system triggered a short-term acceleration of the seed-metering disc, enabling the subsequent normally loaded suction hole to enter the seed-discharge zone in advance. In this manner, miss-seeding compensation was achieved without adding an independent supplementary seeding channel. Bench tests were conducted at different operating speeds, and the integrated system performance was evaluated under the optimized parameter combination of the auxiliary seed-delivery mechanism. The results show that the missed-pickup detection accuracy and compensation success rate ranged from 96.49% to 100.00% and from 94.55% to 100.00% over the operating speed range of 6–12 km/h, respectively. With the proposed system, the qualified seed-spacing rate increased from 92.4% to 96.0%, the miss-seeding rate decreased from 6.4% to 3.0%, and the multiple-seeding rate decreased from 1.2% to 1.0%. These results indicate that the proposed system can identify missed seed pickup before seed discharge and achieve self-compensation through short-term acceleration of the seed-metering disc, thereby improving seeding continuity and seed-spacing uniformity.

Keywords: air-suction seed-metering device; soybean; suction-hole seed-carrying state; missed-pickup detection; miss-seeding compensation



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1. Introduction

Soybean is an important grain and oil crop in China, providing a major source of plant protein and raw materials for edible oil and adjusting the agricultural planting structure. Improving the quality of mechanized soybean seeding is essential for stable yield formation and improvement [1–3]. Seeding is the first operation in mechanized soybean production. Seed distribution within a row directly affects plant spacing consistency and seedling emergence quality. Precision seeding requires the metering device to achieve stable and

continuous single-grain seeding according to the set plant spacing as the core component that affects seeding accuracy and quality [4,5]. The air-suction seed-metering device relies on negative-pressure airflow to complete seed pickup and carrying. It has the advantages of low seed damage, good seed pickup stability, and high operating speed and is widely used in soybean precision seeding equipment [6,7]. However, during actual operation, seed size variations, negative-pressure fluctuations, and seed-metering disc speed changes may cause missed seed pickup at individual suction holes. When a suction hole without a seed enters the seed-discharge zone, no seed is discharged, resulting in a seed-spacing gap and, eventually, miss-seeding [8–12]. Existing methods for miss-seeding detection and compensation are mostly based on the seed state after discharge. However, these methods usually detect seeds downstream of the seed-discharge process, leading to delayed abnormal-state identification, limited compensation response time, and compensation accuracy strongly affected by operating speed [13,14]. Therefore, research on suction-hole seed-carrying state recognition, missed-pickup detection, and compensation control for air-suction soybean seed-metering devices can provide technical support for improving the uniformity and operational stability of soybean precision seeding.

Problems such as miss-seeding and insufficient seed-spacing uniformity still occur during the operation of air-suction seed-metering devices. Previous studies have investigated seeding-state detection, miss-seeding identification, and compensation control. For seeding-state detection, sensors are commonly installed in seed guide tubes, seed-metering tubes, or seed-discharge channels, and seed-passing states are identified using photoelectric occlusion, capacitance variation, impact response, or image features. These methods can be used for seed counting, miss-seeding identification, multiple-seeding judgement, and abnormal operation alarms [15,16]. Among them, capacitive detection is sensitive to changes in dielectric properties caused by seed passage and is suitable for continuous monitoring of seed number and flow. Photoelectric and laser detection methods have relatively simple structures and fast response speeds and are often used to identify seed movement in seed guide tubes, seed-metering outlets, or seed-discharge zones. Piezoelectric detection can reflect changes in the seeding process through seed-impact signals and provide a reference for monitoring the seeding quality of small seeds [17–20]. For miss-seeding compensation, existing methods mainly include auxiliary compensation and self-compensation [21]. Auxiliary compensation usually completes supplementary seeding by adding a supplementary seed-metering device, supplementary seeding channel, or actuator after miss-seeding is detected. This method has been applied to no-tillage seeders and seed-metering devices for rapeseed, potato, garlic, and other crops. Although auxiliary compensation has a clear supplementary seeding target, it increases structural complexity and requires accurate timing coordination between the main seed-metering device and the supplementary seeding mechanism. In contrast, self-compensation adjusts the motion state of the original seeding components so that the subsequent normally loaded unit completes seed discharge in advance, thereby reducing seed-spacing gaps caused by miss-seeding [22–26]. Zhao et al. [27] implemented variable-speed supplementary seeding by changing the rotational speed of a corn spoon-type seed-metering device. Wang et al. [28,29] proposed catch-up compensation and one-way clutch compensation methods for potato seeding without an independent supplementary seeding channel. Zagainov et al. [30] used changes in the rotational speed of seeding components to suppress miss-seeding in single-seed precision metering. These studies provide useful references for miss-seeding compensation without adding an independent supplementary seeding channel. However, most existing methods still detect seed-passing states after seed discharge or seed motion states in the seeding channel. Therefore, the detection position is relatively late, and the compensation response time is strongly affected by operating speed [31,32]. For air-suction soybean

seed-metering devices, miss-seeding mainly results from missed pickup at the suction holes. If the seed-carrying state of each suction hole can be identified after seed cleaning and before seed discharge, the missed-pickup signal can trigger short-term acceleration of the seed-metering disc, allowing the subsequent normally loaded suction hole to enter the seed-discharge zone in advance [33,34]. This strategy enables self-compensation without an independent supplementary seeding channel and improves both the timeliness of missed-pickup identification and the responsiveness of compensation control.

This study developed a missed-pickup detection and self-compensation system based on suction-hole seed-carrying state recognition to address the problems of delayed missed-pickup identification and limited compensation response time in air-suction soybean seed-metering devices. A photoelectric sensor was arranged after the seed-cleaning area and before the seed-discharge zone to detect the seed-carrying state of each suction hole in real time. With a PLC as the control core and an encoder for seed-metering disc speed acquisition, the system realized missed-pickup judgement, compensation pulse output, and operating-state monitoring. When a suction hole without a seed was detected, the control system triggered short-term acceleration of the seed-metering disc according to the missed-pickup signal, enabling the subsequent normally loaded suction hole to enter the seed-discharge zone in advance and compensate for the seed-spacing gap caused by missed pickup without adding an independent supplementary seeding channel.

2. Materials and Methods

2.1. Overall Scheme of the Miss-Seeding Detection and Compensation System

2.1.1. Structural Composition

The structure of the missed-pickup detection and compensation system for the air-suction soybean seed-metering device based on suction-hole seed-carrying state recognition is shown in Figure 1. It mainly consists of an air-suction seed-metering device, a suction-hole seed-carrying state detection module, a compensation execution module, a control system, and an auxiliary seed-delivery unit. The air-suction seed-metering device is the core component for seed pickup and discharge, comprising a seed box, seed-metering disc, suction holes, negative-pressure air chamber, seed-cleaning mechanism, seed-metering device shell, and transmission shaft [35,36]. The suction holes are evenly distributed along the circumferential direction of the seed-metering disc. The suction-hole seed-carrying state detection module identifies whether each suction hole carries a seed, and the compensation execution module completes compensation seeding after a missed-pickup signal is detected. The control system used a ZGM-30T4-7 programmable logic controller (PLC; Xinje Electric Co., Ltd., Wuxi, China) as the control unit to acquire detection signals, determine the missed-pickup state, and output compensation control commands.

When the seed-metering disc operates, soybean seeds are adsorbed and carried via negative-pressure airflow. The seed-cleaning mechanism is arranged in the seed-cleaning area to remove excess seeds around the suction hole, allowing each suction hole to maintain a relatively stable single-seed-carrying state. The suction-hole seed-carrying state detection module is arranged after the seed-cleaning area and before the seed-discharge zone. When a suction hole passes through the detection position, the photoelectric sensor identifies its seed-carrying state. If an effective seed-carrying signal is detected, the suction hole is judged to be normally loaded. If no effective seed-carrying signal is detected, missed pickup is determined and the missed-pickup signal is transmitted to the control system.

The auxiliary seed-delivery mechanism is arranged below the seed outlet of the seed-metering device. It receives seeds discharged during both normal seeding and compensation, guides their terminal motion, and reduces the effects of free fall, collision, and lateral offset on seed-spacing uniformity. The mechanism comprises a reversing wheel, a

seed-delivery belt, finger paddles, pulleys, and a seed guide plate. In this study, it serves as the terminal guidance unit for both normally discharged and compensated seeds. Since this study focuses on suction-hole seed-carrying state recognition, missed-pickup signal judgement, and short-term acceleration compensation control of the seed-metering disc, the structural optimization process of the auxiliary seed-delivery mechanism is not further discussed. Instead, the previously optimized parameters are used as the basis for the comprehensive system performance test.

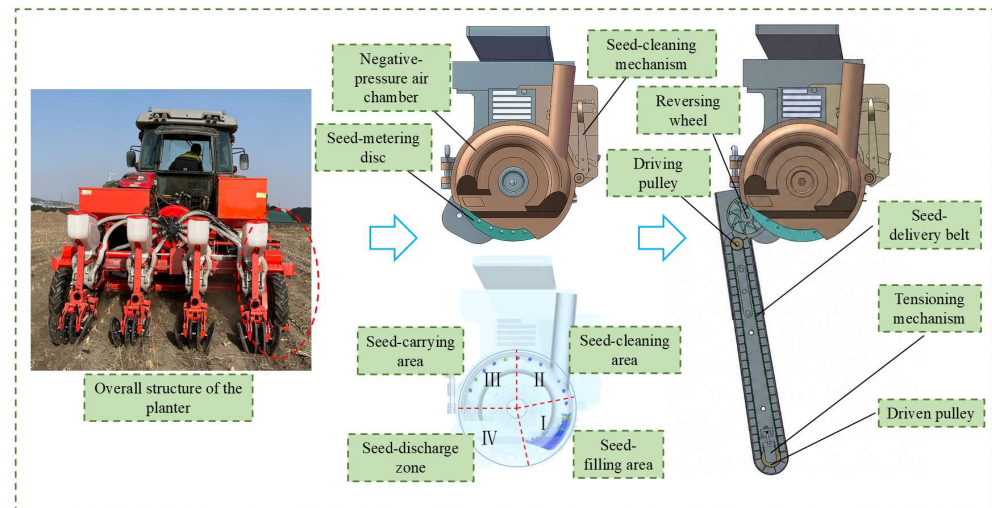


Figure 1. Structural diagram of the miss-seeding detection and compensation system for the air-suction soybean seed-metering device. The red dashed rectangle indicates the location of the seed-metering device on the planter. The red dashed circular outline and radial lines delimit the seed-filling, seed-cleaning, seed-carrying, and seed-discharge zones. The blue arrows indicate the progressive enlargement and structural relationship from the overall planter to the seed-metering device and auxiliary seed-delivery mechanism.

2.1.2. Working Principle

During operation, the transmission system drives the seed-metering disc to rotate continuously at the preset speed, and soybean seeds in the seed box enter the seed-filling area under the combined action of seed mass pressure and negative-pressure airflow. When a suction hole moves into the negative-pressure chamber region, a seed is adsorbed onto the suction hole and rotates with the seed-metering disc. Subsequently, excess seeds around the suction hole are removed by the seed-cleaning mechanism, allowing each suction hole to maintain a relatively stable single-seed-carrying state. After seed cleaning, the seed continues to move through the carrying area with the seed-metering disc. When the suction hole reaches the seed-discharge zone and gradually separates from the negative-pressure region, the seed detaches from the suction hole under the combined effects of gravity, inertial force, and its own motion state and then enters the subsequent delivery path through the seed outlet. Thus, the processes of seed pickup, cleaning, carrying, and discharge are completed.

The missed-pickup detection and compensation system runs synchronously with the seed-metering disc and completes missed-pickup judgement and compensation control in real time according to the seed-carrying state of each suction hole when it passes through the detection position. When a suction hole passes through the detection position, the photoelectric sensor identifies its seed-carrying state. If an effective seed-carrying signal is detected, the suction hole is considered normally loaded, and the system counts it as a normal suction hole. If no effective seed-carrying signal is detected, missed pickup is determined, and the missed-pickup signal is input into the control system. The PLC uses

the missed-pickup signal as the compensation trigger signal and immediately outputs compensation control pulses to drive the seed-metering disc to accelerate for a short period within the preset time so that the subsequent normally loaded suction hole enters the seed-discharge zone in advance and completes compensation seed discharge. The seeds discharged during compensation enter the delivery path through the auxiliary seed-delivery unit, thereby realizing a continuous operation process of suction-hole seed-carrying state identification, missed-pickup judgement, short-term acceleration compensation, and stable seed delivery.

2.2. System Hardware Composition

The hardware composition of the miss-seeding detection and compensation system is shown in Figure 2. It mainly comprises the following modules: power supply, suction-hole seed-carrying state detection, speed acquisition, PLC control, compensation execution, and alarm display [37]. The power supply module provides a stable operating voltage for the photoelectric sensor, PLC controller, stepper motor driver, and alarm display elements. The suction-hole seed-carrying state detection module uses a through-beam photoelectric sensor to collect the seed-carrying state signal of each suction hole on the seed-metering disc and transmit the detection signal to the PLC. The speed acquisition module comprises an encoder to obtain the real-time rotational speed of the seed-metering disc and provide a basis for compensation pulse parameter setting and short-term acceleration control. As the control core of the system, the PLC control module performs detection signal processing, missed-pickup state judgement, compensation pulse output, parameter setting, and operating-state display. The compensation execution module drives the seed-metering disc to perform short-term acceleration compensation under the control of the PLC output signal, while the alarm display module displays the system operating state, the number of missed-pickup events, the number of compensations, and abnormal alarm information.

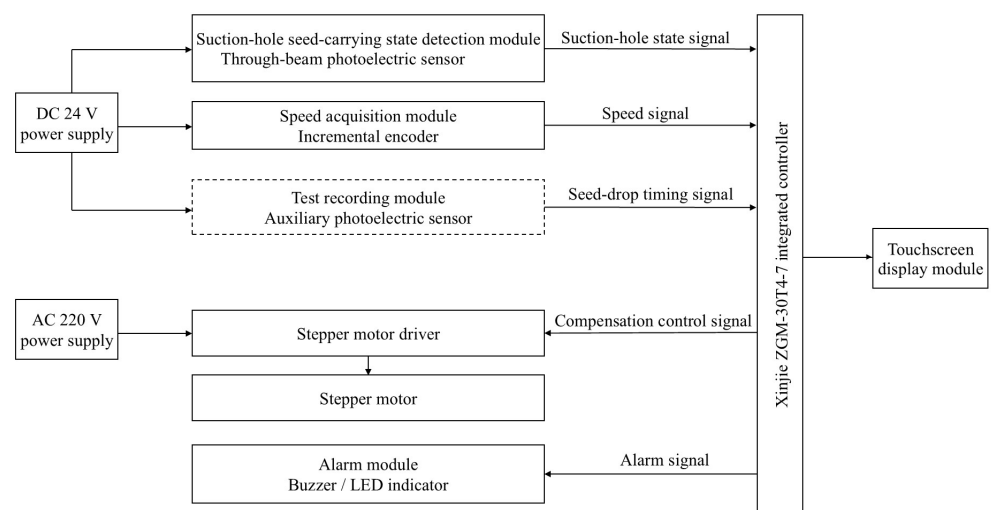


Figure 2. Hardware composition of the miss-seeding detection and compensation system.

During system operation, the photoelectric sensor and encoder transmit the suction-hole seed-carrying state signal and seed-metering disc speed signal to the PLC, respectively. The PLC determines whether missed pickup occurs according to the seed-carrying state of each suction hole. When missed pickup is detected, the PLC uses the missed-pickup signal as the compensation trigger signal and immediately outputs compensation control pulses to the stepper motor driver. The driver then controls the seed-metering disc to accelerate for a short period within the preset time, enabling the subsequent normally loaded suction hole to enter the seed-discharge zone in advance and complete compensation seeding.

After the compensation action is completed, the seed-metering disc returns to its normal speed, and the system continues to detect the seed-carrying state of subsequent suction holes. Meanwhile, the HMI interface displays the rotational speed, number of detections, number of missed-pickup events, number of compensations, and alarm status in real time, thereby integrating missed-pickup detection, compensation control, and operating-state monitoring.

2.3. Missed-Pickup Detection Module

According to the structure of the air-suction seed-metering device and the requirement for early missed-pickup identification, a through-beam photoelectric sensor was used to detect the seed-carrying state of each suction hole on the seed-metering disc in real time. This method has the advantages of a compact structure, fast response, and easy installation within the limited space on both sides of the seed-metering disc, without affecting the normal operation of the seed-metering device.

2.3.1. Suction-Hole Seed-Carrying State Detection Module

To identify the suction-hole seed-carrying state in advance without interfering with the normal operation of the seed-metering disc, a photoelectric sensing method was adopted for real-time detection. Because the seed-metering disc rotates continuously during operation, each suction hole passes through the detection area in a short period of time; therefore, the sensor must have a fast response and stable signal output. The sensor detection distance must satisfy the installation requirements on both sides of the seed-metering disc considering the diameter of the seed-metering disc, the distribution position of the suction holes, and the available installation space. In this study, a Panasonic EX-13AD ultra-thin through-beam photoelectric sensor was selected as the detection element. Its detection distance is 500 mm, and its response time is less than 0.5 ms, meeting the detection requirements for suction-hole seed-carrying state recognition under high-speed rotation of the seed-metering disc.

The detection module mainly comprises a photoelectric sensor group, seed-metering disc, and PLC controller as shown in Figure 3. The transmitting and receiving ends of the photoelectric sensor are arranged on both sides of the seed-metering disc so that the detection beam passes through the trajectory of seeds carried by the suction holes. When a suction hole carrying a soybean seed passes through the detection position, the seed blocks the detection beam, and the sensor outputs an effective blocking signal. Then, the PLC determines that the suction hole is normally loaded. When a suction hole passes through the detection position without producing an effective occlusion signal, the PLC determines that missed pickup has occurred, and the signal is used as the trigger basis for subsequent compensation control. The detection position is arranged after the seed-cleaning area and before the seed-discharge zone, enabling missed pickup to be identified before the suction hole reaches the seed-discharge zone and reserving response time for the compensation action.

To avoid misjudging the no-signal state outside the detection period as missed pickup, the control system combines the encoder signal with the suction-hole distribution pattern of the seed-metering disc to establish an in-position detection window for each suction hole. When the seed-metering disc rotates to the position where a suction hole should pass through the detection area within the corresponding time or angular range, the PLC opens the detection window to determine the seed-carrying state. If the photoelectric sensor generates an effective occlusion signal within the detection window, the suction hole is determined to carry a seed normally. If no effective occlusion signal is detected by the end of the detection window, missed pickup is determined. Through the combined judgement

of encoder positioning and photoelectric sensing, synchronization between suction-hole position recognition and seed-carrying state recognition can be achieved, thereby avoiding misjudgment caused by relying only on the presence or absence of the sensor signal.

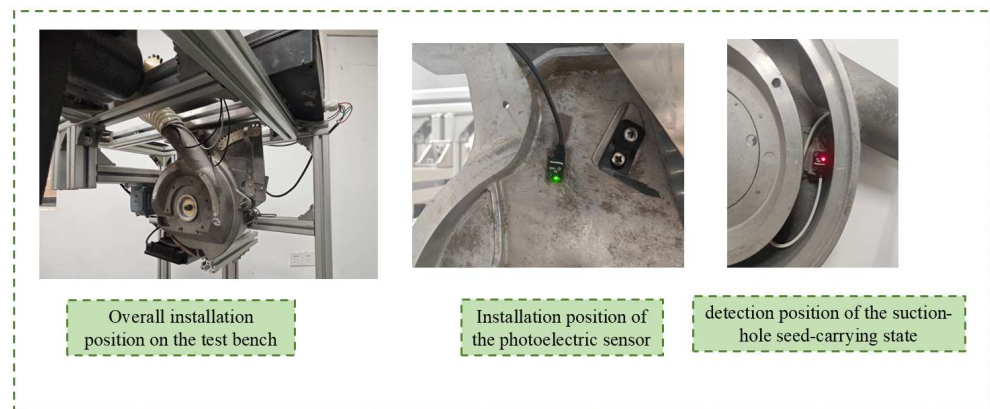


Figure 3. Structural diagram of the seed-carrying state detection module for suction holes.

2.3.2. Verification of Sensor Response Time

According to the requirements for high-speed operation of the air-suction soybean seed-metering device, the rotational speed of the seed-metering disc increases with forward speed, and the time interval between adjacent suction holes passing through the detection position is shortened accordingly [38]. To ensure reliable detection of the suction-hole seed-carrying state during high-speed rotation of the seed-metering disc, the response time of the photoelectric sensor needs to be evaluated. The forward speed of the machine is v , the theoretical plant spacing is D_0 , the number of suction holes in the seed-metering disc is z , and the rotation speed of the seed-metering disc is n . Under the condition of ideal single-seed metering, the time for the machine to advance a theoretical plant spacing should be equal to the time for the seed-metering disc to turn an adjacent suction hole spacing; that is:

$$\frac{D_0}{v} = \frac{60}{nz} \quad (1)$$

where D_0 is the theoretical plant spacing, m; v is the forward speed of the machine, m/s; n is the rotational speed of the seed-metering disc, r/min; and z is the number of suction holes in the seed-metering disc. When the forward speed of the machine is expressed in V , in km/h, there is:

$$v = \frac{1000V}{3600} \quad (2)$$

From Equations (1) and (2), the rotation speed of the seed-metering disc can be obtained as:

$$n = \frac{1000V}{60zD_0} \quad (3)$$

where V is the forward speed of the machine, km/h.

The time interval between adjacent suction holes passing through the detection position in turn is:

$$T_s = \frac{60}{nz} \quad (4)$$

where T_s is the time interval between adjacent suction holes passing through the detection position, s.

From Equations (3) and (4), it can be seen that when the theoretical plant spacing and the number of suction holes are constant, the higher the forward speed of the machine, the greater the rotation speed of the seed-metering disc, the shorter the time interval between the adjacent suction holes through the detection position, and the higher the requirements

for the response speed of the photoelectric sensor and the PLC signal acquisition ability. In this study, the number of suction holes in the seed-metering disc is $z = 26$, and the theoretical plant spacing is $D_0 = 0.2$ m. According to the target operating speed range of 6~12 km/h, the rotation speed of the seed-metering disc is 19.23~38.46 r/min, and the time interval between adjacent suction holes passing through the detection position is 60~120 ms.

To ensure that the seed carrying state of the suction hole can be identified in time, the response time of the photoelectric sensor should be less than the minimum time interval of the adjacent suction holes passing through the detection position within the target operating speed range; that is:

$$t_r < T_{smin} \quad (5)$$

where t_r is the sensor response time, s; T_{smin} is the minimum time interval between adjacent suction holes passing through the detection position within the target operating speed range, s.

The selected photoelectric sensor (EX-13AD, Panasonic Industry Co., Ltd., Kadoma, Osaka, Japan) has a response time of less than 0.5 ms, while the minimum time interval between adjacent suction holes passing through the detection position is 60 ms at the maximum target operating speed of 12 km/h. It can be seen that the response time of the sensor is much shorter than the minimum time interval between adjacent suction holes passing through the detection position, which can meet the instantaneous signal acquisition requirements when a suction hole passes through the detection area.

Because the seed-metering disc rotates continuously, checking only the time interval between adjacent suction holes is insufficient to fully evaluate the influence of sensor response on detection accuracy. Therefore, the response process is further evaluated based on the motion displacement of the suction hole at the detection position. Assuming that the radius of the center distribution circle of the suction hole at the detection position is r , the tangential velocity of the suction hole passing through the detection position is:

$$v_t = \frac{2\pi r n}{60} \quad (6)$$

where v_t is the tangential velocity of the suction hole at the detection position, mm/s; and r is the radius of the pitch circle of the suction-hole centres, mm.

The corresponding motion displacement of the suction hole in the response time of the sensor is:

$$s_r = v_t t_r \quad (7)$$

where s_r is the equivalent displacement of the suction hole along the direction of motion within the sensor response time, mm.

To ensure detection signal stability, the equivalent displacement of the suction hole in the sensor response time should be less than the effective shading length formed when the seed passes through the detection beam; that is:

$$s_r < L_b \quad (8)$$

where L_b is the effective light-blocking length formed by the soybean seed along the moving direction of the suction hole, mm.

2.4. Compensation Module

2.4.1. Compensation Execution Module

According to the miss-seeding compensation requirements of the air-suction soybean seed-metering device, the compensation execution module should adjust the motion state of the seed-metering disc in time after missed pickup is identified so that the subsequent

normally loaded suction hole can reach the seed-discharge zone in advance and compensate for the seed-spacing gap caused by missed pickup. The module mainly consists of a stepper motor, a stepper motor driver, a transmission mechanism, and an auxiliary guidance unit. As the compensation actuator, the stepper motor receives the pulse control signal output by the PLC and drives the seed-metering disc through the transmission mechanism to achieve short-term acceleration. The stepper motor driver converts the PLC pulse signal into the driving signal required for motor operation. The auxiliary seed-delivery unit is used to receive and guide seeds discharged during normal seeding and compensation, reducing collision, rebound, and lateral offset after the seeds enter the delivery path.

When the compensation execution module operates, the suction-hole seed-carrying state detection module first determines whether each suction hole carries a seed. When the PLC determines that missed pickup has occurred, it immediately outputs compensation control pulses to the stepper motor driver, driving the seed-metering disc to accelerate briefly within the preset time. This enables the subsequent normally loaded suction hole to enter the seed-discharge zone in advance and complete compensation seed discharge. After the compensation action is completed, the seed-metering disc returns to normal speed and maintains the original seeding rhythm.

2.4.2. Compensation Timing Control

Effective missed-pickup compensation requires coordinated recognition of the missed-pickup signal, compensation pulse output, and short-term acceleration of the seed-metering disc. The suction-hole seed-carrying state detection module is arranged after the seed-cleaning area and before the seed-discharge zone. When a suction hole passes through the detection position and no effective seed-carrying signal is detected, the PLC determines that missed pickup has occurred and uses the missed-pickup signal as the compensation trigger signal. The compensation control pulse is immediately output to the stepper motor driver, and the seed-metering disc is accelerated from the normal operating speed to the compensation speed for a short period so that the subsequent normally loaded suction hole enters the seed-discharge zone in advance, thereby reducing the seed-spacing gap caused by missed pickup [39,40]. This compensation method does not require an independent supplementary seeding channel, and its control focus is to determine the additional rotation angle, compensation duration, and pulse output during short-term acceleration.

Assuming that the number of suction holes on the seed-metering disc is z , the angular interval between adjacent suction holes can be expressed as follows:

$$\theta_z = \frac{2\pi}{z} \quad (9)$$

where θ_z is the angular interval between adjacent suction holes, rad; z is the number of suction holes on the seed-metering disc.

The normal working speed of the seed-metering disc is n_0 , the speed of the compensation stage is n_c , and the duration of the compensation action is t_c , and the additional rotation angle of the seed-metering disc in the compensation stage relative to the normal seeding state is:

$$\Delta\theta = \frac{2\pi(n_c - n_0)t_c}{60} \quad (10)$$

where $\Delta\theta$ is the additional rotation angle generated by the seed-metering disc during the compensation stage, rad; n_0 is the normal operating rotational speed of the seed-metering disc, r/min; n_c is the rotational speed of the seed-metering disc during the compensation stage, r/min; and t_c is the duration of the compensation action, s.

To enable the subsequent normally loaded suction hole to enter the seed-discharge zone in advance, the additional rotation angle generated in the compensation stage should match the angle interval of adjacent suction holes; that is:

$$\Delta\theta = \lambda\theta_z \quad (11)$$

where λ is the compensation correction coefficient, which is mainly used to correct the response delay of the stepper motor, transmission clearance, and motion deviation of the seed after it leaves the seed-metering disc. According to Equations (9)~(11), the duration of a single compensation action can be obtained as:

$$t_c = \frac{60\lambda}{z[(n_c - n_0)]} \quad (12)$$

According to Equation (12), when the number of suction holes on the seed-metering disc is fixed, a larger difference between the compensation rotational speed and the normal operating rotational speed results in a shorter time required to complete one compensation action. When the compensation rotational speed is fixed, an increase in the normal operating rotational speed of the seed-metering disc shortens the available time for the compensation action, thereby imposing higher requirements on the response speed of the stepper motor and the stability of the control system.

If the number of pulses per revolution of the stepper motor driver is P and the transmission ratio from the motor to the seed-metering disc is i , the number of pulses required for a single compensation action can be expressed as:

$$N_c = \frac{Pi\Delta\theta}{2\pi} \quad (13)$$

where N_c is the number of pulses required for a single compensation action; P is the number of pulses per revolution of the stepper motor driver, pulse/r; and i is the transmission ratio from the motor to the seed-metering disc.

In the actual control process, the normal operating rotational speed n_0 of the seed-metering disc is calculated from the implemented operating speed, theoretical seed spacing, and the number of suction holes on the seed-metering disc. The rotational speed n_c during the compensation stage is determined by comprehensively considering the response capability of the stepper motor, the operating stability of the seed-metering disc, and the required time for the compensation action. The compensation rotational speed is set based on preliminary tests to avoid delayed compensation, which could prevent the subsequent suction hole carrying a seed from entering the seed-discharge zone in time, and to prevent excessive speed variation that could cause unstable seed detachment. The compensation correction coefficient λ is used to correct the start-up delay of the stepper motor, transmission clearance, and motion deviation of the seed after it leaves the seed-metering disc, and its value is adjusted and determined through preliminary tests. The PLC calculates the compensation pulse number N_c according to the number of pulses per revolution P of the driver, the transmission ratio i from the motor to the seed-metering disc, and the additional rotation angle $\Delta\theta$ required for a single compensation action. After the missed-pickup signal is triggered, the PLC outputs the corresponding pulses to make the subsequent suction hole carrying a seed enter the seed-discharge zone in advance.

To avoid overlap between compensation actions under continuous missed-pickup conditions, the duration of a single compensation action should be less than the time interval between two adjacent missed-pickup signals; that is:

$$t_c < T_m \quad (14)$$

where T_m is the time interval between two adjacent missed-pickup signals, s. When $t_c \geq T_m$, it indicates that the previous compensation action has not yet been completed. In this case, the system determines that the compensation interval is insufficient and provides a warning through the alarm module. This control method enables immediate compensation after identifying a missed-pickup signal without changing the basic structure of the seed-metering device, while maintaining the continuity of the subsequent seeding rhythm.

2.5. PLC Control Module

To realize suction-hole seed-carrying state detection, seed-metering disc speed acquisition, and compensation execution control, a ZGM-30T4-7 integrated controller (Wuxi Xinje Electric Co., Ltd., Wuxi, China) was selected as the control core, as shown in Figure 4. The controller integrates PLC logic control and HMI touch-display functions and has the advantages of compact structure, simplified wiring, and convenient on-site debugging. It is equipped with 16 digital input points and 14 transistor output points, which can meet the signal input and output control requirements of the photoelectric sensor, encoder, control keys, stepper motor driver, and alarm module. The high-speed input terminals support encoder pulse acquisition and can be used for real-time speed calculation of the seed-metering disc. The maximum high-speed pulse output frequency is 100 kHz, which meets the pulse control requirements of the stepper motor during compensation. During system operation, the PLC receives the suction-hole seed-carrying state signal and encoder speed signal and performs missed-pickup judgement, compensation pulse output, and short-term acceleration control of the seed-metering disc. Meanwhile, operating parameters are set through the touch screen, and information such as seed-metering disc speed, number of missed-pickup events, number of compensations, and alarm status is displayed.



Figure 4. PLC–HMI control interfaces: (a) parameter-setting interface; (b) operating-status monitoring interface. The Chinese text shown in the photographs represents the original labels embedded in the HMI interface.

2.6. Software Design

The missed-pickup detection and compensation control program was developed using the XDPPro PLC programming environment (available from <https://en.xinje.com/web/home>, accessed on 5 August 2026), and the main control logic was implemented using a ladder diagram. The program flow is shown in Figure 5. The system software mainly includes initialization, parameter setting, suction-hole seed-carrying state detection, missed-pickup judgement, immediate compensation triggering, alarm prompting, and data statistics. After the system starts, initialization operations, such as clearing the detection count, resetting the compensation module, resetting the alarm state, and reading operating parameters, are first completed. Then, the seed-metering disc speed, compensation pulse

parameters, compensation action time, and alarm threshold are set through the touch screen, providing the parameter basis for subsequent detection and compensation control.

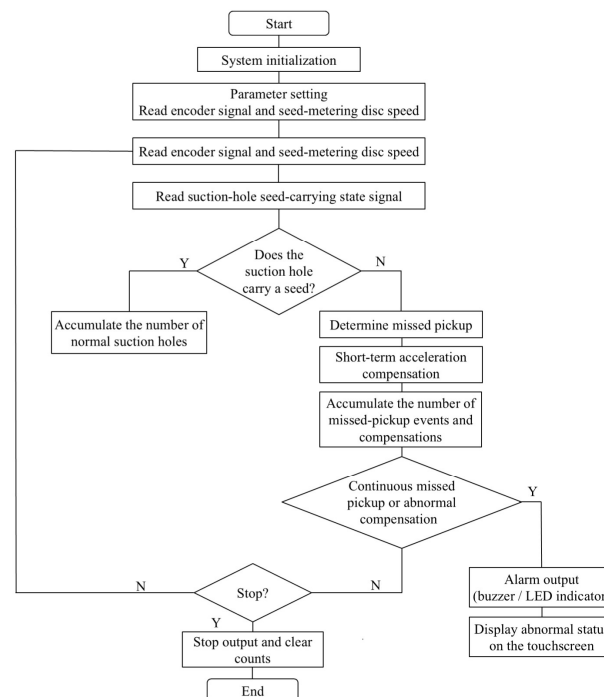


Figure 5. Flowchart of the control program for the miss-seeding detection and compensation system.

During system operation, the PLC reads the encoder signal to determine the real-time speed of the seed-metering disc and establishes the suction-hole detection window according to the number of suction holes and the real-time disc speed. At the same time, the seed-carrying state signal output by the through-beam photoelectric sensor is collected to determine whether the corresponding suction hole in the detection window carries a seed. When a suction hole enters the detection window, if the photoelectric sensor detects an effective occlusion signal, the suction hole is considered normally loaded, and the number of normally loaded suction holes is accumulated. If no effective occlusion signal is detected by the end of the detection window, missed pickup is determined, and the signal is used as the trigger basis for compensation control. The PLC uses the missed-pickup signal as the compensation trigger signal and immediately outputs compensation control pulses to the stepper motor driver, driving the seed-metering disc to accelerate for a short period within the preset time. This enables the subsequent normally loaded suction hole to enter the seed-discharge zone in advance and complete compensation seed discharge. Subsequently, the seed-metering disc returns to the normal speed, and the system continues to detect the seed-carrying state of the next suction hole while accumulating the number of missed-pickup events and compensations. When abnormal conditions such as continuous missed pickup, incomplete compensation action, or insufficient compensation interval occur, the PLC outputs an alarm signal, activates the buzzer and LED indicator, and displays the abnormal state on the touch screen. After receiving a stop or reset instruction, the system stops output and clears the relevant counts, as shown in Figure 5.

2.7. Experimental Design and Evaluation Indices

The bench test comprised two parts (a missed-pickup detection and compensation control test) and an overall performance test under the optimized parameter combination. The missed-pickup detection and compensation control test was mainly used to evaluate the reliability of suction-hole seed-carrying state identification, immediate compensation

triggering, and compensation execution. The test material was Zhonghuang 13 soybean seeds. As shown in Figure 6, the test setup mainly comprised an air-suction seed-metering device test bench, a Panasonic EX-13AD through-beam photoelectric sensor, an incremental encoder, a Xinjie ZGM-30T4-7 integrated controller, a stepper motor and its driver, and an alarm module. The operating speeds were set to 6, 8, 10, and 12 km/h, corresponding to seed-metering disc speeds of 19.23, 25.64, 32.05, and 38.46 r/min, respectively. The theoretical plant spacing was 200 mm. During the test, one suction hole on the seed-metering disc was blocked with transparent tape to simulate missed pickup. Each group used 500 seeds as the statistical sample. Based on the 26 suction holes of the seed-metering disc, the theoretical number of missed-pickup events was approximately 19. The test was repeated three times at each speed, and the number of detected missed-pickup events, compensation triggers, and successful compensations was recorded.

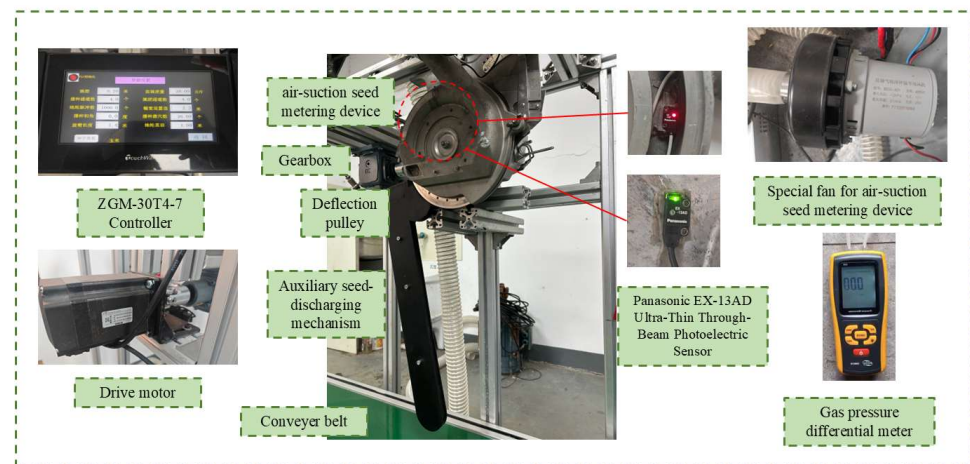


Figure 6. Bench test setup of the miss-seeding detection and compensation system.

On this basis, an overall performance test using the optimized parameter combination was conducted to evaluate seeding quality under the synergistic effect of the missed-pickup detection and compensation system and the auxiliary seed-delivery mechanism. According to the previous simulation and optimization results of the auxiliary seed-delivery mechanism, an operating speed, mechanism inclination angle, and seed-delivery belt spacing of 10.91 km/h, 9.34°, and 13.48 mm were selected as the test parameters, respectively. Two conditions, namely without and with the missed-pickup detection and compensation system together with the auxiliary seed-delivery mechanism, were compared. During the test, one suction hole was also blocked to simulate missed pickup, and each condition was repeated three times. After the seeds fell onto the seed-drop plane, the data from the starting and stopping stages were removed. The center distance between adjacent seed-drop points was measured along the seeding direction, and the qualified seed-spacing, multiple-seeding, and miss-seeding rates were calculated accordingly.

The missed-pickup detection accuracy and compensation success rate were calculated according to Equations (15) and (16), respectively:

$$P_m = \frac{M_s}{M_r} \times 100\% \quad (15)$$

$$P_b = \frac{N_b}{N_t} \times 100\% \quad (16)$$

where P_m is the missed-pickup detection accuracy, %; P_b is the compensation success rate, %; M_r is the manually preset number of missed-pickup events; M_s is the number of missed-pickup events detected by the system; N_t is the total number of system compensation

actions; and N_b is the number of successful compensation actions. Seed-spacing quality was evaluated based on the actual distance between adjacent seed-drop points. When the actual seed spacing was within the range of $0.5D_0 \sim 1.5D_0$, it was classified as qualified seed spacing; when it was less than $0.5D_0$, it was classified as multiple seeding; and when it was greater than or equal to $1.5D_0$, it was classified as miss-seeding, where D_0 is the theoretical seed spacing.

3. Results and Discussion

3.1. Determination of Comprehensive System Test Parameters

To verify the comprehensive performance of the miss-seeding detection and compensation system, the simulation optimization results of the previous auxiliary seed-delivery mechanism were used as the basis for selecting test parameters, and its modelling and parameter optimization processes are not further discussed in this study. In the proposed system, the auxiliary seed-delivery mechanism mainly serves to receive, guide, and stabilize seed delivery, thereby improving the motion state of both normally discharged and compensated seeds after entering the delivery path. Figure 7 shows the auxiliary seed-delivery mechanism model and the seed motion trajectory under the optimized parameter combination: Figure 7a,b show the mechanism model and seed trajectory, respectively. As shown in the figure, after separating from the seed-metering disc, the seed can be received, guided, and conveyed by the auxiliary seed-delivery mechanism and enter the delivery area along the predetermined path, indicating that the mechanism provides more stable guidance conditions for the terminal delivery of both normally discharged and compensated seeds.

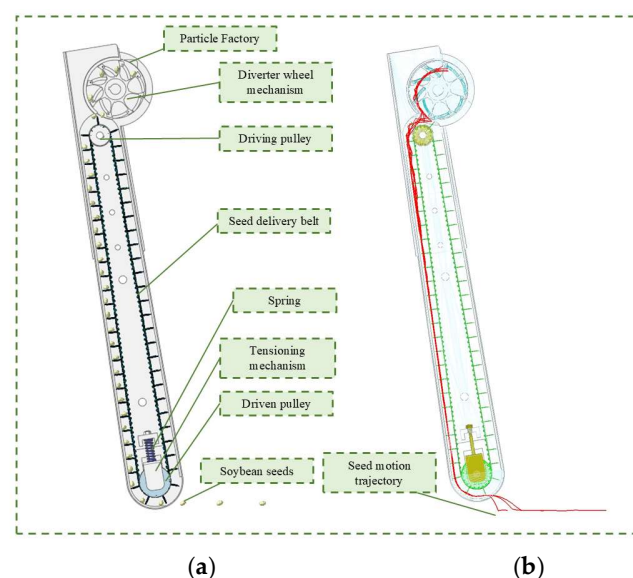


Figure 7. Auxiliary seed-delivery mechanism model and seed trajectory: (a) auxiliary seed-delivery mechanism model; (b) seed trajectory. The red curve indicates the seed motion trajectory, whereas the other colors are used only to distinguish the model components.

According to the previous optimization results, the overall system verification test was conducted at an operating speed of 10.91 km/h, a mechanism inclination angle of 9.34° , and a seed-delivery belt spacing of 13.48 mm. The theoretical plant spacing was set to 200 mm, the number of suction holes on the seed-metering disc was 26, and the corresponding rotational speed of the seed-metering disc was 34.97 r/min.

3.2. Analysis of Miss-Seeding Detection and Compensation Performance

To investigate the response reliability of the miss-seeding detection and compensation control system under different seeding frequencies, bench tests were conducted at four operating speeds: 6, 8, 10, and 12 km/h. The test results are shown in Table 1. As shown in Table 1, the system achieved missed-pickup identification and compensation action triggering within the operating speed range of 6–12 km/h. At operating speeds of 6, 8, 10, and 12 km/h, the average missed-pickup detection accuracies were 100.00%, 100.00%, 98.25%, and 96.49%, respectively, and the average compensation success rates were 100.00%, 98.25%, 96.49%, and 94.55%, respectively. These results indicate that the photoelectric sensors installed on both sides of the seed-metering disc can reliably identify the seed-carrying state of suction holes. The PLC control program was able to output compensation commands based on the missed-pickup judgement results, satisfying the requirements for missed-pickup detection and compensation control at different seeding frequencies.

Table 1. Test results of missed-pickup detection and compensation control at different operating speeds.

Operating Speed/(km/h)	Theoretical Number of Seeds/Seed	Test No.	Manually Set Missed-Pickup Events/Time	System-Detected Missed-Pickup Events/Time	Missed-Pickup Detection Accuracy/%	Compensation Trigger Times/Time	Successful Compensation Times/Time	Compensation Success Rate/%
6	500	1	19	19	100	19	19	100
		2	19	19	100	19	19	100
		3	19	19	100	19	19	100
		Mean	19.00	19.00	100	19.00	19.00	100
8	500	1	19	19	100	19	19	100
		2	19	19	100	19	18	94.74
		3	19	19	100	19	19	100
		Mean	19.00	19.00	100	19.00	18.67	98.25
10	500	1	19	19	100	19	18	94.74
		2	19	19	100	19	18	94.74
		3	19	18	94.74	18	18	100.00
		Mean	19.00	18.67	98.25	18.67	18.00	96.49
12	500	1	19	19	100	19	18	94.74
		2	19	18	94.74	18	17	94.44
		3	19	18	94.74	18	17	94.44
		Mean	19.00	18.33	96.49	18.33	17.33	94.55

Note: There are 26 suction holes in the seed-metering disc. In the experiment, one suction hole was artificially blocked to simulate missed pickup during actual operation. When 500 seeds were counted in each group, the theoretical number of missed-pickup events was $500/26 = 19.23$, and 19 was used as the integer value.

With increasing operating speed, both the missed-pickup detection accuracy and compensation success rate showed a decreasing trend. This was mainly because the rotational speed of the seed-metering disc increased with operating speed, shortening the effective time during which each suction hole passed through the detection area and reducing the time margin for sensor signal acquisition, PLC logic processing, and compensation actuator response. At higher seeding frequencies, individual suction-hole state signals may be missed due to reduced blocking time or changes in seed posture. Meanwhile, the time required for the compensation actuator to complete one compensation action constitutes a larger proportion of the interval between adjacent suction holes, reducing compensation stability.

3.3. Comprehensive System Performance Under the Optimized Parameter Combination

Under the optimized parameter combination of the auxiliary seed-delivery mechanism, bench comparison tests were conducted under two conditions, namely without and with the miss-seeding detection and compensation system together with the auxiliary seed-delivery mechanism, to evaluate the improvement effect of the integrated system on seeding quality. The operating speed, mechanism inclination angle, and seed-delivery belt spacing were 10.91 km/h, 9.34°, and 13.48 mm, respectively. The results are shown in Table 2. Without the system, the average qualified seed-spacing rate, multiple-seeding rate, and miss-seeding rate were 92.4%, 1.2%, and 6.4%, respectively. With the system, the corresponding values were 96.0%, 1.0%, and 3.0%, respectively. Compared with the condition without the system, the qualified seed-spacing rate increased by 3.6 percentage points, the miss-seeding rate decreased by 3.4 percentage points, and the multiple-seeding rate decreased by 0.2 percentage points. The results show that the miss-seeding detection and compensation system can compensate for seed-spacing gaps caused by missed pickup, while the auxiliary seed-delivery mechanism can improve the guidance of normally discharged and compensated seeds.

Table 2. Bench test results of the integrated system under the optimal parameter combination.

Forward Speed/(km/h)	Inclination Angle/(°)	Seed Delivery Belt Spacing/(mm)	Without Miss-Seeding Compensation and Auxiliary Seed-Delivery Mechanism				With Miss-Seeding Compensation and Auxiliary Seed-Delivery Mechanism		
			Test No.	Qualified Rate/%	Multiple-Seeding Rate/%	Miss-Seeding Rate/%	Qualified Rate/%	Multiple-Seeding Rate/%	Miss-Seeding Rate/%
10.91	9.34	13.48	1	92.0	1.4	6.6	95.0	1.2	3.8
			2	92.8	1.2	6.0	96.8	1.0	2.2
			3	92.4	1.0	6.6	96.2	0.8	3.0
			Mean	92.4	1.2	6.4	96.0	1.0	3.0

In the experiment, the theoretical missed-pickup ratio was approximately 3.85% by blocking one suction hole on the seed-metering disc. The measured miss-seeding rate without the system was 6.4%, which was higher than the theoretical setting value. This indicates that the actual miss-seeding rate was affected not only by the artificially blocked suction hole but also by factors such as pickup stability of the seed-metering device, seed collision during discharge, seed-drop point deviation, and seed-spacing classification error. After installing the miss-seeding detection and compensation system together with the auxiliary seed-delivery mechanism, the miss-seeding rate decreased to 3.0%, which was close to the theoretical missed-pickup ratio. Meanwhile, the multiple-seeding rate decreased from 1.2% to 1.0%, indicating that the compensation process did not cause obvious multiple seeding. Overall, under the optimized parameter combination, good coordination was achieved among missed-pickup detection, compensation execution, and auxiliary guided delivery, which helped improve seed-spacing uniformity under bench conditions.

3.4. Discussion

In this study, the detection target was shifted from the post-discharge seed state to the suction-hole seed-carrying state between the seed-cleaning and seed-discharge zones. Thus, missed pickup can be identified before a suction hole without a seed enters the seed-discharge zone, reserving response time for the compensation action. As the operating speed increases, the rotational speed of the seed-metering disc increases, the time interval between adjacent suction holes passing through the detection position is shortened, and the effective occlusion time of seeds passing through the photoelectric sensor is reduced. As a result, the time margin for sensor acquisition, PLC judgement, and compensation execution

decreases. This is the main reason for the reduced missed-pickup detection accuracy and compensation success rate under high-speed conditions.

Compared with compensation methods that add an independent supplementary seeding channel, the proposed method achieves self-compensation through short-term acceleration of the seed-metering disc and reduces seed-spacing gaps by advancing the seed-discharge timing of the subsequent normally loaded suction hole. The structure is relatively simple and can reduce the difficulty of timing coordination between an independent supplementary seeding mechanism and the main seed-metering device. However, the compensation effect of this method is affected by the stability of the subsequent seed-carrying suction hole, the interval between continuous missed-pickup events, the compensation speed setting, and the guidance stability of the auxiliary seed-delivery mechanism. Further experiments under different negative pressures, seed sizes, and field vibration conditions should be conducted to improve the adaptability of missed-pickup identification and self-compensation control under complex operating conditions.

4. Conclusions

(1) A miss-seeding detection and self-compensation system based on suction-hole seed-carrying state recognition was developed for an air-suction soybean seed-metering device. The system uses through-beam photoelectric sensors installed on both sides of the seed-metering disc to acquire the seed-carrying state of each suction hole. Using a Xinjie ZGM-30T4-7 integrated controller and encoder-based speed feedback, the system performs missed-pickup identification, compensation pulse output, and short-term acceleration control of the seed-metering disc, thereby coordinating missed-pickup detection and compensation execution.

(2) Based on the optimization results of the previous auxiliary seed-delivery mechanism, an operating speed, inclination angle, and seed-delivery belt spacing of 10.91 km/h, 9.34°, and 13.48 mm were determined as the comprehensive performance test conditions of the system, respectively. The results show that the auxiliary seed-delivery mechanism could receive, guide, and constrain both normally discharged and compensated seeds, providing stable delivery conditions for compensated seeds entering the delivery path. This enhanced the coordination among missed-pickup detection, short-term acceleration compensation, and terminal seed delivery.

(3) The bench test results show that, under the optimized parameter combination, the installation of the miss-seeding detection and compensation system together with the auxiliary seed-delivery mechanism increased the qualified seed-spacing rate from 92.4% to 96.0%, reduced the miss-seeding rate from 6.4% to 3.0%, and decreased the multiple-seeding rate from 1.2% to 1.0%. These results indicate that the proposed system can compensate for seed-spacing gaps caused by missed pickup, while the auxiliary seed-delivery mechanism improves seed guidance and delivery stability, thereby enhancing seed-spacing uniformity under bench conditions.

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