Design and Test of Sowing Depth Measurement and Control System for No-Till Corn Seeder Based on Integrated Electro-Hydraulic Drive

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Abstract: An electro-hydraulic profiling mechanism has been gradually applied to provide suitable downforce for a no-till row unit and to ensure the consistency of the seed sowing depth. In order to improve the control effect of the sowing depth system and solve the problems of a complex structure, scattered valve sets and equipment suitability of an existing electro-hydraulic row unit, this paper takes the 2BJ-470B no-till row unit as the carrier and innovatively designs an integrated pressure-reducing cylinder (IPRC) based on electro-hydraulic technology by analyzing the sowing depth control process of an electro-hydraulic seeder. In addition, we develop the integrated electro-hydraulic-driven sowing depth measurement and control system. Combined with the feedforward compensation PID control algorithm, the dynamic regulation of the downforce is realized with the IPRC. The field test shows that under the setting of a sowing depth of 50 mm and a vehicle speed of 9~10 km·h⁻¹, the qualified rate of the sowing depth under the three adjustment methods of self-weight adjustment, spring adjustment and electro-hydraulic adjustment is 89.2%, 96.7% and 98.6%, respectively, and the corresponding maximum coefficient of variation of the sowing depth is 16.7%, 12.9% and 6.4%, respectively. The seed groove environmental qualification rate (SFEQ) is further analyzed in combination with the soil compaction, and the mean values of the qualification rates of the three control methods at different vehicle speeds are 88.3%, 91.6% and 98.6%, respectively. The integrated electro-hydraulic-driven row unit has significant advantages over mechanical and self-weight regulation, and its whole machine integration degree and high adaptability realize the comprehensive control of the sowing depth and soil compaction strength.

Keywords: no-till seeder; sowing depth; measurement and control; electro-hydraulic system

1. Introduction

Precision sowing techniques have long been a specific requirement for achieving precision seeding [1,2], and site-specific precision sowing techniques have a key role in promoting maize root development and improving maize yield [3,4]. The sowing depth consistency, as one of the important indicators of the precision sowing level, is influenced by factors including the surface straw cover density, soil texture changes and topographic changes [5–7]. Especially since the development of conservation tillage technology, the amount of straw residue cover in the field has increased greatly, resulting in the inability of the seeder to obtain sufficient downforce to ensure a stable groove depth [8,9].

Downforce is the load applied to the row unit, including the self-weight of the unit and the additional load applied by the profiling mechanism, which is vertically downward and plays a vital role in maintaining a stable and consistent sowing depth [10]. The soil compaction force of the row unit is the remaining load after the downforce systems have...
applied enough force to engage the disk openers to the target sowing depth and is referred to as the gauge wheel load [11].

However, applying more downward pressure than expected will inevitably result in an overload of the soil compaction force, and it can easily cause excessive compaction of the seed groove. This makes it difficult for the seeds to penetrate the wall for rooting and germination and affects the consistency of corn emergence [12,13]. In the face of the complex and variable external soil environment, it is necessary to strengthen the research on the control of the row unit downforce.

In most areas of the country, mechanical profiling row units are still used, and the downforce of these units is limited by the performance of the springs. The number of springs and the pretightening force need to be adjusted manually according to the actual soil conditions before operation [14]. However, the spring mechanism cannot precisely control the value of the downforce in the face of a complex soil environment, nor can it better suppress the vibration of the machine caused by ground heaving, which is likely to cause problems, such as too shallow seed grooves and regional soil compaction. In order to realize the automatic regulation of the downforce, scholars mostly use hydraulic or pneumatic methods to manage the downforce of seeders [15].

Both hydraulics and pneumatics are the application of fluid power. Hydraulic systems use liquids such as oil to transmit power, whereas pneumatic systems use air to transmit power. A pneumatic system has a cleaner energy source, and its structure is relatively simple. The unlimited supply of air and the ease of compression make pneumatics widely used by agricultural machinery [16,17].

Karayel et al. [18–20] developed a sowing depth measurement model to adjust the downforce of the row unit by airbag actuation. It is able to maintain a better sowing depth consistency than mechanical downforce regulation. Gao et al. [21] developed the sowing depth quality monitoring and evaluation software based on the pneumatic downforce adjustment device. Tests were conducted at a 6 to 10 km·h−1 vehicle speed and the sowing depth data were measured: the mean, pass rate, standard deviation and coefficient of variation were 50.01 mm, 78.9%, 8.95 mm and 17.9%, respectively.

Air for pneumatic use is easier to obtain, but on seeders, oil for the hydraulic system can be supplied directly from the tractor system. For hydraulic drives, it is equally convenient and easy. Compared to pneumatics, hydraulics can handle higher loads than pneumatics. Moreover, hydraulics are more accurate and stable than pneumatics in controlling the stroke of the seeder profiling mechanism [22]. Therefore, hydraulically driven profiling devices have been widely studied by scholars [23].

Nielsen et al. [24–26] designed a sowing depth measurement and electro-hydraulic control system to compare three downforce control algorithms, and the variability in the sowing depth measured in field experiments was reduced from 8 mm to 2 mm.

Fu et al. [27] performed a digital modeling simulation of the electro-hydraulic system to determine the PID controller parameters and investigated the dynamic characteristics of the system. The results of the field static tests of the system performance showed that the system overshoot was ≤29.0% and the control error was ≤5.0%.

Wen et al. [28–30] used an electro-hydraulic profiling device to obtain the sowing depth through sensors (e.g., ultrasonic sensors) and established a sowing depth monitoring model. The experiments verified that the electro-hydraulic profiling device can maintain a relatively stable sowing depth.

Bai et al. [31] comprehensively analyzed the control process of the sowing depth and compaction and designed the control system of the downforce and closing force based on hydraulic regulation. The user interface was built to allow the user to adjust and monitor the current downforce and closing force of the system in real time.

Through the above scholars’ studies, it can be found that the row unit downforce control system gradually matured, although there is more progress. However, most of the research is more independent, not yet combining sowing depth and compaction with the analysis, and it lacks comprehensive evaluation criteria of the seed groove environment.
Secondly, the current electro-hydraulic profiling device is more scattered, complex and has a poorly integrated structure. Due to the narrow space of the four-bar linkage, the scattered hydraulic components not only affect the structure of the whole machine but also reduce the control effect of the downforce.

Well-known agricultural companies such as Precision sowing, John Deere, AgLeader, Kinze, etc., already have more mature products for seeder downforce control (DeltaForce, SureForce et al.) [32–38]. These more integrated products are not tailor-made for the seeder we studied due to the different conditions of use (e.g., tractor model, model adaptation, etc.). They suffer from a small number of structural problems as well as performance matching. On the other hand, we currently have less theoretical analyses on designing the electro-hydraulic profiling mechanisms. In addition, an in-depth analysis is also essential for the research on sowing depth–compaction comprehensive control.

For the above problems, through the force and motion analysis of the row unit, we designed the integrated pressure-reducing cylinder (IPRC) based on the model 470B seeder. In this study, we comprehensively analyzed the relationship between the sowing depth and soil compaction and proposed the seed groove environmental qualification rate (SFEQ) for characterizing the effect of the sowing depth and compaction. To achieve a smooth ride as well as a consistent depth, the adaptive PID depth control algorithm was developed based on the CoDeSys V3.5 programming environment. To meet the needs of users, we built an IPRC-driven sowing depth control program and the interactive interface. Through the dynamic adjustment of the IPRC, we aim to realize the real-time regulation and control of the downforce and solve the problem of a scattered profiling structure so as to achieve the purpose of comprehensive control of the sowing depth and compaction.

2. Materials and Methods

2.1. Row Unit Force Analysis

Before designing the sowing depth control system, to ensure the stability of the furrowing operation and the fluency of profiling, it is necessary to conduct a force analysis on the row unit and its key components. The no-till row unit’s ripple disc and double-disc coulter are rigidly connected to the frame, and they are the first to have contact with the soil during tillage. The gauge wheel arm generates the contact force $F_{JC}$ through the depth-limiting block of the sowing depth adjustment mechanism to limit the maximum sowing depth, and the height difference $H$ between the gauge wheel and the coulter is the ideal sowing depth. As shown in Figure 1, for the purpose of force analysis and calculation, the force of the row unit in the vertical direction is taken as the research object, assuming that the sowing row unit uniform linear motion moves forward uniformly and straightly with the same sowing depth on the level ground surface and all the parts work normally under the ideal condition. The downforce is the action force. According to Newton’s third law, ignoring the friction at the hinge of the machine, the theoretical downforce applied to the row unit in the vertical direction at this time is

$$F_{XY} = F_{ny} + F_{Qy} - G$$

where the sum of the positive force of the soil-contacting parts $F_{ny}$ is

$$F_{ny} = F_{py} + F_{Ky} + F_{Sy} + F_{Zy}$$

where $F_{XY}$ is the downforce, the current additional applied force on the ground, N; $F_{Qy}$ is the tractor vertical traction force, N; $G$ is the total weight of the current row unit, N; $F_{py}$ is the ripple disc force reaction force, the support force of the coulter and residue wheels in the vertical direction, N; $F_{Ky}$ is the furrow opening reaction force, the support force on the double-disc coulter in the vertical direction, N; $F_{Sy}$ is the soil compaction reaction force, the support force on the gauge wheels in the vertical direction, N; and $F_{Zy}$ is the furrow reaction force, the support force on the closing wheel in the vertical direction, N.
From Equations (1) and (2), it can be seen that the combined force of the hydraulic force $F_{XY}$, gravity $G$ and traction force $F_{Qy}$ in the vertical direction is equal in size and opposite in direction to the combined forces of $F_{Py}$, $F_{Ky}$, $F_{Sy}$ and $F_{Zy}$. Because the four-bar linkage is floating profiling, the size of $F_{Qy}$ is negligible. Among them, the ripple disc support reaction force $F_{Py}$ is related to the physical characteristics of the straw and mulching density, which gradually changes with the difficulty of breaking stubble. The coulter support reaction force $F_{Ky}$ is related to the physical characteristics of the soil, which fluctuates up and down with the change in soil hardness and moisture content.

According to the mechanical analysis, it is known that the row unit uses the downforce of the whole machine as the working pressure required for stubble breaking and furrowing during tillage. When the seeder works in hard soil or thick vegetation cover, the required stubble-breaking and furrow-opening resistance rises, and the weight $G$ decreases continuously due to the seed and fertilizer discharge, resulting in the change in the downforce required by the machine. At this time, in order to ensure uniform and consistent furrowing operation, the magnitude of the downforce should be adjusted appropriately to meet the operational requirements of the row unit for the downforce.

In this paper, by introducing the hydraulic system as the external pressure source, according to the working principle of the profiling mechanism, as shown in Figure 1, to make the gauge wheel and the coulter maintain the sowing depth $H$ and so there is no soil compaction phenomenon, at this time the hydraulic force $F_Y$ needs to meet

$$\cos \theta_b F_Y = F_{XY} \frac{L_f f_1}{L_f}$$

where $F_Y$ is the hydraulic force, i.e., the current output hydraulic force of the cylinder, N; $L_{f1}$ is the hydraulic force arm, mm; $L_f$ is the effective length of the profiling lower rod, mm; and $\theta_b$ is the cylinder tilt angle, the angle between cylinder axis and plumb line, $^\circ$.

The above Equations (1)–(3) are combined to obtain the relationship between the output hydraulic force $F_Y$ of the cylinder and the applied downforce $F_{XY}$. It can be seen that

![Figure 1. Row unit force diagram: (1) integrated pressure-reducing cylinder (IPRC), (2) four-bar linkage, (3) seed box, (4) closing wheel, (5) sowing depth adjustment mechanism, (6) state II position of gauge wheel, (7) state I position of gauge wheel, (8) double-disc coulter, (9) ripple disc.](image)
the hydraulic force $F_Y$ as the source of external pressure, after the transfer of the mechanical structure, should meet the required downforce $F_{XY}$ changes. In the process of sowing depth control, the downforce $F_{XY}$ changes constantly with internal and external factors. It is necessary to ensure the premise of good contact between the gauge wheel and soil, and to improve the level of downforce as much as possible, so as to avoid the excessive compaction of soil on the sidewall of the seed groove, in order to reduce the influence of the soil resistance and machine weight on the consistency of the sowing depth. From the force analysis, it is known that the contact force $F_{JC}$ indirectly reflects the change in the soil compaction force $F_{Sy}$. Therefore, the sowing depth can be measured and controlled by applying variable hydraulic pressure to the profiling mechanism.

2.2. System Overall Scheme Design

The sowing depth measurement and control system consists of three major parts: mechanical system, electric control system and hydraulic system. During operation, the system ensures a consistent sowing depth by monitoring and regulating the downforce.

2.2.1. System Composition

In this paper, based on the preliminary research, the 2BJ-470B maize no-till precision seeder was selected as the test platform, and the design was optimized and technically improved for the existing spring-like structure.

As shown in Figure 2, the whole machine system is divided into three parts: mechanical system, electric control system and hydraulic system. Among them, the mechanical system consists of four-bar linkage, a depth-limiting mechanism, a sowing depth adjustment mechanism, etc.; the electronic control system consists of a load pin, vehicle controller, vehicle display terminal, etc.; the hydraulic system consists of an integrated pressure-reducing cylinder, a main circuit valve group, etc. The tractor system is an external auxiliary system, in which the vehicle power supply provides power for the electronic control system, and the hydraulic oil tank provides the pressure source for the hydraulic system.

![Figure 2. Schematic diagram of the sowing depth measurement and control system: (1) integrated pressure reducing cylinder (IPRC), (2) pressure-reducing relief valve, (3) hydraulic cylinder, (4) load sensor, (5) angle sensor, (6) sensor unit, (7) hydraulic quick coupling, (8) throttle speed control valve, (9) check valve, (10) main pressure-reducing valve, (11) main valve set.](image-url)
2.2.2. Basic Working Principle

The seeder forms a traction connection with the tractor through the crossbeam. During the sowing operation, due to the continuous changes in external factors (soil texture, stubble cover density) and internal factors (reduction in seed or fertilizer weight), the furrowing resistance changes with the plot, which is expressed as the support reaction force (i.e., the sidewall compaction force of seed groove) of the gauge wheel to the ground surface fluctuating up and down, and the consistency of the sowing depth is affected. Therefore, the axle pin and angle sensor are used to monitor the contact force and angle of the gauge wheel arm, respectively, so as to obtain the current sidewall compaction force indirectly. Transmit the monitoring data to the on-board control unit, judge the sowing depth status, compare with the set compaction force and perform the difference calculation at the same time. Run the PID control algorithm by PWM regulation to calculate the input current of the integrated pressure-reducing cylinder (IPRC) and adjust the output pressure in an intermittent way. The hydraulic force is applied to the mechanical system and transmitted to a series of soil-contacting parts so that it can work completely over the current soil resistance and realize the integrated control of the sowing depth and downforce. The tractor system acts as an external auxiliary system, providing power and pressure to the electrical and hydraulic systems of the whole machine.

2.3. Analysis of Sowing Depth Control Process

The sowing depth measurement and control system is based on the 470B unit design, and the control of the sowing depth involves the profiling mechanism and sowing depth adjustment mechanism. Therefore, the key components of the unit need to be analyzed.

2.3.1. Motion Analysis of the Profiling Mechanism

The range of profiling is a key parameter to characterize the profiling performance of the four-bar linkage, and the size of the profiling range determines the maximum range of the up and down floating profiling during the operation of the seeder. The main factors affecting the profiling performance of the four-bar linkage include the linkage length L, the upper profiling angle $\alpha_1$, the lower profiling angle $\alpha_2$, the traction angle $\alpha$ and so on. As shown in Figure 3, state I and state II correspond to the limit states of the upper and lower profiling angles, respectively.

![Figure 3. Schematic diagram of profiling range of profiling mechanism.](image)

The four-bar linkage is fixed at points A and C and hinged at points B and D. The AB and CD rods are the upper and lower rods of the profiling mechanism, respectively. When working, the BD rod floats up and down along the ground surface to maintain a consistent
wheel stance when riding over uneven ground. The calculation formula of its profiling range is as follows:

\[ h = L_f (\sin \alpha_1 + \sin \alpha_2) \]  

(4)

\[ h = h_1 + h_2 \]  

(5)

where \( h \) is the total profiling range, mm; \( h_1 \) is the upper profiling range, mm; \( h_2 \) is the lower profiling range, mm; \( L_f \) is the length of the linkage of the four-bar linkage, mm; \( \alpha_1 \) is the upper profiling angle, \(^\circ\); \( \alpha_2 \) is the down profiling angle, \(^\circ\); and \( \alpha \) is the traction angle, \(^\circ\).

From Formula (4), it can be seen that when the four-bar linkage moves up and down the same range of the profiling, the longer the length of the linkage, the smaller the range of the profiling angle changes. The change in traction angle depends on the direction of the tractor traction seeder frame. In order to ensure the stable work of the coulter during the sowing operation, the value of the traction angle should be as small as possible. According to the agronomic and other sowing requirements, the up and down profiling angles of the no-till seeder in general range from 6 to 22 \(^\circ\), and the total profiling range \( h \) is 160 to 200 mm, of which the down profiling angle, as a key indicator for performance in varied terrain, has an actual profiling range of about 100 to 120 mm [39]. The effective length \( L_f \) of the 470B seeder linkage is 350 mm. The default size of the upper and lower profiling angles at a traction angle \( \alpha \) of 0 \(^\circ\) is 16 \(^\circ\) and 20 \(^\circ\). Substituting into Equations (4) and (5), we can obtain that the new profiling range \( h \) of the four-bar linkage is 215 mm.

The safety stroke \( S_{safe} \) of the cylinder is the length of the cylinder when the profiling mechanism is in the maximum limit profiling; the safety stroke of the cylinder is generally less than the actual stroke of the cylinder. When designing the installation position of the cylinder, the relationship between the cylinder stroke and the range of profiling should be fully considered. When the four-bar linkage is in the upper and lower limit profiling state (the upper and lower linkages are stuck by the limit plate), the cylinder should be within the safe stroke. So as to avoid the damage of the cylinder when the seeder is transported, turn or limit the action. At the same time, the position of the fixed hole at the top of the cylinder determines the upper limit of the profiling when the cylinder is in the shortest state, and the position of the bottom hole of the cylinder along the lower rod determines the proportion of the profiling of the cylinder within the safe stroke. In other words, the closer the position of the bottom hole is to the top plate, the greater the hydraulic force and the shorter the cylinder stroke. See the cylinder profiling ratio Equation (6). It can be seen that the cylinder safety stroke is influenced by factors such as the force arm \( L_{f1} \) or linkage length, and it determines the motion relationship between the cylinder and four-bar linkage.

\[ \frac{S_{safe}}{h} = \frac{L_{f1}}{L_f} \]  

(6)

where \( S_{safe} \) is the safe profiling stroke of the cylinder, mm; and \( L_{f1} \) is the length of the equal force arm of the cylinder, mm.

According to the design principle of the profiling mechanism and the structure of the 470B row unit, we designed the cylinder bracket and the cylinder press plate. The cylinder bracket is connected with the top plate for clamping the top of the cylinder, and the cylinder press plate is connected with the original spring tie bar through bolts for mounting the bottom hole of the cylinder. The spring tie bar position, i.e., the cylinder iso-effective arm \( L_{f1} \), is 105 mm, and the profiling ratio \( L_{f1}/L_f \) is 0.3. Due to the profiling of the space structure of the four-bar linkage, the safety stroke \( S_{safe} \) of the cylinder is initially set to 55 mm in combination with the field conditions and usage scenarios, and the lower limit is used as the design benchmark, and the optimized total profiling range \( h_0 \) is 183.3 mm, calculated by the profiling ratio Formula (6). As shown in Figure 4, the relative positions of the upper and lower limits of the four-bar linkage are shown. The piston rod of the cylinder is not fully extended when the profiling mechanism reaches the maximum profiling lower limit, and the upper and lower profiling angles \( \alpha_1 \) and \( \alpha_2 \) are 10.5 \(^\circ\) and 20 \(^\circ\), respectively,
and the upper and lower profiling ranges are 63.6 mm and 119.7 mm, respectively, which meet the design requirements of the profiling mechanism profiling range.

![Figure 4. Schematic diagram of the upper and lower limits of the four-bar linkage: (1) integrated pressure-reducing cylinder (IPRC), (2) upper rod, (3) limit plate, (4) lower rod, (5) spring tie rod, (6) cylinder pressure plate, (7) top plate, (8) cylinder bracket.](image)

The cylinder platens on both sides apply downforce to the row unit by having contact with the four-bar linkage lower rod. The magnitude of the downforce is determined by the weight of the row unit, the tillage environment, the cylinder performance and other factors. Its extreme value determines the basic parameters, such as the material and size of the workpiece. The weight of the 470B row unit is about 90 kg. Combined with the literature [40,41] and the preliminary experimental study, it was found that the soil reaction force on the row unit was about 4000 N, when the sowing depth was set to 10 cm and the coefficient of variation of the sowing depth was small. Because the cylinder was installed vertically, the amount of variation in the working inclination \( \theta \) was small. Ignoring the effect of \( \theta \) on the hydraulic force, the hydraulic force \( F_Y \) at the IPRC is about 10.3 kN according to the conversion of Equation (3).

### 2.3.2. Mechanical Analysis of Sowing Depth Adjustment Mechanism

To facilitate the acquisition of the soil compressive force \( F_{S_y} \), the depth-limiting contact force \( F_{JC} \) between the gauge wheel arm and the depth-limiting block is monitored by a load pin.

Figure 5 shows the structure of the sowing depth adjusting mechanism. Pulling the sowing depth adjusting handle can make the depth-limiting stopper move back and forth around the rotating axis D to adjust the target sowing depth. The load pin is installed in the contact position of the depth-limiting block and the gauge wheel arm, the periphery is wrapped in the depth-limiting block and fixed by the axle pin support, the gauge wheel arm and the gauge wheel are hinged in OA and the frame, respectively, and the working time of the gauge wheel arm swings around the point A and the contact limit with the depth-limiting block at the point B. The force analysis with point A where the gauge wheel arm is located as the research object shows that

\[
F_{Sy1}L_x + F_{JC}L_{x1} = 0
\]  

where \( F_{JC} \) is the depth-limiting contact force, the contact force between the depth-limiting block and gauge wheel arm, and the direction is always perpendicular to OA, \( N_i; F_{Sy1} \) is the fractional force of \( F_{Sy} \) in the vertical OA direction, \( N_i; L_x \) is the effective length of the gauge wheel arm, mm; \( L_{x1} \) is the length of the force arm of \( F_{JC} \) on OA, mm; \( \theta_c \) is the angle between the gauge wheel arm OA and the horizontal plane, °.
where $F_{JC}$ is the depth-limiting contact force, the contact force between the depth-limiting block and gauge wheel arm, and the direct impact is always perpendicular to OA, $N$; $g$ is the gravitational acceleration, take $9.8 \text{ m·s}^{-2}$.

Joining Equations (7)–(9), the contact force $F_{JC}$ is obtained as

$$F_{JC} = \cos \theta_c \frac{(1 + n) m_{\text{max}} g L_x}{L_{x1}}$$  (10)

The measured $m_{\text{max}}$ is about 120 kg, the angle $\theta_c$ of the gauge wheel arm in the minimum sowing state is 30° and the force arm action ratio $L_x:L_{x1}$ of the contact force $F_{JC}$ is 0.25. When $n$ is taken as 2, the maximum contact force $F_{JC}$ is 8700.5 N when substituted into Equation (10).

2.4. Electro-Hydraulic Integrated Sowing Depth Measurement and Control System Design

The electro-hydraulic integrated sowing depth system is developed based on the 470B seeding unit and the system includes a hardware part and a software part. The IPRC is used as the downforce driver and the sowing depth control algorithm based on feedforward regulation runs on the control unit.

2.4.1. Hardware Design
(a) Integrated Pressure-Reducing Cylinder (IPRC)

In order to facilitate the multi-row expansion and reduce the wiring and improve the system response speed, the electro-hydraulic IPRC is designed adaptively, which consists of a cartridge-type pressure-reducing valve and a single piston cylinder. As shown in Figure 6, the cylinder rod cavity is directly connected to the return path B, and the piston cavity is directly connected to the proportional pressure-reducing valve and connected...
In order to facilitate the multi-row expansion and reduce the wiring and improve the integration of the system, when the IPRC is working, the coil YA0 is energized, and the left position of the solenoid valve is pressurized; when the power is lost, the right position is decompressed, and the spool is dynamically balanced, so that the hydraulic force is stabilized near the target value.

Figure 6. (a) Diagram of the IPRC, (b) IPRC schematic: (1) valve block, (2) return pipe, (3) piston rod, (4) cylinder, (5) cartridge-type pressure-reducing valve.

In Section 2.3.1, the theoretical hydraulic force value of at least 10.3 kN needs to be applied at the four-bar linkage. Taking into account the no-till sowing environment, seed and fertilizer consumption and other factors, the design is carried out according to the maximum thrust limit \( P_n \) of the cylinder which is 16 kN and the pressure drop \( \Delta F_y \) which is 12~16 kN within the range of the mechanical adjustment of the sowing depth. According to the safe stroke \( S_{safe} \) of the cylinder which is 55 mm, the permissible stroke of the cylinder is determined as 60 mm and the installation distance is 30 cm. After consulting the work manual of the tractor, the oil supply pressure \( p \) of the tractor is selected as 16 MPa and the rated flow rate is 40 L·min\(^{-1}\).

The cylinder speed ratio is the area ratio of the rodless chamber to the rod chamber. Generally speaking, when the cylinder stroke is long and subject to thrust (piston rod extension when there is force), in order to improve the piston rod pressure stability, one should choose a higher cylinder speed ratio. We take the speed ratio factor of 1.38 commonly used in agricultural machinery. According to the design criteria of the hydraulic cylinder [42], the formula for calculating the hydraulic cylinder bore \( D \) is

\[
D = \sqrt{\frac{4P_n\phi}{\pi p}}
\]  \hspace{1cm} (11)

where \( D \) is the hydraulic cylinder inner diameter, m; \( P_n \) is the hydraulic cylinder theoretical thrust, take 16 kN; \( p \) is the system oil supply pressure, take 16 MPa; and \( \phi \) is the speed ratio coefficient, take 1.38.

The calculation can be obtained \( D \approx 0.0419 \) m, according to the hydraulic cylinder design manual, and the preliminary determination of the hydraulic cylinder bore \( D \) is 40 mm.

From the speed ratio formula,

\[
\phi = \frac{D^2}{D^2 - d^2}
\]  \hspace{1cm} (12)

Figure 6. (a) Diagram of the IPRC, (b) IPRC schematic: (1) valve block, (2) return pipe, (3) piston rod, (4) cylinder, (5) cartridge-type pressure-reducing valve.

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From the speed ratio formula,

\[
\phi = \frac{D^2}{D^2 - d^2}
\]  \hspace{1cm} (12)
where $D$ is the hydraulic cylinder inner diameter, take 0.04 m; $d$ is the hydraulic cylinder piston rod diameter, m; and $\phi$ is the speed ratio coefficient, take 1.38.

The calculation can be obtained $d = 20.1$ mm, according to the design manual of the hydraulic cylinder piston rod, and the diameter of the piston rod $d$ is 20 mm.

According to Pascal’s principle, the pressure-reducing range of the cylinder is

$$\Delta P = \frac{\Delta F_Y}{\pi \left( \frac{D}{2} \right)^2}$$

The theoretical downforce drop $\Delta F_Y$ is 4 kN, and the theoretical pressure reduction range is 3.184 MPa by substituting into Equation (13). Take the pressure reduction range as 0–3 MPa and choose the IPRC model ZH0001790 from Zaneda Transmission Control Co., Dalian, China. The 12 V DC proportional solenoid is selected with an operating current range of 0–1500 mA, a typical resistance value of 7.1 ± 5% $\Omega$ at 20 ℃, a recommended dither frequency of 350 Hz and a PWM frequency of 200 Hz; operating temperature: −40–10 ℃.

(b) Selection of the Pin and Angle Sensor

In Section 2.3.2, the maximum contact force $F_{JC}$ is 8700.5 N. Considering the range accuracy and the safety factor of the pin, the range of the load pin is 10 kN, and the LZ-HZ11-25 load pin is from Hefei Lizhi Sensor System Co., Anhui, China. The range is 1000 kg and the integrated accuracy is 0.5%, which meets the operation requirements (Figure 7a).

![Load pin and angle sensor](image)

Figure 7. (a) Load pin, (b) tilt angle sensor.

The inclination sensor is used to monitor the change in the angle $\theta_c$ between the gauge wheel arm and the horizontal surface in real time. Transmit the monitoring data to the control unit to complete the calculation of the ground compaction force. An SHS-001 (Chinese Academy of Agricultural Mechanization Sciences Group Co., Beijing, China) angle sensor is adopted (Figure 7b). The measuring range is ±45°, the measuring accuracy is ±0.1° and the response frequency is 20 Hz. Using the RS485 output interface, and a 9~36 V power supply, can realize a three-axis stable signal output.

2.4.2. Software Design

(a) Design of the Control System Structure

At present, although the cost of the PLC controller for vehicle engineering is higher than a micro-controller, it has the characteristics of fast computing speed, large storage capacity, simple and intuitive programming and easy modification, strong anti-interference ability and short development cycle, so it has been widely used in the industrial electrical automation field [43].

This sowing depth measurement and control system adopts the SPC-SFMC-X2214A vehicle controller as the seeder control unit, which complies with the IEC-61131-3 standard, supports CoDeSys programming and is waterproof at the IP67 level. The controller has 2 CAN buses, 1 RS232 serial communication, 7 PWM and 29 IO resource ports. In addition, the port is highly multiplexed and can directly drive the solenoid valve. The controller core
As shown in Figure 9, after suspending the row unit soil-contacting parts, the force of

(b) F-I Model Establishment

The electronic components such as the sensors installed on one row unit share a CAN bus communication network. The control programs are all written, downloaded and debugged in the CODESYS V3.5 SP14 programming environment, using the ST structured text language.

Due to the signal time lag, hydraulic system nonlinear changes and the presence of inertial loads on the machine, we introduced a PID closed-loop control algorithm that can be better adapted to complex field environments. In addition, based on the feedback PID regulation, a feedforward compensation algorithm is introduced to superimpose the fitted F-I model with the PID output, which can converge to the target downforce faster and make the system enter the steady-state quickly. The closed-loop PID depth control system with feedforward compensation is shown in Figure 8.

![Figure 8. Closed-loop PID depth control system with feedforward compensation.](image)

In PID controllers, the determination of the control parameters directly affects the speed, accuracy and stability of the depth control system. There are various methods to adjust the PID parameters. We use the most commonly used trial method in closed-loop control systems, also called the empirical method. In this method, $K_p$ is used to improve the response speed of the downforce and reduce the deviation in the compressive force; $K_i$ is used to reduce the downforce overload, as the overshoot is difficult to suppress, and a smaller $K_i$ and a larger $K_d$ should be taken to prevent the system from overshoot and reach the target compressive force quickly; $K_d$ is used to regulate the downforce in the future, and a smaller $K_d$ should be taken to avoid the high-frequency oscillation of the downforce.

We conducted the tests in the order of $K_{ff}$, $K_p$, $K_i$, $K_d$ accordingly, and the combination of parameters with the fastest response and highest accuracy were as follows: the feedforward control gain constant $K_{ff}$ is 0.1, proportional gain constant $K_p$ is 0.25, integral gain constant $K_i$ is 0.04 and differential gain constant $K_d$ is 130. To improve the real-time performance of the system, the PID control cycle time is set to 5 Hz by default, and the output range of the effective current with the deadband removed is 500–1400 mA.

(b) F-I Model Establishment

In order to approximate the target value more quickly when generating compressive force, combined with mechanical calculations, we have established the F-I relationship model between the input current of the IPRC and the downforce by field calibration. As shown in Figure 9, after suspending the row unit soil-contacting parts, the force of both sides of the gauge wheel on the ground was measured by using the self-researched intelligent weighing instrument, which is mounted on the gauge wheel support blocks. The input current range was 500–1400 mA (remove deadband), the step size was set to 50 and
the number of steps was 18. The weighing instrument readings were recorded and the data were imported into the MATLAB 2018 linear fitting tool, and the relationship between the input current value \( y \) of the IPRC and the downforce \( x \) was obtained as

\[
y = 1.231x - 614.666 \quad (500 \leq x \leq 1400) \tag{14}
\]

where \( y \) is the measured downforce value, N; and \( x \) is the input current value of the pressure-reducing valve, mA.

After the validation test of the model, Equation (15) was used as the F-I model for the relationship between the current and downforce. This model is used for the feedforward adjustment of the sowing depth control. When the difference in the downforce is measured, the output current can be adjusted according to the F-I model and superimposed with the output of the PID, which is able to reach the target downforce quickly in complex operating conditions.

(c) Sowing Depth System Control Flow Design

The system compares the actual value of the load pin with the target value of the compaction by collecting the load pin, and then calculates the difference by the control unit, outputs the incremental current according to the F-I model and runs the PID depth algorithm to achieve the target compaction force. All the control steps are shown in Figure 10.
The system compares the actual value of the load pin with the target value of the compaction by collecting the load pin, and then calculates the difference by the control unit, outputs the incremental current according to the F-I model and runs the PID depth algorithm to achieve the target compaction force. All the control steps are shown in Figure 10.

Figure 10. Sowing depth control flow chart.

1. The program opens the serial port to establish communication and starts initializing each operating parameter when it detects that the system is on;
2. The control unit receives the target value of the compaction force \( F_{\text{targ}} \) range \([F, f]\) set by the user on the display through the CAN communication program. By default, the depth control system gives three different compaction levels of “low, medium and high” for different crops. To avoid frequent starting and stopping of the IPRC, the default value range of \( F_{\text{targ}} \) is ±500 N and the CAN communication flag bit is used to determine whether the data are received successfully. \( F_{\text{targ}} \) is the average of \( F \) and \( f \);
3. Collect the analog output signal of the load pin, read the measured contact force actual value \( F_{JC} \), use the first-order low-pass filtering method to process the sensor data, and then replace it by the model for the measured compaction force \( F_{YS} \) and send the data to the CAN bus and display it on the screen;
4. The system judges whether the \( F_{YS} \) measurement is within the regulation range. If not, the system cycle re-monitors after delaying one sampling interval; if yes, the difference \( \Delta F \) between the \( F_{YS} \) measurement and \( F_{targ} \) is calculated, and the input current of the IPRC is adjusted according to the F-I model. Afterward, the downforce is driven to the target value by a PID closed-loop control algorithm with feedforward compensation;
5. Judge whether the system is closed. If yes, end the monitoring cycle; if no, delay the sampling interval and return to the starting point of the cycle.
(d) **HMI Development**

The system’s upper computer uses the SPD-070-Ax, a 7-inch display from Shobo Electronics, to communicate with the control unit through the RS-485 serial port, with default communication parameters of baud rate 9600 b/s, 8-bit data and no checksum. The HMI design and programming are written in the same CODESYS V3.5 SP17 programming environment based on the creation of the HMI Project module. The debugging and downloading of the program are performed via Ethernet connection to the PC. The \( F_{\text{targ}} \) for the on-screen parameter setting is sent to the PLC control unit via the CAN bus interface. The design of the HMI is shown in Figure 11, which mainly includes a communication switch, hydraulic switch and compression force range setting. In order to facilitate users to observe the system working condition, the real-time display of the current downforce \( F_{XY} \), the sidewall compaction force \( F_{YS} \) and the downforce quality evaluation index are set at the bottom of the interface.

![Figure 11. System display interface design.](image)

Among them, the sidewall compaction force setting range represents the triggering condition of the sowing depth system; the communication switch configures and initializes the parameters of each interface in the way that the control system turns on and off; the hydraulic switch controls the energization of the reversing valve of the main circuit; the current downforce can display the current downforce level of the single unit in real time, and its principle is the actual value of the downforce derived from the conversion of the feedback signal of the pressure-reducing valve; the sidewall compaction force made the monitoring value of the load pin be displayed in real time after filtering and calculating, and the data indicate the actual value of the comprehensive downforce of the gauge wheel on the soil; and the downforce quality index fluctuates and changes in real time with the operation, which reflects the evaluation index of the control effect of the downforce at that moment, and the downforce quality index \( W \) is calculated as follows:

\[
W = \frac{n_c}{N_c} \times 100\%
\]  

(16)

where \( W \) is the downforce mass index, %; \( n_c \) is the number of samples in the set compaction range; and \( N_c \) is the total number of samples per unit time of the compaction force.
2.5. Test Equipment and Methods

2.5.1. Experimental Arrangement

To test the effect of the sowing depth control of the system at different vehicle speeds and to compare the profiling performance of the mechanical adjustment and electro-hydraulic adjustment. The field test was conducted on November 10, 2022, in Hujiazhuang Township, Laishui County, Baoding City, Hebei Province, China. As shown in Figure 12, the test plot was no-till land, divided into an operating area of 150 m long and 25 m wide. The soil temperature of 5 cm below the surface of the test area was 10 °C and the relative humidity was 18.0% using the five-point sampling method (measured by RS-ECH-I20 temperature and humidity meter, Shandong Renke Measurement and Control Technology Co., Ltd., Jinan, China). The resolution of the measurement was 2.5 cm and 35 kPa (TJSD-750-IV soil compactness measuring instrument, Zhejiang Topunnong Technology Co., Hangzhou, China), as shown in Figure 13a. The test device was a 2BJ-470B corn no-till precision seeder (Hyundai Agricultural Equipment Technology Co., Ltd.) equipped with this paper’s sowing depth control system, with an overall mass of 1700 kg, a supporting power of 66.15 kW, an operating width of 2.8~3.2 m and a tractor traction connection, with a working row number of 4 and a row spacing of 0.7 m.

![Figure 12](image1.png)

Figure 12. Field tests.

![Figure 13](image2.png)

(a) (b)

Figure 13. Field tests. (a) Soil compaction measurement; (b) sowing depth measurement.

According to the agronomic requirements of the area, the sowing depth of all the row units was uniformly set to 50 mm by the sowing depth adjustment handle before the test, and the test plot was divided into three blocks in order to compare and test the sowing depth effect of different vehicle speeds. Three different speeds of 5~6 km·h⁻¹, 7~8 km·h⁻¹ and 9~10 km·h⁻¹ were used for the test. In order to compare the effect of the sowing depth with different adjustment methods, No.1 and No.2 were set as the mechanical spring adjustment in two pretightened, No.3 as the self-weight adjustment and No.4 as the electro-hydraulic adjustment. Before the test, the target compressive force range was set to...
[200, 500] N through the display. A total of 4 × 1500 kg counterweights were added to the seed drill to ensure that the downforce can be applied properly.

In order to facilitate visual measurement data, the closing wheel assembly at the end of the row unit was removed, the furrow closing operation of the seeder was cancelled and only the furrowing opening test was conducted. In order to reduce the influence of tractor acceleration and deceleration on the test results when turning around the ground, points were selected in the middle area 25 m away from the ground edge, and one measurement point was selected every four theoretical seed distances. The sowing depth was measured as the vertical distance from the surface plane to the bare seed skin (Figure 13b). Each vehicle speed was divided into 3 areas of the front, middle and back, and each area measured 10 sowing depth data as a group to carry out 3 sets of sowing performance tests under different vehicle speeds. The soil compaction of the seed groove after sowing was also measured using a soil compactness measuring instrument. The compaction measurement method is measure and record the soil compaction data of 2.5 cm, 5 cm, 7.5 cm and 10 cm depth below the ground surface on both sides of the seeds.

2.5.2. Evaluation Indicators

According to the determination standard of the qualified sowing depth range (h ± 10) mm in the agricultural industry standard NY/T 1768-2009 [44], the qualified sowing depth range of this test is set to 40–60 mm, and the calculation formula of each index is as follows:

$$\eta_1 = \frac{n_1}{N_1} \times 100\%$$ (17)

$$\bar{h} = \frac{\sum h_i}{N}$$ (18)

$$S_h = \sqrt{\frac{\sum (h_i - \bar{h})^2}{N}}$$ (19)

$$V_h = \frac{S_h}{\bar{h}} \times 100\%$$ (20)

where $\eta_1$ is the qualified rate of the sowing depth, %; $n_1$ is the number of the qualified sowing depth; $N_1$ is the total number of the sowing depth measurement points; $\bar{h}$ is the mean value of the sowing depth, mm; $h_i$ is the sowing depth measurement value, mm; $S_h$ is the standard deviation of the sowing depth, mm; and $V_h$ is the variation coefficient of the sowing depth, %.

In addition, according to the control principle of the downforce and the sowing depth, the situation in which the sowing depth is qualified but the compaction of the seed groove is too high is likely to occur when the downforce is overloaded. Especially for the no-till, the compactness of the soil before sowing is much higher than the soil condition of the tilled land, and the compaction of the sidewall of the seed groove should be reduced as much as possible during the no-till sowing. In order to comprehensively measure the suitability of the sowing depth and sidewall compaction, combined with the qualified compaction test data of no-till land [45,46], this test set the “seed groove environmental qualification rate” (SFEQ), and the method to determine whether the groove environment is qualified is if the sowing depth of a measurement point is within the set sowing depth ($h \pm 10$) m and the compaction data are within the interval of $[c,(1 + 20\%)c]$ of the post-sowing soil compactness. The point is judged as the “seed groove environmental qualification rate” (SFEQ). Where $c$ is the pre-sowing soil compaction/kPa, obtained by measuring the soil compaction data below $H$ (the set sowing depth) at the tire marks of the gauge wheel, and one measurement point corresponds to one pre-sowing soil compaction data.
The seed groove environmental qualification rate (SFEQ) is calculated by the following formula:

\[ \eta_2 = \frac{n_2}{N_2} \times 100\% \]  

(21)

where \( \eta_2 \) is the seed groove environmental qualification rate (SFEQ), %; \( n_2 \) is the number of the qualified seed groove environment; and \( N_2 \) is the total number of measuring points of the seed groove environment.

3. Results and Discussion

3.1. Dynamic Response Test of the Control System

In order to evaluate the actual control effect of the sowing depth measurement and control system, we conducted dynamic tests on the IPRC in the field. The commonly used compaction setting value range of 0~280 N was selected, with a setting interval of 70 N. Four compaction adjustment ranges were selected: 70 N, 140 N, 210 N and 280 N. The data sampling frequency was selected as 10 Hz, the sampling time was 15 s and the test results were obtained, as shown in Figure 14.

![Figure 14](image)

Figure 14. Step response test results of the depth system at different compressive force settings. (a) 0~70 N; (b) 0~140 N; (c) 0~210 N; (d) 0~280 N.

The test results show that when the target compressive force is in the range of 0~280 N, the steady-state error of the system response is less than 10. When the target compressive force is 280 N, the adjustment time and rise time are at a maximum, 6.1 s and 0.64 s, respectively. The overshoot range of the four tests is 18.7%~26.6%, and the average value is 21.8%. The range of the steady-state error is 6.2~10.7, the average value is 8.63 and the error is within 10% when the system is stable. Looking at the curve, it can be seen that the pressure at the end of the system response is slightly reduced, the natural leakage of the system pressure is caused and the introduction of feedback regulation not only eliminates the system static difference but also compensates for the hydraulic pressure leakage. The detailed test result data are shown in Table 1.
Table 1. Sowing depth system dynamic test results.

<table>
<thead>
<tr>
<th>Number</th>
<th>Target Compressive Force/N</th>
<th>Steady-State Value/N</th>
<th>Peak/N</th>
<th>Overshoot/%</th>
<th>Steady-State Error/N</th>
<th>Adjustment Time/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>70</td>
<td>73.1</td>
<td>88.10</td>
<td>20.52</td>
<td>3.1</td>
<td>3.9</td>
</tr>
<tr>
<td>2</td>
<td>140</td>
<td>144.25</td>
<td>164.83</td>
<td>14.26</td>
<td>4.25</td>
<td>5.2</td>
</tr>
<tr>
<td>3</td>
<td>210</td>
<td>204.18</td>
<td>252.13</td>
<td>23.48</td>
<td>5.82</td>
<td>5.7</td>
</tr>
<tr>
<td>4</td>
<td>280</td>
<td>272.83</td>
<td>299.28</td>
<td>9.69</td>
<td>7.17</td>
<td>6.1</td>
</tr>
<tr>
<td><strong>avg</strong></td>
<td></td>
<td><strong>16.99</strong></td>
<td>8.63</td>
<td><strong>5.23</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Compared with other studies on sowing depth control, we provide a more powerful and stable sowing depth measurement and control system for seeders with the help of a tractor hydraulic system. In response testing, for example, Bai Huijuan’s study [31] used a split hydraulic valve group design with common PID control. The response speed measured under a bench test was 2.69 s, steady-state error 91.5 N and overshoot 2.9%. In this paper, we chose to complete the dynamic response test in the field to be able to predict the actual effect of the control system intuitively. Under the field test, the overshoot was reduced by 25.9% on average, and the response accuracy was improved by 90.6%. This is due to the sowing depth measurement and control algorithm which can adjust itself according to the soil environment, so our system has higher response accuracy.

3.2. Analysis of Field Tests Results

3.2.1. Effect of Sowing Depth Control

Figure 15 shows the sowing depth measurement data of three vehicle speed levels under three types of downforce regulation. In order to reduce the error, the mid-range measurement data of each vehicle speed were selected. The one with the best sowing depth was selected as the comparison data among the two sets of mechanical spring adjustment data. As shown in Figure 15, the black line is the sowing depth data, and the stacked area graph is the soil compaction data after sowing. Although the test machine has high profiling accuracy for homogeneous profiling, there will be profiling advance and lag due to the terrain, so a small amount of measured sowing depth data will slightly exceed the set sowing depth $h$.

By comparing the sowing depth data of three kinds of pressure adjustment methods, it can be seen that the sowing depth under electro-hydraulic adjustment is the closest to the set value on the whole, and the sowing depth stability from high to low is electro-hydraulic adjustment, mechanical spring adjustment and self-weight adjustment; by comparing three kinds of vehicle speed levels, it can be seen that with the increase in the operating speed, electro-hydraulic adjustment has the least influence on the sowing depth effect, mechanical adjustment is second and self-weight adjustment is the most influenced by vehicle speed.

3.2.2. Sidewall Compaction Force Control Effect

The compaction was measured at 50 mm (set sowing depth) on the sidewall of the seed groove using a soil compactness meter and the average value was taken. The experimental study found that the mean value of post-sowing soil compaction with electro-hydraulic adjustment was 1100 kPa, which was about 15.8% higher than the mean value of the pre-sowing no-till soil compaction of 950 kPa. The soil compaction under the self-weight adjustment state fluctuated the most due to the vibration of the row unit during operation, caused by the undulation of the ground surface. The peak soil compaction at a depth of 50 mm below the ground surface was 1000 kPa during 5–6 km·h$^{-1}$ operation, while the peak compaction reached 1500 kPa during fast operation. Compared with the mechanical spring adjustment, the soil compaction degree of the electro-hydraulic adjustment is less affected by the vehicle speed and is more stable. Combined with the analysis of the sowing depth data, it can be found that the shallow sowing depth point is always accompanied by low soil compaction, which shows that the downforce of the row unit is not enough to meet
the working pressure required by the coulter, resulting in the gauge wheel being suspended on the surface without pressure, thus causing the sowing depth to be too shallow. This is also consistent with the growth relationship in Figure 15 where the sowing depth is positively related to the compaction.

![Figure 15. Sowing depth and compaction data of three adjustment methods at different vehicle speeds: (a–c) self-weight adjustment; (d–f) mechanical adjustment; (g–i) electro-hydraulic adjustment.](image)

The total sowing depth measurement data of the front, middle and back sections were compiled and analyzed. The calculation results according to the index calculation method of Equations (17)–(20) are shown in Table 2. It can be seen that the error of the electro-hydraulic regulation in the average value of the sowing depth is the smallest, and the maximum error with the set value (50 mm) is only 0.73 mm, which appears at 9–10 km·h⁻¹. It can be seen from the qualified rate of the sowing depth that the self-weight regulation is influenced by the vehicle speed, while the mechanical regulation and electro-hydraulic regulation do not change much in value. The reason for the analysis is that the downforce provided when the row unit passes through some of the plots is overloaded, resulting in reaching the upper limit of the sowing depth while causing excessive soil compaction on the sidewalls of the seed groove. A further analysis of the standard deviation of the sowing depth showed that the standard deviation of the self-weight adjustment was 6.72 mm, which occurred at 7–8 km·h⁻¹. Combined with the analysis in Figure 15, this was due to the shallow sowing caused by the row unit’s inability to provide sufficient downforce when encountering hard plots, while the mechanical and electro-hydraulic adjustments reduced the coefficient of variation of the sowing depth by virtue of sufficient downforce and improved the sowing depth qualification rate.
Table 2. Field test results of sowing depth control.

<table>
<thead>
<tr>
<th>Plotting Parameters</th>
<th>Adjust Method</th>
<th>Vehicle Speed / (km·h⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>5–6</td>
</tr>
<tr>
<td>Average sowing depth/mm</td>
<td>Self-weight</td>
<td>44.39</td>
</tr>
<tr>
<td></td>
<td>Mechanical</td>
<td>49.52</td>
</tr>
<tr>
<td></td>
<td>Electro-hydraulic</td>
<td>49.63</td>
</tr>
<tr>
<td>Sowing depth qualification rate/%</td>
<td>Self-weight</td>
<td>95.81</td>
</tr>
<tr>
<td></td>
<td>Mechanical</td>
<td>98.54</td>
</tr>
<tr>
<td></td>
<td>Electro-hydraulic</td>
<td>100.00</td>
</tr>
<tr>
<td>Standard deviation of sowing depth/mm</td>
<td>Self-weight</td>
<td>5.23</td>
</tr>
<tr>
<td></td>
<td>Mechanical</td>
<td>3.26</td>
</tr>
<tr>
<td></td>
<td>Electro-hydraulic</td>
<td>3.80</td>
</tr>
<tr>
<td>Coefficient of variation of sowing depth/%</td>
<td>Self-weight</td>
<td>11.78</td>
</tr>
<tr>
<td></td>
<td>Mechanical</td>
<td>6.58</td>
</tr>
<tr>
<td></td>
<td>Electro-hydraulic</td>
<td>7.66</td>
</tr>
</tbody>
</table>

In this section, the data of Bai huijuan’s study [31] show that the sowing depth qualification rates under electro-hydraulic control conditions are 88%, 82% and 78%. For the same electro-hydraulic-based sowing depth control, the integrated electro-hydraulic drive design has about 10% more of the qualification rate than the split design. In comparison, the coefficient of variation of the depth system using feedforward PID adjustment is reduced by about 53%. At a 5 cm depth setting, our integrated drive system has better suppression of vibration at high speed, which reduces the depth mismatch during high-speed operation.

The coefficient of variation of the sowing depth shows that the difference between the mechanical and electro-hydraulic regulation is not significant, which is presumed to be the reason that the mechanical group data are qualified in sowing depth but over-compacted due to the vibration bounce of the machine. For this reason, the seed groove environmental qualification rate (SFEQ) was established to further analyze the combined effect of the sowing depth and seed groove compaction.

3.2.3. Seed Groove Environmental Qualification Rate (SFEQ)

The seed groove environmental qualification rate (SFEQ) reflects the contact effect between the seeds and soil in the seed bed, including two important indexes of the sowing depth and seed groove compaction. According to the criteria for determining the qualified seed groove environment in Section 2.5.1, the data in Figure 15 were extracted and calculated to obtain a comparison chart of the SFEQ under three regulation methods, as shown in Figure 16.

Figure 16. The seed groove environmental qualification rate (SFEQ).
It can be seen that there is a 7% mean difference between the mechanical and electro-hydraulic regulation in the SFEQ. Combining the two sowing depth qualification rates confirms that although mechanical regulation can achieve the ideal sowing depth, excessive downforce will inevitably cause excessive soil compaction. Comparing the pass rate of the self-weight-adjusted seed groove environment, it can be found that the self-weight downforce of the single unit cannot meet the downforce requirement of the no-till soil environment. In the case of setting the sowing depth of 50 mm, the best rate of the SFEQ of the electro-hydraulic regulation was 98.6% with the maximum error of 2.4, the mechanical regulation was 91.6% with the maximum error of 4.29, and the self-weight regulation was 88.3% with the maximum error of 2.8. It confirmed that the control of soil compaction by electro-hydraulic regulation was more stable and reliable than mechanical and self-weight regulation, which further demonstrated the importance of electro-hydraulic regulation in high-speed no-till operation. Electro-hydraulic regulation in high-speed no-till operation is superior.

4. Conclusions

In this paper, we analyzed the process of sowing depth control of a 470B row unit, optimized the profiling mechanism with the IPRC, developed the feedforward adjustment sowing depth control algorithm under the CODESYS environment and designed an integrated electro-hydraulic-driven sowing depth measurement and control system. It solves the problems of the complex structure of the profiling mechanism, improves the stability of the sowing depth and reduces the compaction of the sidewall of the seed groove. The main research conclusions are as follows.

(1) The step response test results show that when the target compressive force is in the range of 0~280 N, the steady-state error of the system response is less than 10. When the target compressive force is 280 N, the adjustment time and rise time are at a maximum, 6.1 s and 0.64 s, respectively. The overshoot range of the four tests is 18.7%~26.6%, and the average value is 21.8%. The range of the steady-state error is 6.2~10.7, the average value is 8.63 and the error is within 10% when the system is stable.

(2) The field performance test results show that under the condition that the sowing depth is set at 50 mm and the vehicle speed is 9~10 km·h⁻¹, the sowing depth qualification rates of the three adjustment methods of self-weight, mechanical and electro-hydraulic adjustment are 89.2%, 96.7% and 98.6%, respectively. The corresponding maximum sowing depth coefficients of variation are 16.7%, 12.9% and 6.4%, respectively. The SFEQ was further analyzed in combination with soil compaction, and the average pass rates under the three adjustment methods are 88.3%, 91.6% and 98.2%, respectively. The test confirms that suitable downforce can effectively reduce the effect of vehicle speed on sowing depth and soil compaction, while electro-hydraulic regulation can avoid over-compaction of seed groove soil while ensuring the sowing depth. It further shows the superiority of electro-hydraulic regulation in high-speed no-till operation and reflects the importance of seeding row unit downforce regulation in building a qualified seed groove environment.

(3) Seed depth and soil compaction are an opposite problem; when we guarantee 100% seed depth, we necessarily give up some compaction issues. This paper for soil compaction tests only in the same plot, and the soil hardness variation range is small. The compaction effect of the seeder under different degrees of soil hardness was not examined. In the follow-up study, we will test the consistency of seedling emergence in a changing environment, such as different soil types and conditions, tillage practices, etc. In addition, the generally high pass rate of the sowing depth measured in this paper’s experiment is due to the good uniformity of the plots and the lack of a large sample size, and the need to define the criteria more strictly in subsequent experiments. Based on future test data, we aim to optimize the sowing depth measurement and control algorithm and gradually improve the performance of the multi-row seeder.
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