Variable comprehensive coefficient draft-position integrated tillage depth control method of tractor based on traction resistance interval division

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Abstract: Aiming at the problem that the draft-position integrated tillage depth control method with fixed comprehensive coefficient of tractor electro-hydraulic hitch system is difficult to adapt to the working environment with large changes in soil conditions, a tractor draft-position integrated tillage depth control method with variable comprehensive coefficient was proposed. A comprehensive coefficient control scheme based on traction resistance was designed and its working principle was clarified. Aiming at the time-varying tillage depth control system, a tillage depth control algorithm based on the sliding mode control with a differential observer was designed. In order to verify the performance of the control scheme, a control system simulation model and a bench test platform were built, and the performance was compared with the draft-position integrated control method with a fixed comprehensive coefficient of 0.5. The results showed that the variable comprehensive coefficient tillage depth control method can automatically adjust the comprehensive coefficient according to the change of soil conditions, and has higher traction efficiency. In the small resistance range, it can better ensure the quality of operation; in the large resistance range, it can ensure the engine performance and protect the tractor from damage. This method is more adaptable to the complex field operation environment, which provides a reference for the research of tillage depth control method.
Keywords: tractor, variable comprehensive coefficient, draft-position integrated tillage depth control, traction resistance
DOI: 10.25165/j.ijabe.20251806.9394

Citation: Sun X X, Song Y, Wang L, Lu Z X, Qian J, Wang T. Variable comprehensive coefficient draft-position integrated tillage depth control method of tractor based on traction resistance interval division. Int J Agric & Biol Eng, 2025; 18(6): 66–74.

1 Introduction

Precision agriculture serves as a critical approach for enhancing agricultural output, promoting sustainable agricultural development, and improving the efficiency of agricultural resource utilization[1,2]. Within this framework, engineering equipment technology plays a fundamental and supportive role in realizing the integrated system of precision agriculture[3,4]. The tractor electro-hydraulic hitch system, as a core component connecting the tractor to agricultural implements, undertakes essential functions including implement traction and working depth control. However, the complexity of field operating environments leads to strongly nonlinear and highly disturbed characteristics in tractor operations, which significantly increase the control difficulty of the electro-hydraulic hitch system and challenge the consistency of operational quality and efficiency[5]. With continuously rising demands for refined operations, the implementation of specific control methods to achieve automatic tillage depth control and enhance tractor operational quality and efficiency has become a key research focus[6,7].

Tractor electro-hydraulic hitch depth control methods can be categorized into single-factor control and integrated control strategies. Currently, widely used single-factor control methods mainly include position control[8,9] and draft control[10,11], which regulate tillage depth based on implement position and ploughing resistance, respectively. These methods are extensively adopted due to their operational simplicity. However, single-factor control methods exhibit several limitations. For instance, position control lacks terrain-following capability on uneven terrain, while draft control demonstrates poor depth stability in regions with significant soil variability. Therefore, under complex and variable field conditions, relying solely on single-factor control methods can hardly guarantee satisfactory operational performance.

A commonly used integrated approach is the draft-position integrated control method, which combines position and draft control through a comprehensive coefficient. This method integrates the advantages of both control strategies, exhibits better adaptability to complex field environments, enhances operational quality, and holds considerable potential for long-term research and practical application[12]. Shafaei et al.[13] developed a fuzzy control system for tractor depth-draft integration, formulating fuzzy rules based on wheel slip and actual tillage depth. Field validation demonstrated that the proposed system improved traction efficiency and overall energy efficiency by 20% and 73%, respectively, compared to conventional draft control systems. Shang et al.[14] investigated two

Received date: 2024-09-23 **Accepted date:** 2025-10-30
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integrated depth control strategies—switching method and weighting coefficient method—and concluded that the weighting coefficient method holds greater research potential. Xu et al.[15], Xiao et al.[16], and Han et al.[17] designed draft-position integrated depth control systems and analyzed control performance under different comprehensive coefficients. However, these studies were limited to manually set coefficients, which are subject to subjective influence. Li[18] proposed a variable-weight draft-position integrated control strategy, where the operator sets an initial comprehensive coefficient and adjusts the draft control weight according to soil condition variations during operation. Nonetheless, both the initial coefficient setting and subsequent adjustments still rely heavily on operator experience. Xi et al.[19] established a desired comprehensive coefficient model based on a BP neural network aiming at tillage depth uniformity, enabling coefficient adjustment according to variations in tillage depth and draft resistance. However, the model's accuracy has not been experimentally validated. Wang et al.[20] developed a simulation model for tractor variable-weight draft-position integrated control and derived an approximate relationship between the weighting coefficient range and soil specific resistance through simulation. Experimental results verified the advantages of the variable-weight integrated control method.

In summary, considerable research has been conducted on tractor draft-position integrated control. However, most studies are confined to comparative analyses based on manually set comprehensive coefficients, which are susceptible to human factors. There has been limited research on self-adaptive comprehensive coefficient adjustment for draft-position integrated control under complex field conditions. To address this gap, this paper proposes a variable comprehensive coefficient-based draft-position integrated tillage depth control method, which determines the coefficient through predefined draft resistance intervals. By establishing a relationship between draft resistance and the comprehensive coefficient with the objective of improving traction efficiency, this method aims to achieve automatic selection and adjustment of the comprehensive coefficient according to complex field conditions, thereby enhancing tractor operational quality and efficiency.

2 Materials and methods

2.1 System structure and working principle

The structure of the tractor electro-hydraulic hitch tillage depth control system is shown in Figure 1. The system was mainly composed of controller, operating panel, hydraulic pump, hydraulic cylinder, solenoid valve, and so on. It was equipped with wheel speed sensor, draft sensor, displacement sensor, pressure sensor, radar, and other sensing elements. Each electronic control unit on the tractor transmits data through the CAN bus. The driver only needs to select the appropriate working mode through the operation panel according to the actual operation requirements, so that the tractor has high operation efficiency and operation coordination ability. The working principle of the tractor electro-hydraulic hitch tillage depth control system is as follows: the driver selects different tillage depth control modes through the control panel, and sets the target tillage depth value to the controller. At the same time, each sensor will collect the actual signal for real-time feedback. The controller compares the target signal obtained by the control panel with the actual signal fed back by the sensor, calculates the corresponding deviation and inputs it into the control algorithm to obtain the corresponding control quantity. The displacement of the valve core of the plow depth control valve is changed by the output control quantity, which drives the hydraulic cylinder to elongate and contract, so as to control the rise and fall of the suspension plow.

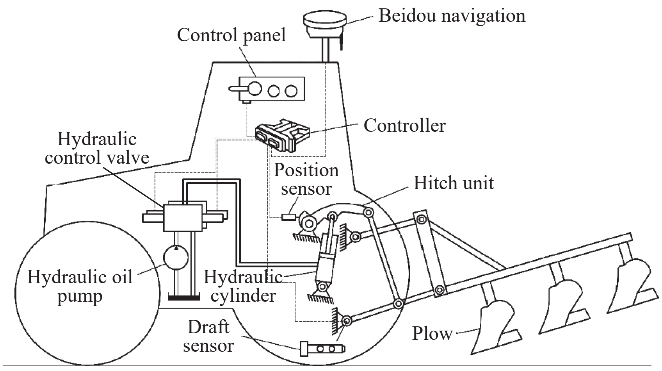
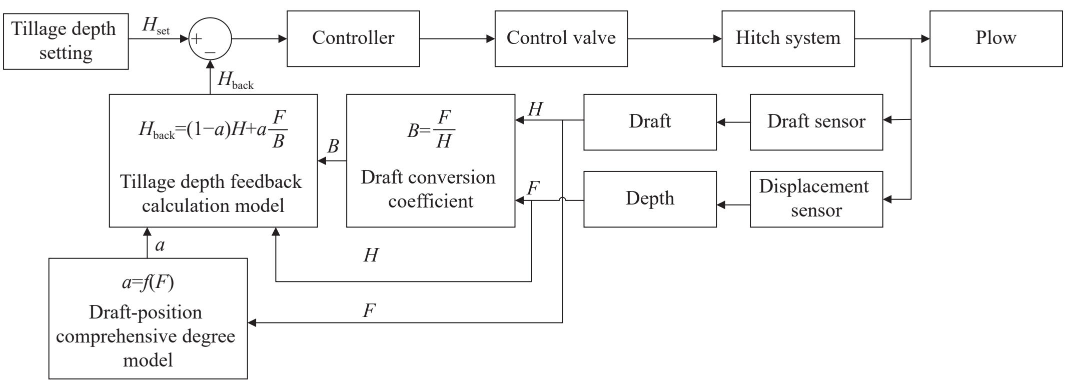


Figure 1 Structure of tractor electro-hydraulic hitch control system

2.2 Tillage depth control methods

2.2.1 Draft-position integrated tillage depth control method

The draft-position integrated tillage depth control method of tractor electro-hydraulic hitch system is a tillage depth control method that comprehensively applies the characteristics of position control and draft control. It combines the advantages of better tillage depth uniformity of position control and better engine traction load stability of resistance control. The principle of the tractor variable weight gravity potential comprehensive tillage depth control method is shown in Figure 2.



Note: H_{set} represents the target tillage depth; H_{back} represents the actual tillage depth feedback; B represents the draft conversion coefficient; H represents the tillage depth measured by the displacement sensor; F represents the draft measured by the draft sensor; a represents the weight coefficient for draft control.

Figure 2 Structure of tractor electro-hydraulic hitch tillage depth control system

The driver sets the target value of tillage depth H_{set} through the operation panel. Before the start of the operation, the tractor first performs pre-tillage operation. The actual tillage depth H fed back by the displacement sensor and the actual traction resistance F fed back by the traction sensor are used to calculate the initial draft-equivalent tillage depth coefficient B_0 of the working environment. After the start of the operation, the actual working resistance of the draft sensor feedback and the initial draft-equivalent tillage depth coefficient B_0 calculate the equivalent tillage depth of the real-time resistance. The actual working resistance feedback from the draft sensor and the actual tillage depth feedback from the displacement sensor are used to calculate the real-time draft-equivalent tillage depth coefficient B. The variable weight model outputs the weight coefficient a at this time according to the real-time ploughing resistance feedback from the draft sensor. Finally, the tillage depth feedback calculation model uses the weight a and the feedback of the current displacement sensor and the draft sensor to calculate the final tillage depth feedback value H_{back} and compares it with the tillage depth target value H_{set} set by the driver. The actual tillage depth deviation is input into the tillage depth controller to control the tillage depth.

2.2.2 Variable comprehensive coefficient control method based on traction resistance interval division

Tractor traction performance is affected by a variety of parameters[21-23]. Traction resistance is a key factor affecting the traction efficiency of tractors. The traction efficiency of tractors during operation can be expressed as:

$$\eta_T = \eta_f \eta_\delta \eta_c \tag{1}$$

where, η_T is traction efficiency; η_f is rolling efficiency; η_δ is slip efficiency; η_c is transmission system efficiency.

The efficiency of the tractor's transmission system varies slightly and can be treated as constant. Thus, the overall traction efficiency is primarily governed by the rolling and slip efficiencies. Prior experimental studies on the driving wheel slip rate have demonstrated that Equation (2) accurately fits the slip rate curve[24,25]:

$$\varphi = \varphi_{\max}\left(1 - e^{-\frac{\delta}{\delta^*}}\right) \tag{2}$$

where, φ is driving force coefficient, defined as the ratio of the driving force to the vertical load on the driving wheel; φ_{max} is the limit value of φ on the φ-δ curve; δ is the slip rate; δ^* is the characteristic slip rate.

Therefore, the slip efficiency of the tractor can be expressed as:

$$\eta_\delta = 1 + \delta^* \cdot \ln\left(1 - \frac{\varphi}{\varphi_{\max}}\right) \tag{3}$$

The rolling efficiency of the tractor is defined as the ratio of the tractor traction to the driving force, which can be expressed as:

$$\eta_f = \frac{F_T}{F_q} = \frac{F_q - F_f}{F_q} \tag{4}$$

where, F_T is tractor traction, N; F_q is the driving force of the tractor, N; F_f is the rolling resistance of the tractor, N.

According to the Equations (1)－(4), the tractor traction efficiency is obtained as follows:

$$\eta_T = \frac{\varphi - f}{\varphi}(1-\delta) = \frac{\varphi_{\max}\left(1 - e^{-\frac{\delta}{\delta^*}}\right) - f}{\varphi_{\max}\left(1 - e^{-\frac{\delta}{\delta^*}}\right)}(1-\delta) \tag{5}$$

where, f represents the rolling resistance coefficient.

According to the experimental data of the slip rate curve of the tractor traction test summarized by the predecessors, the characteristic value of the drive wheel slip rate curve equation is obtained by fitting, as listed in Table 1.

The eigenvalues of Table 1 are substituted into Equations (2) and (5). The corresponding traction efficiency curve is obtained as shown in Figure 3.

Table 1 Statistical results of eigenvalues of slip curve[26]

Terra type	φ_{max}	δ^*	f
Stubble-field	0.704	0.15	0.06

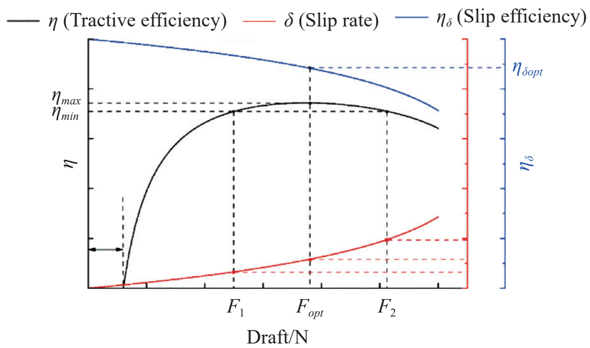


Figure 3 Traction efficiency curve of tractor

It can be seen from Figure 3 that there is a most favorable traction resistance value F_{opt} when the tractor operates under certain soil conditions. When the actual traction resistance is less than F_{opt}, the traction efficiency of the tractor increases with the increase in the traction resistance. However, when the traction resistance reaches the optimal traction resistance F_{opt}, the traction efficiency begins to decrease as the traction resistance continues to increase. On the other hand, with the increase in traction resistance, the tractor slip rate also increases, and the tractor slips seriously. Therefore, controlling the size of the traction resistance in a certain range can enable the tractor to obtain higher traction efficiency.

In the process of tillage depth control, the tractor's traction resistance can be effectively controlled by changing the comprehensive coefficient of draft control and position control. Therefore, this paper proposes a variable comprehensive coefficient tillage depth adjustment method based on traction resistance interval division. During the tractor plowing operations, the operating tractor traction resistance is divided into three intervals of small resistance, medium resistance, and large resistance. The regulation rules of tillage depth mode are listed in Table 2.

Table 2 Rule table of tillage depth mode adjustment

	Small resistance	Medium resistance	Large resistance
Range of traction resistance	$F < F_1$	$F_1 < F < F_2$	$F > F_2$
Control method	Position control	Draft-position integrated control	Draft control

F_1 is the minimum value of the traction resistance of the tractor in the range of high traction efficiency, that is, the traction resistance value corresponding to the minimum slip rate δ_{min} in the allowable optimal slip rate range. When the tractor works under the condition that the working resistance is less than F_1, because the actual working load is relatively easy compared with the working tractor at this time, in order to obtain higher uniformity of tillage depth, the position control mode is fully adopted, that is, the comprehensive coefficient a=0. F_2 is the maximum traction resistance of the tractor in the range of high traction efficiency, that is, the traction resistance value corresponding to the maximum slip rate δ_{max} in the allowable optimal slip rate interval. When the tractor works under the condition that the working resistance is greater than F_2, the slip rate of the tractor will increase due to the large actual working load. In order to maintain high working efficiency, the resistance control working mode is completely adopted, and the comprehensive coefficient a=1. When the tractor works under the condition that the working resistance is greater than F_1 and less than F_2, the draft-position integrated control working mode is adopted to adjust the comprehensive coefficient to change with the working resistance, so as to integrate the uniformity of tillage depth and the traction efficiency of the tractor. The relationship between comprehensive coefficient and work resistance is shown in Equation (6).

$$a = \frac{1}{F_2 - F_1}F - \frac{F_1}{F_2 - F_1} \tag{6}$$

2.3 Transfer function of electro-hydraulic hitch system

The signal transmission of tractor electro-hydraulic hitch hydraulic system is mainly divided into two parts. First, the control valve receives the electrical signal, which is converted into the electromagnetic force to promote the movement of the valve spool according to the principle of electromagnetic induction, and realizes the conversion of the electrical signal and the valve spool displacement signal. Second, the spool displacement changes the valve opening, resulting in changes in the flow of the valve. Based on flow balance and external load balance, the conversion of valve core displacement and piston displacement is realized. The simplified model of the valve-controlled cylinder system is shown in Figure 4.

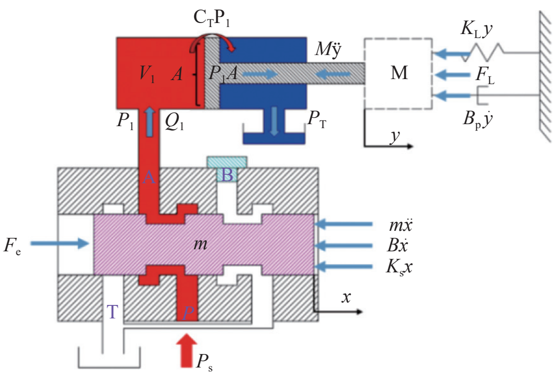


Figure 4 Simplified model of valve-controlled cylinder system

2.3.1 Voltage-valve spool displacement

The solenoid valve is mainly based on the principle of electromagnetic induction, which converts the electrical signal input by the control unit into electromagnetic suction, so as to overcome the spring preload to promote the movement of the valve spool and realize the conversion of electricity-draft-displacement. The electromagnet suction equation and the electromagnet dynamics equation are as follows:

$$\begin{cases} F_e = K_i i - K_y x \\ F_e = m\frac{d^2_x}{dt^2} + B_e\frac{d_x}{d_t} + K_s x \end{cases} \tag{7}$$

where, F_e is the suction of proportional electromagnet, N; K_i is the current gain of proportional electromagnet, N/A; i is the proportional electromagnet working current, A; K_y is the displacement gain of proportional electromagnet, N/mm; x is the displacement of the valve spool, mm; m is the quality of the valve spool, kg; B_e is the damping coefficient, N·s/m; K_s is the spring stiffness, N/m.

The Laplace transform of Equation (7) is obtained such that:

$$(ms^2 + B_e s + (K_s + K_y))X(s) = K_i I(s) \tag{8}$$

where, $X(s)$ and $I(s)$ are the Laplace transforms of x and i.

The relationship between the control voltage and the working current of the electromagnet can be expressed as:

$$i = K_e u \tag{9}$$

where, K_e is the proportional relationship between input voltage and working current, A/V; u is the control voltage of solenoid valve, V.

According to Equation (8) and Equation (9), the relationship between voltage and spool displacement is linearized to obtain:

$$X(s) = K_U U(s) \tag{10}$$

where, K_U is the gain from voltage to displacement, mm/V; $U(s)$ are the Laplace transforms of u.

2.3.2 Spool displacement-hydraulic cylinder displacement

In order to simplify the mathematical model of the control valve, it is assumed that the opening area at the orifice is symmetrical. When the control valve works normally, the valve core leaves the set dead zone, and the linearized flow equation of the control valve, the flow equation of the hydraulic cylinder, and the force equation of the piston are obtained as follows.

$$\begin{cases} Q_1 = K_q x - K_C P_1 \\ Q_1 = A\frac{dy}{dt} + \frac{V_t}{4\beta_e}\frac{dP_1}{dt} + C_t P_1 \\ P_1 A = M\frac{d^2y}{dt^2} + B_p\frac{dy}{dt} + K_L y + F_L \end{cases} \tag{11}$$

where, Q_1 is flow of hydraulic cylinder working chamber, L/min; P_1 is the pressure of hydraulic cylinder working chamber, MPa; K_q is the flow gain of the valve, L/min·mm; K_C is the flow-pressure gain of the valve, L/min·MPa; A is the cross-sectional area of the hydraulic cylinder working chamber, m²; V_t is the total stroke volume, m³; β_e is the elastic modulus, Pa; C_t is the leakage coefficient, L/min·MPa; M is the equivalent mass of load, kg; B_p is the viscous-damping coefficient, N·s/m; K_L is the load spring stiffness, N/m; y is the displacement of hydraulic cylinder, mm; F_L is the external load, N.

The Laplace transform of Equation (11) is obtained such that:

$$\begin{cases} Q_1(s) = K_q X(s) - K_C P_1(s) \\ Q_1(s) = AY(s)s + \frac{V_t}{4\beta_e}P_1(s)s + C_t P_1(s) \\ AP_1(s) = MY(s)s^2 + B_p Y(s)s + K_L Y(s) + F_L \end{cases} \tag{12}$$

According to Equation (10) and Equation (12), the relationship between the control voltage and the displacement of the hydraulic cylinder piston is:

$$\frac{Y(s)}{U(s)} = \frac{K_U K_q / A}{\frac{MV_t}{4\beta_e A^2}s^3 + \left[\frac{M(K_C + C_t)}{A^2} + \frac{B_p V_t}{4\beta_e A^2}\right]s^2 + \left[1 + \frac{B_p(K_C + C_t)}{A^2} + \frac{K_L V_t}{4\beta_e A^2}\right]s + \frac{K_L(K_C + C_t)}{A^2}} \tag{13}$$

2.4 Tillage depth control strategy based on sliding mode control with differential observer

The mathematical model of the tractor electro-hydraulic hitch system is transformed into state space equation:

$$\begin{cases} \dot{x}_1 = x_2,\ \dot{x}_2 = x_3 \\ \dot{x}_3 = -b_3 x_3 - b_2 x_2 - b_1 x_1 + a_0 u \\ y = x_1 \end{cases} \tag{14}$$

where, x_1 is the displacement of the hydraulic cylinder, mm; x_2 is the velocity of the hydraulic cylinder, mm/s; x_3 is the acceleration of the hydraulic cylinder, mm/s^2; u represents the control voltage, V; a_0, b_1, b_2, and b_3 are coefficients of the state-space model, which can be expressed as:

$$\begin{cases} a_0 = 4AK_U K_q \beta_e / MV_t \\ b_1 = -4K_L(K_C + C_t)\beta_e / MV_t \\ b_2 = -[4\beta_e\left(A^2 + B_p(K_C + C_t)\right) + K_L V_t] / MV_t \\ b_3 = -[4M(K_C + C_t)\beta_e + B_p V_t] / MV_t \end{cases} \tag{15}$$

The sliding surface s is defined as:

$$s = c_1 e + c_2 \dot{e} + \ddot{e} \tag{16}$$

$$e = x_1 - r \tag{17}$$

where, c_1 and c_2 are the sliding mode surface parameters, s^{-1}; and r denotes the input position command, mm.

The constant velocity reaching law is selected, and according to Equation (14), we have:

$$u = -\frac{1}{a_0}(\eta s - b_1 x_1 - b_2 x_2 - b_3 x_3 + c_1 e + c_2 \dot{e} - \dddot{r}) \tag{18}$$

where, η is the control law parameter.

It can be seen from the above formula that when the control rate is Equation (18), it is necessary to know the speed and acceleration of the tillage depth change of the tractor electro-hydraulic hitch system. However, in the actual operation process, the estimation of the speed and acceleration of the tillage depth information measured by the angular displacement sensor has certain challenges in engineering. Therefore, the differentiator is introduced to realize the extraction and derivation of the signal. The third-order high-gain differentiator of the system obtained by Equation (14) is:

$$\begin{cases} \dot{\hat{x}}_1 = \hat{x}_2 - \dfrac{k_3}{\varepsilon}(\hat{x}_1 - x_1(t)) \\ \dot{\hat{x}}_2 = \hat{x}_3 - \dfrac{k_2}{\varepsilon}(\hat{x}_1 - x_1(t)) \\ \dot{\hat{x}}_3 = -\dfrac{k_1}{\varepsilon^2}(\hat{x}_1 - x_1(t)) \end{cases} \tag{19}$$

where, $\hat{x}_1$, $\hat{x}_2$, and $\hat{x}_3$ are the estimates of x_1, x_2, and x_3, sharing the same units; $x_1(t)$ is the measured cylinder displacement, mm; k_1, k_2, k_3 are the dimensionless gains of the third-order differentiator; ε is the time constant that determines its bandwidth, s.

When $s^3 + k_1 s^2 + k_2 s + k_3 = 0$ satisfies the Hurwitz condition, we have: $\hat{x}_1 \to x_1$, $\hat{x}_2 \to x_2$, $\hat{x}_3 \to x_3$. That is, the estimated values asymptotically converge to their true values.

The control rate Equation (18) is changed to obtain:

$$u = -\frac{1}{a_0}\left(\eta s - b_1 \hat{x}_1 - b_2 \hat{x}_2 - b_3 \hat{x}_3 + c_1 \hat{e} + c_2 \dot{\hat{e}} - \dddot{r}\right) \tag{20}$$

$$\begin{cases} \hat{e} = \hat{x}_1 - r \\ \hat{s} = c_1 \hat{e} + c_2 \dot{\hat{e}} + \ddot{\hat{e}} \end{cases} \tag{21}$$

Then

$$\dot{s} = c_1 \dot{e} + c_2 \ddot{e} + \dddot{e} = c_1 \dot{e} + c_2 \ddot{e} - b_3 x_3 - b_2 x_2 - b_1 x_1 - \eta \hat{s} + b_1 \hat{x}_1 + b_2 \hat{x}_2 + b_3 \hat{x}_3 - c_1 \dot{\hat{e}} - c_2 \ddot{\hat{e}} \tag{22}$$

$$\begin{cases} v = c_1 \dot{e} + c_2 \ddot{e} - c_1 \dot{\hat{e}} - c_2 \ddot{\hat{e}} \\ \alpha(x) = -b_3 x_3 - b_2 x_2 - b_1 x_1 \end{cases} \tag{23}$$

$$\dot{s} = -\eta \hat{s} + v + \alpha(x) - \alpha(\hat{x}) \tag{24}$$

The Lyapunov function is defined as:

$$V = \frac{1}{2}s^2 \tag{25}$$

Then

$$\dot{V}_1 = -\eta s^2 + s((\eta c_1 - b_1)\tilde{x}_1 + (\eta c_2 - b_2 + c_1)\tilde{x}_2 + (\eta - b_3 + c_2)\tilde{x}_3)s \tag{26}$$

$$\begin{cases} \tilde{x}_1 = e - \hat{e} \\ \tilde{x}_2 = \dot{e} - \dot{\hat{e}} \\ \tilde{x}_3 = \ddot{e} - \ddot{\hat{e}} \end{cases} \tag{27}$$

When the observation error of the differentiator is small, then:

$$\dot{V} \leq 0 \tag{28}$$

The parameters of the third-order high-gain differentiator observer were tuned based on mechanism analysis and the trial-and-error method. In accordance with the control system stability requirements, the selection of k_1, k_2, and k_3 should be determined by the Hurwitz polynomial. The Hurwitz polynomial is constructed as follows:

$$P(s) = (s + w)^3 = s^3 + 3ws^2 + 3w^2 s + w^3 \tag{29}$$

where, s is the complex frequency domain variable, s^{-1}; and w is the constructed variable, rad/s.

Thus, the following expression can be obtained:

$$\begin{cases} k_1 = 3w \\ k_2 = 3w^2 \\ k_3 = w^3 \end{cases} \tag{30}$$

Therefore, the observer parameters can be characterized by w and ε. Subsequently, based on the trial-and-error method, the range of w and ε is determined according to whether the system oscillates. Finally, through parallel simulation in MATLAB with the objective of minimizing system overshoot, the ultimate parameter values were determined.

2.5 Construction of bench test system

The bench test system consists of two parts: suspension control and simulated loading. The structure is shown in Figure 5. It mainly includes hydraulic pump, plough depth control valve, lifting cylinder, loading cylinder, test plough frame, controller, data acquisition card, host computer, draft sensor, and displacement sensor. During the test, the data acquisition card generates a control signal to control the loading cylinder to simulate the loading of the test plow frame; the draft sensor sends the actual traction resistance to the slip rate model through the CAN bus to realize the real-time monitoring of the slip rate. At the same time, the controller receives the signals of the displacement sensor and the draft sensor, calculates the tillage depth control signal according to the control algorithm, sends it to the plough depth control valve, and adjusts the tillage depth by driving the lifting cylinder.

3 Results and discussion

3.1 Analysis of simulation results

The factors affecting the traction resistance are plow structure, tillage depth, tillage width, tillage speed, and soil mechanical properties. Assuming that the structure of the plough body is unchanged, when the tractor operates at a constant speed at the target tillage depth, the soil mechanical properties are the main reason for the change in the traction resistance of the ploughing

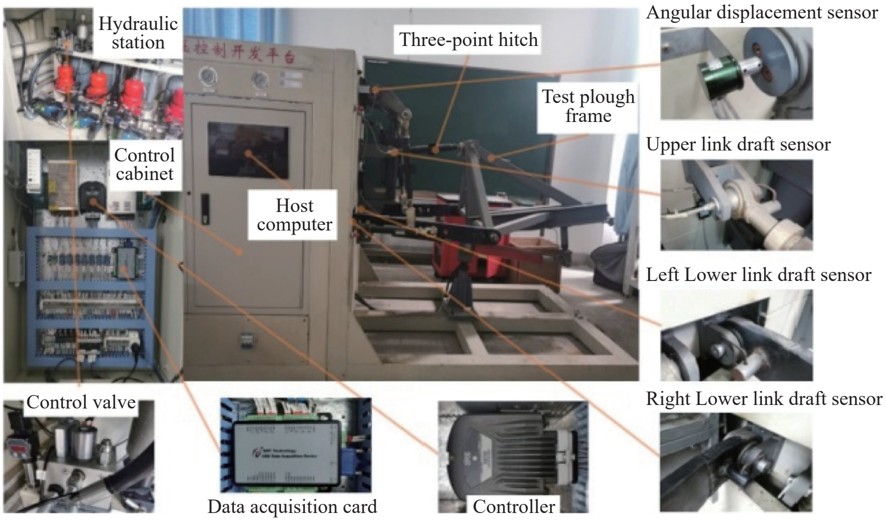


Figure 5 Field diagram of bench test

operation, which is generally described by the soil specific resistance. According to the relevant literature, the soil specific resistance of different types of soil is about 2.5-8.5 N/cm². In order to verify the dynamic performance of the tractor electro-hydraulic hitch tillage depth control system under the change of traction resistance, this paper simulates the change of actual traction resistance through soil specific resistance. According to the range of soil specific resistance, random signals with mean values of 3.5 N/cm², 5.5 N/cm², 7.5 N/cm², and fluctuation range of 0.5 N/cm² were selected to simulate different soil conditions. The target value of tillage depth is set to 25 cm, and the target value of draft is set to 14 000 N. Under the same soil conditions, the simulation research of draft-position comprehensive control with fixed comprehensive coefficient of 0.5 and variable comprehensive coefficient draft-position comprehensive control proposed in this paper is carried out respectively. The comparison results are shown in Figures 6 and 7.

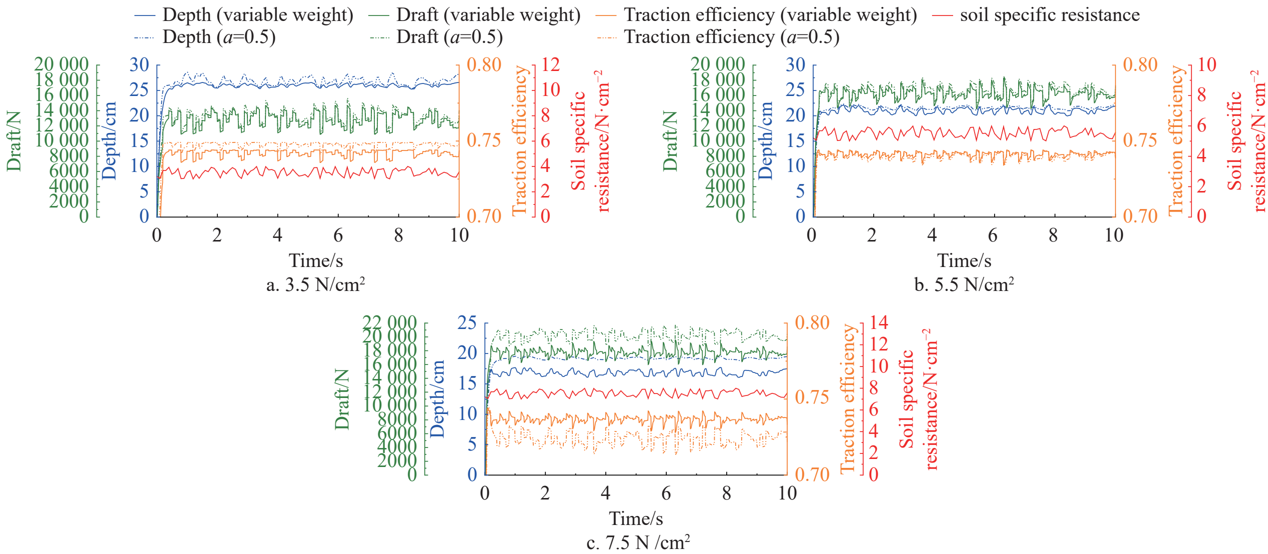


Figure 6 Comparison of the draft-position integrated control method with variable comprehensive coefficient and fixed comprehensive coefficient under different soil specific resistance

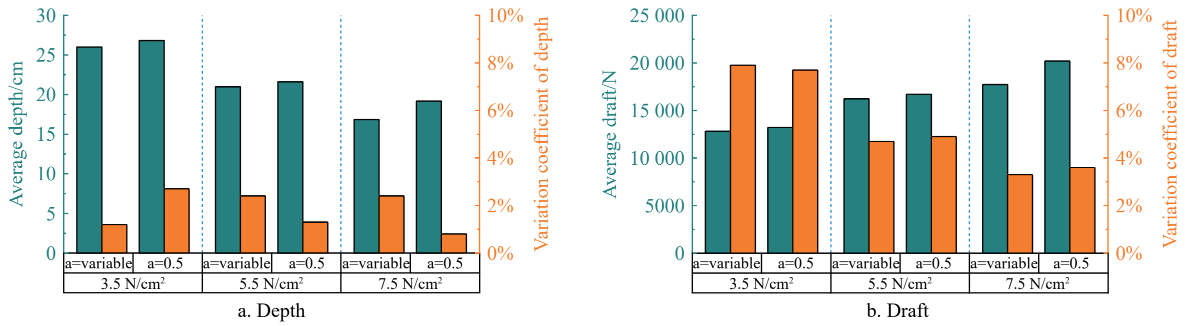


Figure 7 Comparison of the draft-position integrated control method with variable comprehensive coefficient and fixed comprehensive coefficient operation quality under different soil specific resistance

It can be seen from Figure 6a and Figure 7 that when the soil specific resistance fluctuates randomly around 3.5 N/cm², the average tillage depth was 26.8 cm, the coefficient of variation of tillage depth was 2.7%, the average draft was 13 217 N, the coefficient of variation of draft was 7.7%, and the average traction efficiency was 74.8% when the draft-position integrated control method with a fixed comprehensive coefficient of 0.5 was adopted. When the variable comprehensive coefficient tillage depth control method was adopted, the mean value of tillage depth was 25.9 cm, the coefficient of variation of tillage depth was 1.2%, the mean value of draft was 12 819 N, the coefficient of variation of draft was 7.9%, and the mean value of traction efficiency was 74.2%. The deviation between the mean value of tillage depth and the target tillage depth under the variable comprehensive coefficient method was significantly smaller than the error between the mean value of tillage depth and the target tillage depth under the fixed comprehensive coefficient method, and the coefficient of variation of tillage depth under the variable comprehensive coefficient method is significantly smaller than the coefficient of variation of tillage depth under the fixed comprehensive coefficient method. In terms of tillage depth deviation and tillage depth stability, the variable comprehensive coefficient method has obvious advantages. However, the traction efficiency under the variable comprehensive coefficient method is less than that under the fixed comprehensive coefficient method. This is because the traction resistance is small at this time, and the actual workload is easier than the tractor. In order to obtain higher operating quality, part of the traction efficiency is sacrificed.

According to Figure 6b and Figure 7, when the soil specific resistance fluctuates randomly around 5.5 N/cm^2, the average tillage depth was 21.6 cm, the coefficient of variation of tillage depth was 1.3%, the average draft was 16 701 N, the coefficient of variation of draft was 4.9%, and the average traction efficiency was 74% when the draft-position integrated control method with fixed comprehensive coefficient of 0.5 was adopted. When the variable comprehensive coefficient tillage depth control method was adopted, the average tillage depth was 20.9 cm, the coefficient of variation of tillage depth was 2.4%, the average draft was 16 218 N, the coefficient of variation of draft was 4.7%, and the average traction efficiency was 74.1%. At this time, the soil specific resistance is moderate, and the variable comprehensive coefficient method is more dominant in the stability of tillage depth. In terms of traction control and traction efficiency, the control effects obtained by the two control methods are not much different.

According to Figure 6c and Figure 7, when the soil specific resistance fluctuates randomly around 7.5 N/cm^2, the average tillage depth was 19.2 cm, the coefficient of variation of tillage depth was 0.8%, the average draft was 20 200 N, the coefficient of variation of draft was 3.6%, and the average traction efficiency was 72.3% when the draft-position integrated control method with fixed comprehensive coefficient of 0.5 was adopted. When the variable comprehensive coefficient tillage depth control method was adopted, the average tillage depth was 16.8 cm, the coefficient of variation of tillage depth was 2.4%, the average draft was 17 720 N, the coefficient of variation of draft was 3.3%, and the average traction efficiency was 73.7%.

3.2 Analysis of bench test results

In order to verify the effectiveness of the variable comprehensive coefficient integrated control method proposed in this paper, the test verification was carried out by using the tractor electro-hydraulic hitch test bench. The target value of tillage depth was set as 25 cm, and the sinusoidal signals with mean values of 3 N/cm^2, 5 N/cm^2, 7 N/cm^2 and amplitude of 1 N/cm^2 were selected to simulate different soil conditions. The draft-position integrated control test with a fixed comprehensive coefficient of 0.5 and the draft-position integrated control test with a variable comprehensive coefficient proposed in this paper were carried out respectively. The test results are shown in Figure 8.

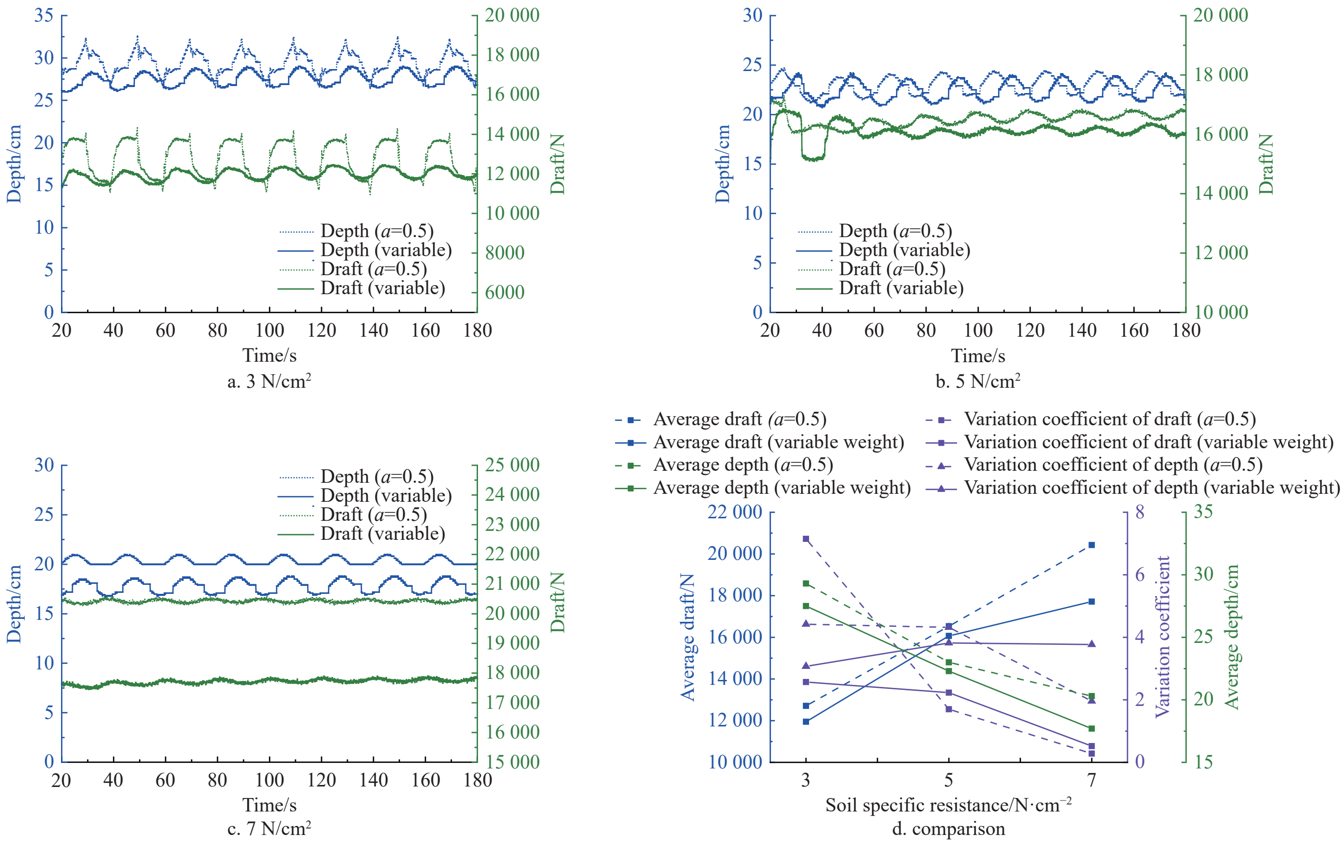


Figure 8 Bench test results

According to Figure 8, when the soil specific resistance fluctuates randomly around 3.5 N/cm^2, the average tillage depth was 29.3 cm, the coefficient of variation of tillage depth was 4.4%, the average draft was 12 721 N, and the coefficient of variation of draft was 7.2% when the draft-position integrated control method with a fixed comprehensive coefficient of 0.5 was adopted. When the variable comprehensive coefficient tillage depth control method was adopted, the average tillage depth was 27.5 cm, the coefficient of variation of tillage depth was 3.1%, the average draft was 11 950 N, and the coefficient of variation of draft was 2.6%. When the soil specific resistance fluctuates randomly around 5.5 N/cm^2, the average tillage depth was 23.0 cm, the coefficient of variation of tillage depth was 4.2%, the average draft was 16 533 N, and the coefficient of variation of draft was 1.7% when the draft-position integrated control method with a fixed comprehensive coefficient of 0.5 was adopted. When the variable comprehensive coefficient tillage depth control method was adopted, the average tillage depth was 22.3 cm, the coefficient of variation of tillage depth was 3.8%, the average draft was 16 068 N, and the coefficient of variation of draft was 2.2%. When the soil specific resistance fluctuates randomly around 7.5 N/cm^2, the average tillage depth was 20.3 cm, the coefficient of variation of tillage depth was 1.9%, the average draft was 20 427 N, and the coefficient of variation of draft was 0.3% when the draft-position integrated control method with fixed comprehensive coefficient of 0.5 was adopted. When the variable comprehensive coefficient tillage depth control method was adopted, the average tillage depth was 17.7 cm, the coefficient of variation of tillage depth was 3.8%, the average draft was 17 712 N, and the coefficient of variation of draft was 0.5%.

It can be seen from the test results that when the soil specific resistance is small, compared with the draft-position integrated control method with a fixed comprehensive coefficient of 0.5, the deviation between the average value of the actual tillage depth and the target tillage depth is small and the stability of the tillage depth is better under the variable comprehensive coefficient control method. In terms of draft, the mean value of the draft under the two methods is not much different, but compared with the fixed comprehensive coefficient method, the fluctuation range of the draft under the variable comprehensive coefficient method is smaller. When the soil specific resistance is moderate, the mean value of tillage depth and the mean value of the draft are basically the same under the two methods, and the coefficient of variation of tillage depth and the coefficient of variation of draft are not much different. Therefore, at this time, the control effects of the two methods are not much different. When the soil specific resistance is large, in terms of tillage quality, whether it is the deviation between the actual tillage depth and the target tillage depth or the stability of the tillage depth, the fixed comprehensive coefficient method has more advantages. However, at this time, the average draft under the variable comprehensive coefficient method is significantly smaller than the average draft of the fixed comprehensive coefficient method. This is because the traction resistance is large at this time, and the actual working load is close to the rated draft of the tractor. In order to ensure the passing performance of the tractor, prevent the tractor from slipping, and obtain higher traction efficiency, part of the operation quality is sacrificed.

In summary, the test results were basically consistent with the simulation results. The coefficient of the variable comprehensive coefficient tillage depth control method can be automatically judged and selected according to the soil condition during the operation process, which verifies the practicability of the algorithm. Through the comparative test, it is found that the variable comprehensive coefficient tillage depth control method can ensure that the tillage depth gives full play to the position control method and obtains a smaller tillage depth error when the soil specific resistance is small. When the soil specific resistance is large, the performance of the tractor can be guaranteed to give full play to the advantages of the draft control method, and the operation efficiency is also improved.

4 Conclusions

To address the limitations of the conventional draft-position control method with a fixed comprehensive coefficient for tractor tillage depth, this paper develops a novel control method with a variable comprehensive coefficient. The corresponding control model was established and the control strategy was formulated. The effectiveness of the proposed method was verified through computer simulations and bench tests. The main conclusions are as follows:

Based on the synovial control algorithm with differential observer, an electro-hydraulic hitch tillage depth automatic control system was developed. The feasibility and correctness of the draft-position integrated tillage depth control method with variable comprehensive coefficient were verified by simulation and bench test. The bench test results are basically the same as the simulation results, which verified the accuracy of the simulation model. The test results show that in the small resistance interval, the error between the actual tillage depth under the variable comprehensive coefficient control method and the set target tillage depth is small, and the fluctuation range of draft under the draft-position integrated control method with a fixed comprehensive coefficient of 0.5 is higher. In the middle resistance range, the control effects of the two methods are basically the same. In the large resistance range, the stability of the draft under the variable comprehensive coefficient control method is higher, and the error between the actual tillage depth and the set target tillage depth under the draft-position integrated control method with a fixed comprehensive coefficient of 0.5 is smaller.

In summary, the proposed variable comprehensive coefficient method dynamically adjusts the coefficient based on soil condition changes. This approach significantly outperforms methods with a fixed coefficient in improving tillage quality and maintaining draft stability.

Acknowledgements

This research was funded by the National Key Research and Development Plan of China (Grant No. 2022YFD2001202), The Open Project of the State Key Laboratory of Intelligent Agricultural Power Equipment (SKLIAPE2023019), and The Postgraduate Research and Practice Innovation Program of Jiangsu Province, China (Grant No. KYCX22_0716).

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