RESEARCH ON PLC SYSTEM DESIGN OF A NEW TYPE OF ROTARY TILLER CONTROL PARAMETERS (Programmable Logic Controller)

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一种新型旋耕机调控参数的 PLC 系统设计研究

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ABSTRACT

The purpose of this paper is to design a rotary tiller control system based on programmable controller technology, and verify the application of this control system. In this paper, the traction and depth control of rotary tiller are transformed into the control of piston rod displacement of hydraulic cylinder, and the intelligent fuzzy control of axial extension displacement of rotary tiller and output torque of piston rod is realized. According to the characteristics of the mathematical model, the objective function is determined and the motion parameters are optimized by the steepest descent method, which provides a reliable calculation model for the optimization design of the overall parameters of the rotary tiller. The rotary tiller control system based on PLC (Programmable Logic Controller) can realize the effective control of rotary tillage depth and speed, and the error of rotary tillage depth can be guaranteed within 4.5%. When the soil resistance of the rotary tiller suddenly increases, the fuzzy control of the comprehensive tillage depth value of the stressed position can effectively improve the rotational speed stability of the hydraulic motor for tillage depth control. PLC technology puts the digital control of rotary tiller on a higher technical platform, thus reducing the labour required for agricultural planting, providing a good growth environment for crops and realizing the intelligence of rotary tiller.

摘要

本文设计了一种基于可编程控制器技术的旋耕机控制系统，并验证该控制系统的应用。将旋耕机的牵引力和深度控制转化为液压缸活塞杆位移控制，实现了旋耕机轴向伸出位移和活塞杆输出扭矩的智能模糊控制。根据数学模型的特点确定目标函数和用最速下降法优化运动参数，为旋耕机总体参数的优化设计提供了可靠的计算模型。基于 PLC 的旋耕机控制系统实现了旋耕深度和速度的有效控制，旋耕深度误差保证在 4.5%以内。当旋耕机土壤阻力突然增大时，应力位置综合耕深值的模糊控制可以有效地提高液压马达的转速稳定性。PLC 技术将旋耕机的数字化控制置于更高的技术平台上，减少了农业种植所需的劳动力，为农作物提供了良好的生长环境，实现了旋耕机的智能化。

INTRODUCTION

Solving the food problem of national population is the top priority of agricultural development, and maintaining national food security is the top priority of agricultural production *(Chen Y. L. et al., 2018)*. Farming is the first link of agricultural production. The purpose of tillage and soil preparation is to increase the deep plough layer and promote the development of crop roots, which is the basic condition for high yield of crops. Through tillage and soil preparation, the subsoiling layer can be obtained, which is conducive to the smooth extension and transplanting of crop roots. At the same time, the soil aggregate structure can be restored and the soil maturity can be promoted *(Pretty J. et al., 2018)*. The improved subsoil was transferred to the upper layer to keep the permeability and ventilation of the soil. Field preparation can also reduce the occurrence of plant diseases and insect pests.

In agricultural production, the most important and basic link is cultivated land operation, and its cultivation quality directly affects the growth of crops *(Storm H. et al., 2020)*. The literature adopts the parameter index of roller-skating rate of operating units to control the cultivation depth *(Minakov I. A. and Nikitin A. V. 2019)*. The monitoring module group including radar, magnetic and other hardware sensors is used to feed back the actual farming depth of farming machinery in real time.

Ahmed I. et al., (2017) developed the tractor electro-hydraulic suspension system, which can adjust the resistance value of the tillage parts of the tillage machinery, the position of the parts, the working pressure of the hydraulic system actuator and the slip rate in real time to a great extent. *Kerr W. C. et al., (2019),* innovatively proposed to introduce the time domain analysis method into the research of dynamic performance. At the same time, based on this, the mathematical model of some components of hydraulic system with resistance adjustment was constructed, and the research work focused on the effects of two parameters, namely resistance coefficient and natural frequency, on the system. *Mariotte P. et al., (2018)* made a detailed inquiry into the motion and mechanical characteristics encountered in the field of tillage depth adjustment of hydraulic system of tillage machinery. By introducing the dynamic balance relationship into the establishment of the mathematical model of the system, the balance equation was successfully written, and on this basis, the transfer mathematical relationship between the natural frequency value and the loaded hydraulic system was obtained.

Ji J. T. et al., (2019) studies the arrangement of blades. The experimental results show that the spiral arrangement is simple and the parameters are single, but the lateral offset torque produced in the operation process is large, which is easy to cause the soil or straw to move laterally. *Zhou Z. et al., (2017),* conducted field experiments on micro rotary tillers with different blade arrangement forms and numbers. Before the experiment, the soil firmness was determined to be 245-1442kPa, and the soil moisture content was 34.6%. The test results showed that the micro rotary tiller with double four rotary tillers arranged opposite to each other had the best operation performance and less power consumption during operation. *Ma L. et al., (2019)*, when studying the structural parameters and arrangement of blades, it also devotes itself to studying the wear resistance of rotary tillage blades. By processing rotary tillage blades, the corresponding operation performance can be improved. *Aliev E. B. et al., (2018),* studied the rotary tillage blades, and carried out laboratory soil trough experiments by optimizing the existing three types of rotary tillage blades, namely C-shaped, L-shaped and RC-shaped. The rotation angles of the three blades are different, and the cutting distances during working are also different. *Rasmussen L. V. et al., (2018),* studied the deep ploughing rotary tiller and the reverse rotary tiller respectively, with the aim of improving the operation quality and increasing the tillage depth of the rotary tiller under the premise of low power consumption. *Du X. et al., (2020),* applied smooth fluid dynamics theory to simulate the soil cutting process of rotary tiller, and analysed the soil cutting process of rotary tiller. The simulation results provided theoretical basis for the optimization design of the whole machine or its parts.

Rotary tiller is mainly powered by tractor, which is composed of control system, frame, transmission mechanism, cutter roller, soil retaining cover and levelling pallet *(Huang Y. et al., 2018)*. Different control systems use different control methods to exchange information between the controller and the executive parts of the rotary tiller, which cannot achieve mutual compatibility between different systems. Programmable Logic Controller (PLC), as a logic control operating system, can edit and store programs, and realize the input/output, operation and control of control programs *(Taheripour F. and Tyner W. E., 2018)*. Therefore, a control system of rotary tiller is designed based on PLC technology, and the application of the control system is verified.

MATERIALS AND METHODS

Working principle of control system

The electric control hydraulic system of rotary tiller mainly includes three parts: hydraulic, electric control and mechanical. Among them, the hydraulic system mainly includes hydraulic components such as hydraulic pump, hydraulic cylinder and control valve. The electronic control system mainly includes ploughing depth, resistance sensor and controller in its hardware composition. Mechanical system mainly includes three-point suspension mechanism, cutter shaft and cutter. The theory of realizing digital control of rotary tiller is to use PLC technology to control the rotary tillage depth and the walking speed of rotary tiller, and to combine computer with sensors. The field information is collected by sensors, and the information is fed back to the control centre for analysis. The output results control the lifting of the horizontal adjusting rod, so as to achieve the purposes of uniform rotary tillage depth, stable walking speed and guarantee the rotary tillage quality.

The working principle of the system is as follows: by transmitting the displacement signals of traction resistance and tillage depth of rotary tiller detected by the resistance and tillage depth sensors in the electronic control system to the controller, the actual resistance and tillage depth values are calculated. At the same time, the controller takes the tillage depth value set on the control panel as the target signal, compares it with the actual value, adjusts the function control valve in the system, and completes the control of the rotary tillage depth of the rotary tiller.

The comprehensive control of force and position firstly synthesizes the traction resistance and tillage depth control of rotary tiller into the control of telescopic displacement of hydraulic cylinder (rotary tillage depth control), then uses the deviation between target and actual value as the input signal of the system control centre, outputs the control signal after processing, and adjusts the control valve in the hydraulic system, thus completing the control of the tillage depth of rotary tiller.

The comprehensive coefficient α is expressed as the proportion of rotary tiller tillage depth control in the comprehensive control formula of rotary tiller traction resistance and tillage depth. The actual tillage depth measured by the tillage depth sensor is h_1, and the traction resistance F of the rotary tiller is measured in real time by the resistance sensor. Use the following formula to transform F into the depth value h_2.

$$h_2 = \frac{F}{\beta \cdot b} \tag{1}$$

In the formula 1, β is soil specific resistance, (N/mm^2); b is ploughing width, (mm).

$$h = \alpha h_1 + (1-\alpha) h_2 \tag{2}$$

In the formula 2, h is the comprehensive actual ploughing depth.

The control system takes the rotary tillage depth detection signal, $x(t)$, collected by the sensor as negative feedback, and forms an annular control analysis system with the setting signal $y(t)$, when the rotary tiller works. The setting signal $y(t)$ in the single chip microcomputer is compared with the signal $x(t)$ detected by the sensor installed on the rotary tiller.

When the set signal is greater than the detection signal, that is, the actual rotary tillage depth is less than the set rotary tillage depth, the control system will send a signal, reduce the output power, reduce the walking speed of the rotary tiller or stop, control the horizontal rod to descend, adjust the rotary tillage depth of the blade to reach the set value, and then continue to work.

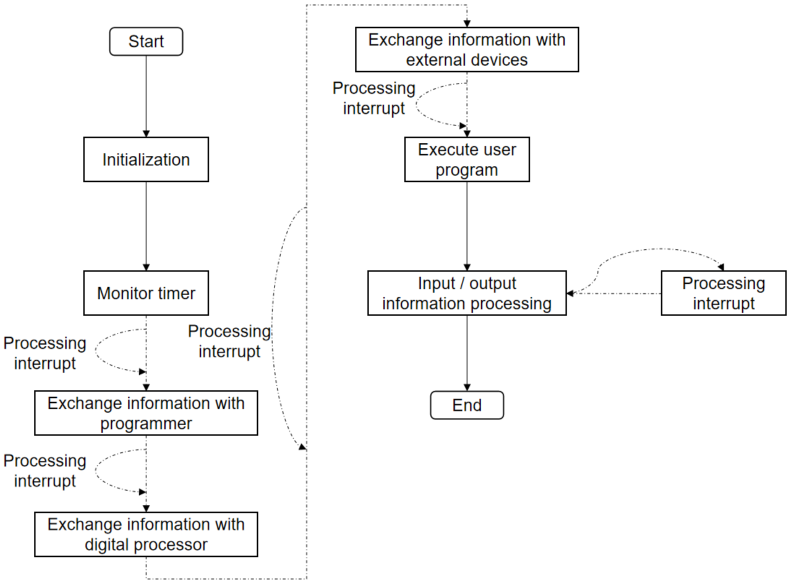

Fig. 1 - Working procedure of PLC technology control system

When the set signal is less than the detection signal, that is, the actual rotary tillage depth meets or even exceeds the set rotary tillage depth, then the control system outputs a signal to order the rotary tiller to continue to move forward and carry out the next rotary tillage of soil. The working procedure of the control system is shown in Figure 1.

The control system converts and compares the collected signals, analyses the comparison results, generates signals and outputs judgment signals, and adjusts the machines and tools to meet the requirements. The control of rotary tillage depth and walking speed is mainly by changing the output power of the engine, which is mainly accomplished by frequency converter. Changing the frequency can control the rotation speed of the engine, thus controlling the walking speed and rotary tillage depth. The main task of MCU is to digitize, pre-emphasize, filter and window the signal, and output the analysis results.

Fuzzy controller design

Fuzzy control has great similarities with people's thinking mode. By transforming the empirical knowledge of engineers and technicians in this field into language rules that the controller can handle, the decision is completed. Therefore, compared with the traditional control mode, fuzzy control does not need an accurate mathematical model of the controlled object, and makes the control mechanism and strategy easy to be understood by engineers and technicians. Therefore, the design of the control system is simple and the application is convenient. This control method has five core components: fuzzy controller, actuator, input/output interface, controlled object and detection device. As shown in figure 2.

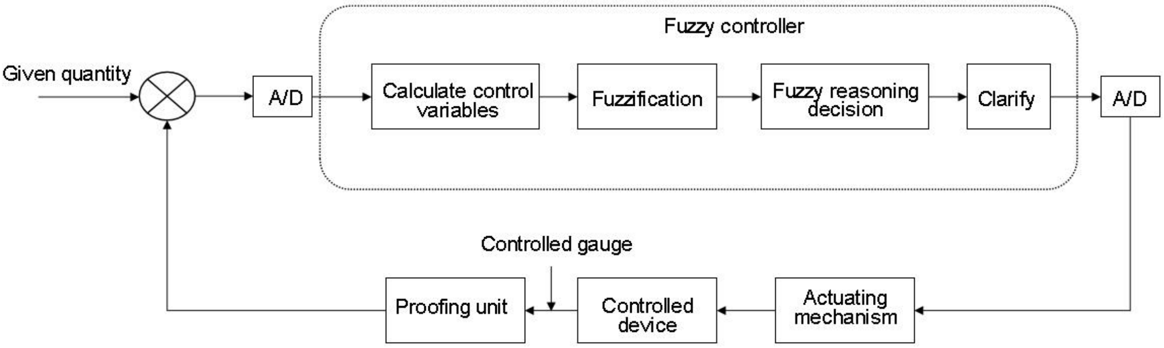

Fig. 2 - Schematic diagram of fuzzy control system

To a great extent, this kind of controller fully absorbs the knowledge and experience of engineers and technicians in this field, and transforms human experience into language rules. The working principle of the controller is that the digital quantity x_1 input by the system is firstly converted into fuzzy quantity by fuzzification (D/F), and then the converted fuzzy quantity is processed by the inference module containing fuzzy rules to obtain fuzzy output signals, and finally converted into clear quantity u by the defuzzification module (F/D), which is output to the controlled object, finally realizing fuzzy control.

The inputs of fuzzy controller are displacement deviation e and deviation change rate de/dt of hydraulic cylinder piston, and their fuzzy definitions are shown in Table 1.

Table 1

Input parameters of fuzzy controller

Input parameter	Definition
Displacement of piston rod of hydraulic cylinder (mm)	0-280
Basic universe of piston rod displacement deviation e	[-280-280]
Deviation e discrete universe	{-5,-4,-3,-2,-1,0,1,2,3,4,5}
Fuzzy subset of deviation e	NB, NM, NS, Z, PS, PM, PB
Basic universe of deviation e, change rate de/dt	[-80, 80]
de/dt discrete universe	{-5,-4,-3,-2,-1,0,1,2,3,4,5}
de/dt fuzzy subset	NB, NM, NS, Z, PS, PM, PB

The output of the fuzzy controller is the control current I, and the fuzzy definition is shown in Table 2.

Table 2

Output parameters of fuzzy controller

Output parameters	Definition
Control current I	[-1300, 1300]
Discrete universe of control current I	{-6,-5,-4,-3,-2,-1,0,1,2,3,4,5,6}
Fuzzy subset of control current I	

The quantization and scaling factors obtained from Table 1 and Table 2 are as follows: K_e=5/280=0.018; K_{de}=5/80=0.063; K_I=1300/6=217.

The fuzzy controller used in this paper is double input-single output, in which the control language rules are the most common form.

See Table 3 for the control rules of the comprehensive fuzzy control system of rotary tiller force and position.

Table 3

Fuzzy control rule table

		Displacement deviation e						
		NB	NM	MS	Z	PS	PM	PB
Deviation rate of change de/dt	NB	PB	PB	PM	PS	Z	PS	PB
	NM	PB	PM	PS	PS	Z	PS	PB
	NS	PM	PS	PS	Z	MS	PM	PB
	NS	PS	PS	PS	PM	MS	PM	Z
	Z	Z	PS	Z	PM	MS	PM	Z
	Z	Z	Z	Z	PS	PB	NM	NB
	PB	PS	PS	Z	PS	PB	NB	NB

PLC programming

PLC is a controller developed in recent years, which has played a great role in industry. The design and installation of PLC are convenient. In PLC, the complex wiring in relay control system can be replaced by soft relay system to realize the internal logic system, which is convenient for debugging and modification. PLC also has the functions of self-diagnosis, fault alarm, fault alarm type display and network communication, which is convenient for operators and maintenance personnel to check.

Siemens S7-200 series PLC system is simple and easy to program, and can work normally under different environments, such as high temperature, high humidity, strong vibration and impact interference. It has good adaptability and good economy, and can be used for automatic steering design of rotary tiller blade hot rolling. Its control system is stable and reliable, which improves the generation efficiency and meets the application requirements.

According to the requirements of automatic steering control, in which each sensor signal detection original occupies an input point, each power execution original occupies an output point, and the display of each indicator lamp also occupies an output point, so the device has four input signals and five output signals. The input and output points corresponding to each signal are shown in Table 4.

Table 4

I/O allocation table

Input signal	**I point**	**Output signal**	**O point**
Sensor signal K_1	X_{001}	Actuation of cylinder 4	Y_{001}
Sensor signal K_2	X_{002}	Actuation of cylinder 12	Y_{002}
Sensor signal K_3	X_{003}	Indicator lamp HL1	Y_{003}
Sensor signal K_4	X_{004}	Indicator lamp HL2	Y_{004}
		Indicator lamp HL3	Y_{001}

Note: The cylinder 4 realizes that before the blade slides down to the cylinder, the sensor senses and the cylinder executes the push-out action; The air cylinder 12 is used to push the incoming blades to the production line and realize automatic steering. Sensor K_1 is the signal before sensing blade sliding down, sensor K_2 is the signal of blade before cylinder 4, sensor K_3 is the signal of blade before cylinder 12, and sensor K_4 is the demand signal of production line, in which status indicator HL1 before blade sliding down, indicator HL2 before blade sliding down cylinder 4 and indicator HL3 before blade sliding down cylinder 12 are on.

According to the I/O port allocation table of PLC, I/O electrical wiring diagram can be designed from the input points and output points, as shown in fig. 3.

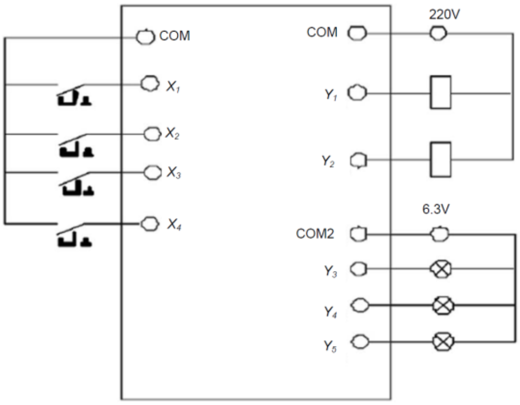

Fig. 3 - I/O wiring diagram

In the design process, the designed program should be able to complete the automatic steering function of rotary tiller blade hot rolling. Try to use simple programs to achieve the required functions and the programs should be easy to read. The ladder diagram of program design is shown in Figure 4.

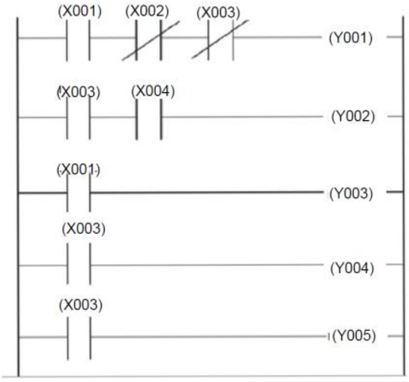

Fig. 4 - Ladder diagram

Ploughing width design module

The theoretical value of the bulge height is equal to the distance c between the intersection of two adjacent cycloids and the bottom of the ditch, and the bulge height of the bottom of the ditch is generally less than 20% of the cultivated depth. Therefore, the bulge height conditions of the bottom of the ditch are as follows:

$$
\begin{aligned}
&c < 0.2h \\
&R\sqrt{1-\frac{(R-c)^2}{R}}+\frac{v_m}{\omega}\arcsin\frac{(R-c)}{R}=\frac{v_m}{\omega}\left(\frac{\pi}{z}+\frac{\pi}{z}\right)
\end{aligned}
\tag{3}
$$

For rotary tillage blades cutting soil in the same longitudinal plane, the advancing distance of the unit is called the cutting pitch in the time interval of cutting soil one after another. According to the test, the S (soil cutting distance) is about 100-110mm for dry ploughing of cultivated land (water content 20%-30%); Farming light and medium viscosity soil (water content is more than 35%), S is 70-90mm; S should be 50-60mm for heavy soil and grassland. Therefore, the cutting pitch conditions are as follows:

$$\frac{S_{\min}}{2\pi}z < \frac{v_m}{\omega} < \frac{S_{\max}}{2\pi}z \tag{4}$$

Efficiency

When the rotary cultivator works, the forward speed directly affects the tillage quality of the rotary cultivator. Therefore, in order to ensure better soil tillage quality, the forward speed of the unit can neither be too fast nor too slow, and if the forward speed is too fast, the tillage quality is not good, and if it is too slow, it leads to the decrease of production efficiency and the increase of power.

The power consumption of rotary tiller is one of the important factors affecting the cultivation width. The formula of total power consumption of rotary tiller is as follows:

$$N = N_P + N_Q + N_T + N_F + N_K \tag{5}$$

Where N is the total power consumed by the rotary tiller; N_p is throwing power; N_Q is cutting power; N_T is the forward power; N_F is transmission friction power; N_K is the blocking power of soil. The energy consumption ratio of rotary tillage is also one of the important factors affecting the tillage width. The commonly used energy consumption ratio of rotary tillage is the energy consumed by rotary tillage per unit volume of soil, and the formula is:

$$K_R = \frac{N}{BHV_M} \tag{6}$$

Where N is the total power consumed by the rotary tiller; B is the width of rotary tillage; H is the depth of rotary tillage; V_M is the forward speed.

RESULTS

Accuracy analysis of rotary tillage depth and rate control of rotary tiller

In order to test the precision of rotary tillage depth and speed control of rotary tiller in actual situation, a 200m × 200m dry land was selected as the experimental site, and the sensors were installed on the rotary tiller and the initial parameters of the control system were set for the experiment. Figure 5 shows the working process of the rotary tiller based on the PLC control system.

Fig. 5 - Working process of rotary tiller based on PLC control system

The performance test of digital control system of agricultural rotary tiller based on PLC technology, the initial rotary tillage depth is set as 5 rotary tillage depth tests of 8, 9, 10, 11 and 12 cm, the rotary tiller runs freely in the ground, each rotary tillage depth is tested for 3 times, and the rotary tillage depth is detected manually, and the walking speed of the rotary tiller is detected by a speed measuring instrument. Test data are shown in Table 5.

Table 5

Rotary tillage depth detection data

Depth setting	1 times/cm	2 times/cm	3 times/cm	Average error/%
8cm	8.2	8.1	8.4	4.3
9cm	9.3	9.6	9.1	3.6
10cm	10.2	10.6	10.5	4.5
11cm	11.3	11.7	13.6	3.7
12cm	14.7	13.9	14.8	3.9

The detection results of the above data show that the maximum average error of rotary tillage depth is 4.5%, which can meet the requirements of cultivated land. It can be seen from the data in table 5 that the rotary tillage speed of the three groups of tests is not much different, that is, the numerical control system of agricultural rotary tiller based on PLC technology works stably. In the simulation test, the accuracy of the test data from multiple test points is controlled within an acceptable range, which meets the requirements of field levelling.

Simulation and result analysis

The experiment simulates that rotary tillage parts move from off-the-ground state to specific tillage depth position (working condition 1) and the tillage depth needs to be adjusted according to the change of soil conditions (working condition 2). It is necessary to consider not only the working condition that the rotary tillage knife reaches the designated tillage depth from zero position when just started, but also the working condition that the soil structure changes and changes the tillage depth during the rotary tillage operation. At the same time, when the rotary tillage operation is considered, the rotary tiller encounters the sudden increase of soil resistance. During the simulation process, the soil load was 0.1 under normal conditions and kept for 2.5s seconds, and then the soil load suddenly changed to 0.25(KN). The changes of soil load change signal and tillage depth target set value signal are shown in Figure 6 and Figure 7 respectively.

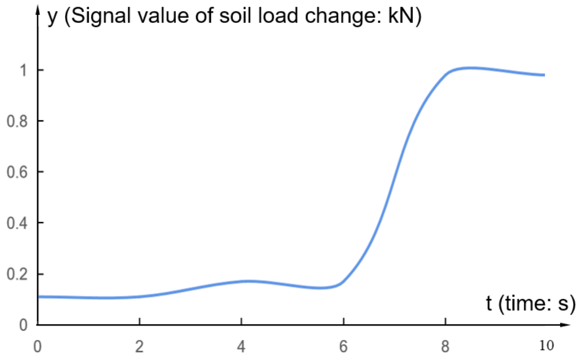

Fig. 6 - Soil load change signal

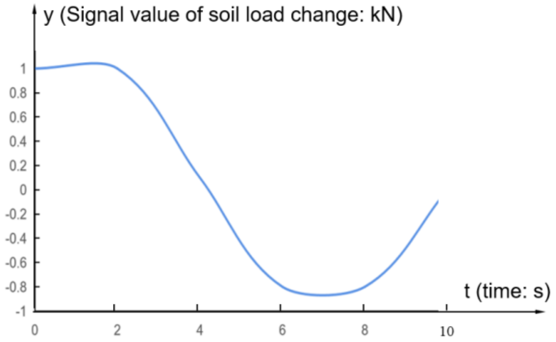

Fig. 7 - Ploughing target set value signal

The simulation results of overflow flow of rotary tiller hydraulic actuator system are shown in Figure 8.

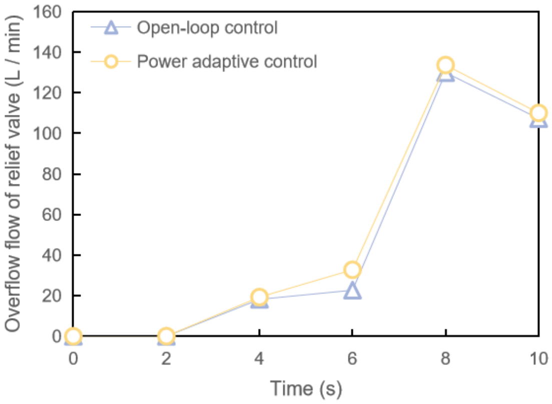

Fig. 8 - The simulation results of overflow flow of rotary tiller hydraulic actuator system

The analysis shows that when the rotary tiller blade reaches the designated tillage depth, the electro-hydraulic reversing valve loses power, and the system stops supplying high-pressure oil to the hydraulic cylinder (tillage depth control actuator), and all of it flows into the hydraulic motor that drives the rotary tiller blade shaft to rotate, thus causing a large overflow loss.

When the system working condition changes, the fuzzy control mode with comprehensive tillage depth value of force position can effectively improve the volumetric efficiency and power utilization rate of the hydraulic system of the rotary tiller, reduce oil consumption and improve operation efficiency.

The simulation results of hydraulic motor output speed are shown in Figure 9.

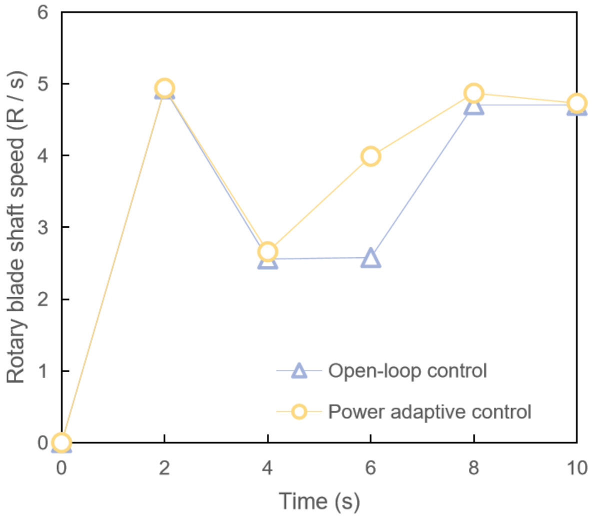

Fig. 9 - Simulation results of output speed of hydraulic motor

The analysis shows tht, when the soil resistance of the rotary tillage knife suddenly increases during the rotary tillage operation, the fuzzy control of force and position comprehensive tillage depth value can effectively improve the speed stability of the hydraulic motor for tillage depth control, reduce the speed fluctuation of the rotary tillage knife shaft and improve the system stability and the efficiency of rotary tillage operation under the condition of self-adaptive system power.

Comparative simulation analysis of hydraulic cylinders under working conditions 1 and 2 is carried out. Figure 10 below shows the comparison of simulation results of hydraulic cylinders under working conditions 1 and 2.

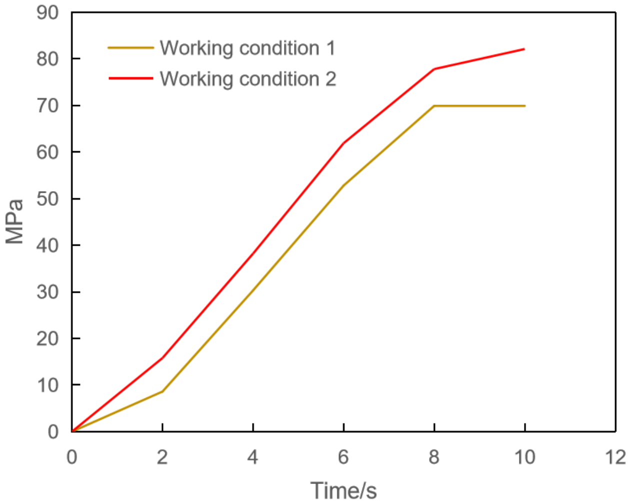

Fig. 10 - Comparison of hydraulic cylinder simulation results between working condition 1 and working condition 2

According to the simulation results of two working conditions, in the process of rotary tillage, after the rotary tiller blade reaches the designated tillage depth, the electro-hydraulic reversing valve loses power, the system stops supplying high-pressure oil to the hydraulic cylinder, and all of it flows into the hydraulic motor that drives the rotary tiller blade shaft to rotate, which will undoubtedly produce a large overflow loss and reduce the efficiency of the rotary tiller engine. In view of the low efficiency and low energy saving effect of the system, it is necessary to improve the parameters of the control system, optimize the control effect, improve the output efficiency of the rotary tiller engine, and reduce the oil consumption, so that the tillage depth control system can achieve better control effect.

CONCLUSIONS

In view of the present situation of agricultural land preparation technology, this paper takes the level automatic control system of tractor rotary tiller as the research object, and puts forward a new PLC system design for adjusting and controlling parameters of rotary tiller based on the application research of related technologies and agricultural machinery horizontal automatic control system. Experiments show that the rotary tiller control system based on PLC can effectively control the rotary tillage depth and speed, and the error of rotary tillage depth can be guaranteed within 4.5%. In the process of rotary tillage, when the soil resistance of rotary tillage knife suddenly increases, the fuzzy control of comprehensive tillage depth value of force position can effectively improve the rotational speed stability of hydraulic motor for tillage depth control, reduce the speed fluctuation of rotary tillage knife shaft and improve the system stability and efficiency of rotary tillage operation under the condition of self-adaptive system power. PLC technology puts the digital control of rotary tiller on a higher technical platform, reduces the labour required in agricultural planting, provides a good growth environment for crops, is beneficial to the improvement of crop yield, realizes the intelligence of rotary tillage operation, and provides a reference for modern agricultural mechanization production.

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