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Experimental Study on HMCVT Adaptive Control of Cotton Pickers

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Abstract: Aiming at the stability of the output speed and the poor adaptability of the transmission system during the operation of a cotton picker, a control strategy of hydro-mechanical continuously variable transmission (HMCVT) for cotton pickers based on gray prediction and fuzzy PID is proposed. Firstly, the hardware and software of the existing hydraulic mechanical coupling transmission test-bed of cotton pickers are designed, and the HMCVT human-computer interaction measurement and control system is built by using LABVIEW 2020 software. Then, combined with the transmission theory, the control strategy and gray prediction model are designed. Finally, the continuity test, transmission efficiency test, and adaptive control verification test are carried out. The results show that as the input speed increases, the peak time of the pump motor output speed is prolonged, while the overall speed regulation process is smoother, and the output speed process of the HMCVT system is continuous. As the displacement ratio of the variable pump increases, the transmission efficiency of the hydraulic system increases accordingly, but the highest efficiency is around 0.8. At a working speed of 10 km/h, the transmission efficiency of the HMCVT system of the cotton picker is more than 80%, and the high efficiency of the mechanical system in the whole system makes up for the low efficiency of the hydraulic system, and the transmission efficiency of the cotton picker is the highest at 15–25 km/h. The speed under the adaptive control strategy is better, with good robustness to sudden torque changes and speed fluctuations in the range of ±0.0125% under external load conditions. This study provides a reference for future adaptive control of transmission output speed for heavy-duty vehicles and construction machinery.

Keywords: HMCVT; cotton picker; test; adaptive control

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1. Introduction

Cotton is one of the most important cash crops in China and an important strategic reserve material, playing a vital role in economic and national defense construction [1,2]. Xinjiang region is the largest cotton-producing area in China, and its cotton industry has become a pillar of local agriculture [3–5]. In recent years, mechanized harvesting technology has been introduced in the Xinjiang region to improve the efficiency of cotton harvesting and to reduce the cost of cotton picking, and cotton pickers have been widely used [6–9]. Due to the low degree of intelligence and low picking efficiency of domestic cotton pickers, mechanical stepped transmissions are commonly used, which have poor speed matching and unstable speed changes [10–12]. Hydraulic-mechanical continuously variable transmission (HMCVT) technology was proposed in 1980 in foreign countries and was first applied to heavy engineering vehicles [12]. HMCVT technology adopts the form of coupling convergence between hydraulic transmission and mechanical transmission, which has the characteristics of high transmission power, high efficiency, a wide range of applications, good shift quality, etc., and realizes the stepless speed regulation of the vehicle through the pump-controlled motor system [13,14]. However, the chain CVT, dual-clutch CVT structure is complex and comes with a high cost and torque limitations. It is mostly used in small and medium-displacement passenger cars. The power shift transmission structure is complex, price cost and control system requirements are high and is rarely used in agricultural machinery. It is mainly used in construction machinery [15,16]. Currently, the application of hydraulic mechanical CVT transmission technology in agricultural and heavy vehicles is a research hotspot both domestically and internationally. Cheng et al. have established various new transmission models for tractors and other non-road vehicles based on HMCVT's transmission theory and characteristics. They have also conducted research on vehicle transmission shift quality and analyzed the impact of input parameters on shift quality [17–21]. Fu proposed a powershift tractor start control method based on time-varying disturbance suppression, which effectively reduces the shock degree and slippage work during the powershift tractor start [22]. Liu proposed a data-driven adaptive control of the dual-clutch automatic transmission shift process, which ensures the shift quality when the system behavior changes or there are internal and external disturbances [23]. Wang and Li explored the effects of hydraulic faults on the gearshift quality of CVT and HMT [24,25]. Cheng proposed an optimization design method for HMCVT transmission parameters based on an improved GA algorithm for tractors and other engineering vehicles; meanwhile, to obtain the system response, a system identification method based on the prior-model-heuristic-intelligent-optimization algorithm was proposed [26,27]. Little domestic and foreign research has been conducted on cotton-picker travel gearboxes. Wang and Zhao designed the HMCVT control system for cotton pickers based on the test bench [28,29]. Bao simulated and analyzed the HMCVT shift law and hydraulic system of cotton pickers [30,31]. And Zhao proposed the HMCVT control strategy for cotton pickers based on an RBF neural network and PID control [32]. Few studies have been conducted on the adaptive control of HMCVT transmission speed and torque for cotton pickers.

In this paper, the cotton picker transmission system is taken as the research object. The overall composition and transmission requirements of the cotton picker were analyzed, and based on the HMCVT transmission system of the cotton picker, the dynamic test bench of the cotton-picker HMCVT was constructed, and the HMCVT measurement and control system was designed. And the adaptive control strategy based on the grayscale prediction combined with the fuzzy PID control was proposed, then the transmission continuity test, efficiency test, and adaptive control test were carried out for the adaptive control strategy through the bench test. The test verifies the speed continuity of the cotton-pickeer's transmission system, the transmission efficiency under different driving speeds, and the adaptive control strategy, which lays the foundation for the later loading and utilization of the HMCVT system.

2. Materials and Methods

2.1. Composition and Transmission Requirements of the Cotton Picker

A cotton picker mainly consists of a cotton box, engine, fan, picking drive system, hydraulic system, clearing and screening system, transmission system, and so on. Its structure schematic diagram can be seen in Figure 1. When the cotton picker is operating, the driver selects the operating speed of the cotton picker according to the cotton planting range and road surface information, and after processing by the controller, the output speed of the engine and transmission is controlled to reach the target speed of the cotton picker.

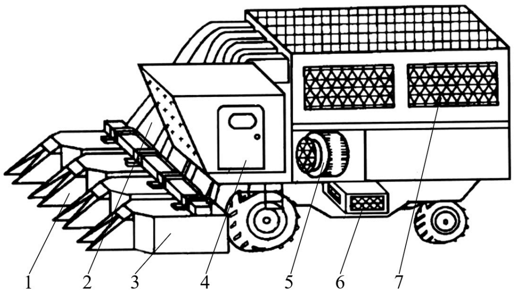

Figure 1. Structure diagram of a cotton picker. 1. sheaves 2. transport tubes 3. picking device 4. cab 5. fan 6. power chassis 7. cotton container.

2.2. Transmission System Structure

According to the output power of the walking system of the cotton picker, the change of working speed, and the resistance load, the hydraulic-mechanical coupling transmission of the cotton picker shown in Figure 2 is determined. The transmission system is driven by fixed-axis gears, and the planetary gear sets the mechanical circuit power and the hydraulic circuit power to control input changes to the pump-controlled motor system and the side-by-side double planetary gear trains. This enables output speed changes and achieves stepless speed change for the cotton picker HMCVT [11].

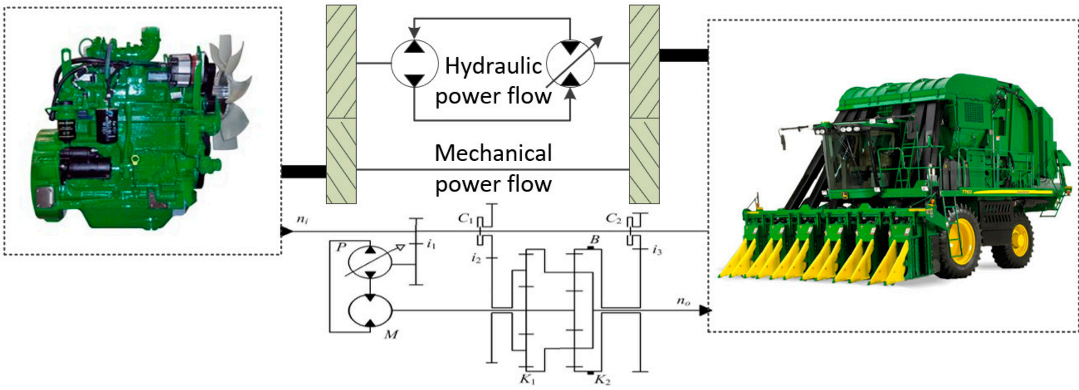

Figure 2. Hydro-mechanical coupling transmission diagram of the cotton picker. N_i and n_o are input speed and output speed; i_1~i_3 is the transmission ratio of each gear pair; K_1 and K_2 are planetary row 1 and planetary row 2; C_1 and C_2 are clutches; B is the brake; P and M are variable displacement pump and quantitative motor, respectively.

The power transfer routes in different sections of the HMCVT are shown in Figure 3. When the cotton picker starts, HMCVT is located in H section and B secures the planetary gear ring in K_2. Power is moved to the sun gear in K_2 using the variable pump-motor system. After that, the power is released through the planetary carrier in K_2. At present, the output speed of HMCVT is n_{oH}. When the speed goes over the H section's maximum speed, HMCVT shifts to the HM1 section. At the same time, C_1 is braked. Firstly, the power flows through the pump-motor system and C_1, respectively, to the sun gear and the carrier in K_1. Finally, the ring gear is merged in K_1 and the output is produced. As of now, the output speed of the HM1 section is n_{oHM1}. If the speed exceeds the HM1 section's maximum speed, HMCVT shifts to the HM2 section. Power is moved to the sun gear and the ring gear in K_2 through the pump-motor system and the C_2, respectively. Simultaneously, the carrier of K_2 outputs power. Currently, the output speed of the HM2 section is n_{oHM2}.

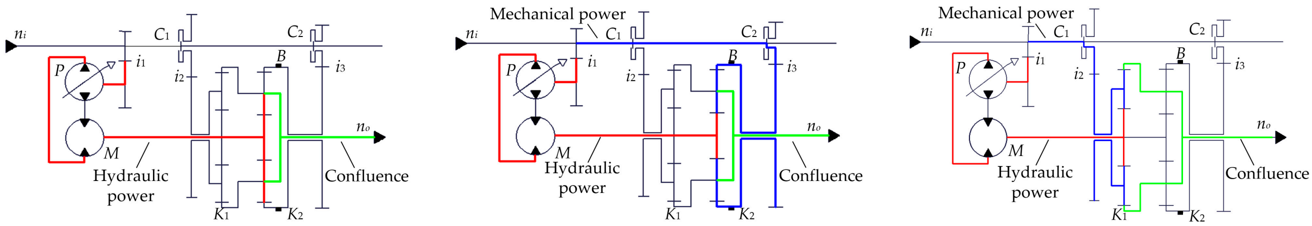

Figure 3. Power transfer routes in different sections of the HMCVT. (**a**) H section; (**b**) HM1 section; (**c**) HM2 section.

The speed range of the HMCVT transmission system of the cotton picker is generally 0–25 km/h, its working speed is 5.6 km/h, and its transportation speed is more than 15 km/h. The transmission system is divided into three sections, and the principle of each working section is shown in Table 1. The pure hydraulic section relates to the starting and reversing of the cotton picker, and the hydraulic mechanical section meets the requirements of the working speed and transportation speed of the cotton picker, respectively.

Table 1. Principle of HMCVT segment change.

Clutch/Brake	Section		
	H	***HM*1**	***HM*2**
C_1	0	1	0
C_2	0	0	1
B	1	0	0

2.3. Analysis of HMCVT Dynamics

As per the planetary gear design manual and the literature [33], the relationships between the sun gear, the ring gear, and the planet carrier of the planetary gear differential gear train are as follows:

$$\begin{cases} n_{oH} = \frac{\varepsilon n_i}{(1-k_2)i_1} \\ n_{oHM1} = \frac{\varepsilon i_2+(k_1-1)i_1}{k_1 i_1 i_2}n_i \\ n_{oHM2} = \frac{\varepsilon i_3-k_2 i_1}{(k_2-1)i_1 i_2}n_i \end{cases} \tag{1}$$

where n_{oH}, n_{oHM1}, and n_{oHM2} are the output speed of the HMCVT, r/min; n_i is the input speed, r/min; ε is the variable pump and the quantitative motor displacement ratio; and k_1 and k_2 are the conversion wheel train ratios of planetary row K_1 and planetary row K_2, respectively.

The torques of different sections of the HMCVT are interrelated in the following manner:

$$\begin{cases} M_e = \frac{\varepsilon i_1}{k_1-1}M_o + \Delta M_H \\ M_e = \frac{\varepsilon i_1+k_1-1}{k_1}M_o + \Delta M_{HM1} \\ M_e = \frac{\varepsilon i_1-k_2}{k_2-1}M_o + \Delta M_{HM2} \end{cases} \tag{2}$$

where M_e is the output torque of the engine, N·m; M_o is the output torque of the HMCV, N·m; ΔM_H, ΔM_{HM1}, and ΔM_{HM2} are equivalent torques of other components, N·m.

The hydraulic drive system, which is composed of a variable pump and a fixed motor, is a vital component of the HMCVT. The mathematical model of the volume-speed regulating circuit in a hydraulic system:

$$T_P = Jp\frac{d\omega_P}{dt} + \Delta p V_{P\max}\varepsilon + k_{dP}\mu\omega_P + k_{dP}(p_1+p_2)sign(\omega_P) \tag{3}$$

where T_P signifies the pump's input torque, N·m; μ stands for the oil's dynamic viscosity; J_P represents the variable inertia of the variable pump; k_{dP} represents the pressure resistance coefficients of the pump; ω_p refers to the input speed of the pump, rad/s; $V_{P\max}$ refers to the nominal volume of the variable pump, m^3; and p_1, and p_2 symbolize high-side and low-side pressures, Pa, respectively.

$$\Delta p V_m = J_M \frac{d\omega_M}{dt} + T_M + k_{dM}\mu\omega_M + k_{dM}(p_1 + p_2) sign(\omega_M) \tag{4}$$

where $\Delta p = -1 - p_2$, Pa; V_m signifies the quantitative motor's nominal volume, m^3; J_m stands for the quantitative motor's variable inertia, kg·m^2; k_{dM} represents the motor's pressure resistance coefficients; T_M represents the motor's input torque and the output torque, N·m; and ω_m refers to the output speed of the motor, rad/s.

$$\omega_P V_{P\max}\varepsilon = V_m\omega_m + \frac{C_s\Delta p(V_{P\max} + V_m)}{\mu} + \frac{v}{\beta e}\frac{d\Delta p}{dt} \tag{5}$$

where C_s signifies the total leakage coefficient, Pa·s; V stands the high-pressure side oil working volume, which is the sum of the pump, motor, and pipeline oil volume, m^3; and β_e refers to the integrated modulus of elasticity of hydraulic systems.

2.4. Test Bed Structure

The HMCVT dynamic characteristic test-bed of a cotton picker consists of a mechanical system, hydraulic system, and control module, as shown in Figure 4. The mechanical system consists of an engine, coupling, HMCVT, and supporting devices for fixing and assembling various instruments. The hydraulic system mainly includes a clutch and brake hydraulic control oil circuit (referred to as a low-pressure oil circuit) and a pump-controlled motor volume speed regulation circuit (referred to as a high-pressure oil circuit). A high-pressure oil circuit adjusts the change of displacement ratio of a variable pump to control the output speed of the motor. The low-pressure oil circuit controls the working state of the clutch and brake and then controls the meshing of the corresponding output gears [32]. The control module is the core of the transmission system, which is composed of TCU, speed and torque sensor, magnetic particle brake, pressure gauge and flowmeter in the hydraulic oil circuit, upper computer interface, data acquisition and processing, and other related software and hardware. The key parameters of the test are shown in Table 2.

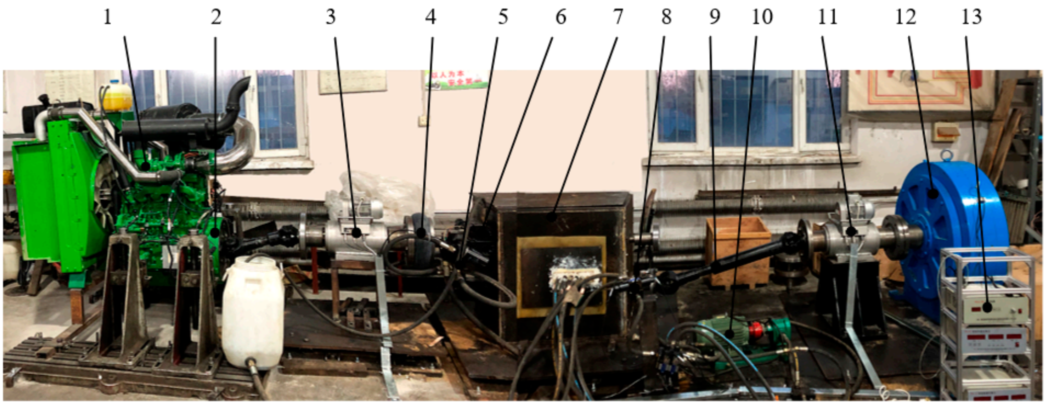

Figure 4. HMCVT dynamic characteristic test bench. 1. Engine; 2. Elastic coupling; 3. Torque speed sensor; 4. Elastic coupling; 5. Hydraulic motor; 6. Variable displacement pump; 7. Gearbox; 8. Electromagnetic reversing valve; 9. Universal joint coupling; 10. Auxiliary pump; 11. Torque speed sensor; 12. Magnetic powder brake; 13. Data acquisition instrument.

Table 2. The parameters of the test.

Name	Type	Parameter	Value
diesel engine	4045HYC11	rated power rated speed	104 kW 2400 r/min
speed and torque sensors	ZJ Series	rated torque speed range	2000 N·m 0~3000 rpm
variable pump	HPV-02	displacement	54.7 mL/r
fixed displacement motor	HMF-02	displacement	51.3 mL/r
hall sensor	3144E	operating voltage	3~3.5 V
pressure sensor	AS-131	output signal supply voltage	4~20 mA 12~36 V
turbine flow sensor	LWGY-DN15	flow range	0.6~10 m^3/h
charge pump	YB1-6.3	displacement	6.3 mL/r
three-phase asynchronous motors	Y2-100L2-4	rated speed	1430 r/min

2.5. Design of HMCVT Measurement and Control System

2.5.1. Hardware Design of Measurement and Control System

(1) Hardware composition

The hardware of the HMCVT control module of the cotton picker consists of a TCU system composed of an STM32, electromagnetic reversing valve, and photoelectric coupler for controlling the clutch, a 74HC244 intelligent chip for controlling the pump motor system, a BTN7970 intelligent driver, sensors, and data acquisition instrument, etc. Figure 5 is the hardware composition diagram of the HMCVT test bench of the cotton picker.

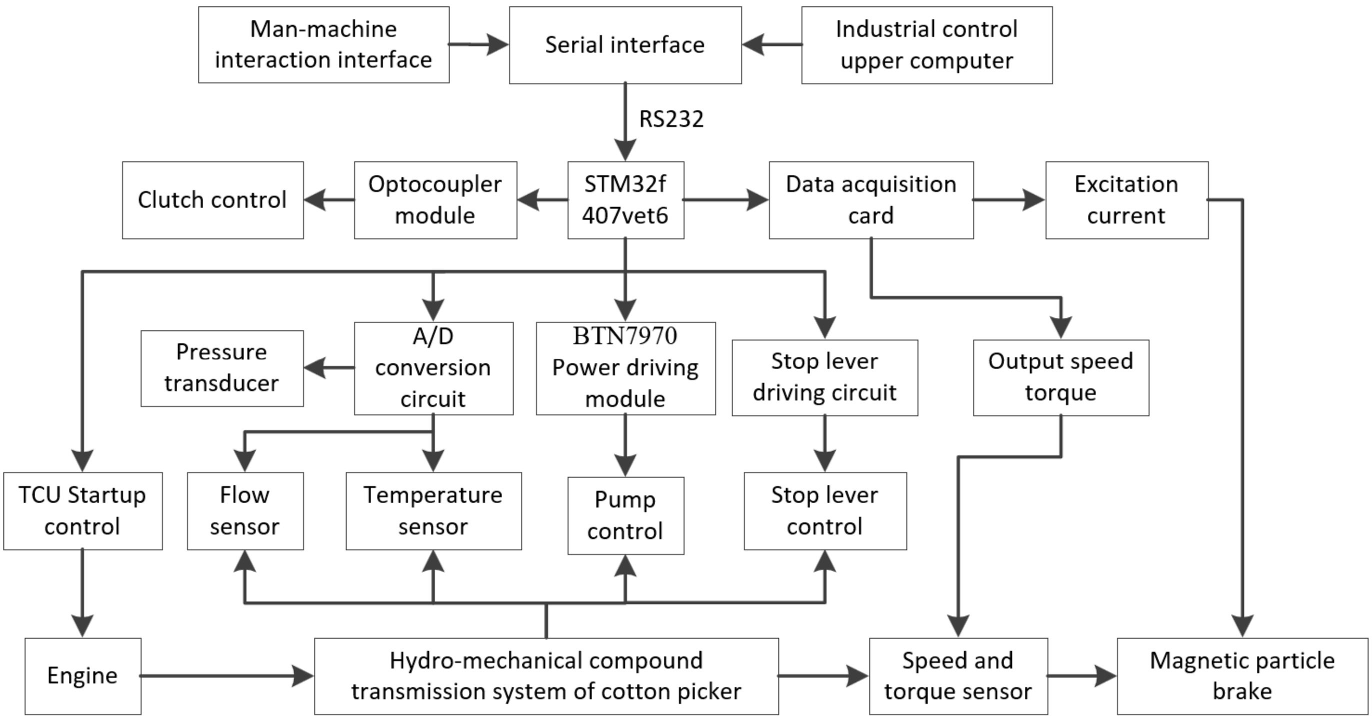

Figure 5. Hardware diagram of the control module.

(2) Sensor configuration

Based on simulating the working state of a cotton picker, a loading test should be carried out on the HMCVT transmission test bench of the cotton picker to monitor the performance parameters of the hydraulic system and mechanical system. The performance parameters of the sensors are shown in Table 2. According to the simulated load change of the magnetic particle brake, the input and output speeds of the engine and transmission are measured by speed and torque sensors, and the key parameters of the hydraulic system are collected by pressure sensors and flow sensors to complete the dynamic characteristics analysis of the cotton-picker transmission test-bed.

(3) Control Circuit Design

Figure 6 is a partial control circuit diagram of the control system. The TCU system, based on the STM32F407 core board, contains an FPU unit and DSP instruction, which can carry out floating-point operation and DSP processing. The processor meets the requirements of signal processing and control and has 14 timers, multiple ADC, DAC, DMA, FSMC, and DCMI interfaces, etc., which meet the control requirements of a cotton picker's transmission system. The circuit diagram of the control module is shown in Figure 6a. PC0-PC2 collects the state information of hydraulic oil pressure and temperature; PB12, PB13, PB14, and PB15 are used to control the working state of the clutch and brake so that the cotton picker can work at different stages; PE7–PE10 is manual control and segment selection; PA1 uses a timer to collect the high and low levels produced by the flowmeter in the HMCVT system of the cotton picker; and PB8 and PB9 control the displacement ratio of the variable displacement pump through the PWM signal produced by the timer, and realize the speed change of the transmission system in a certain section.

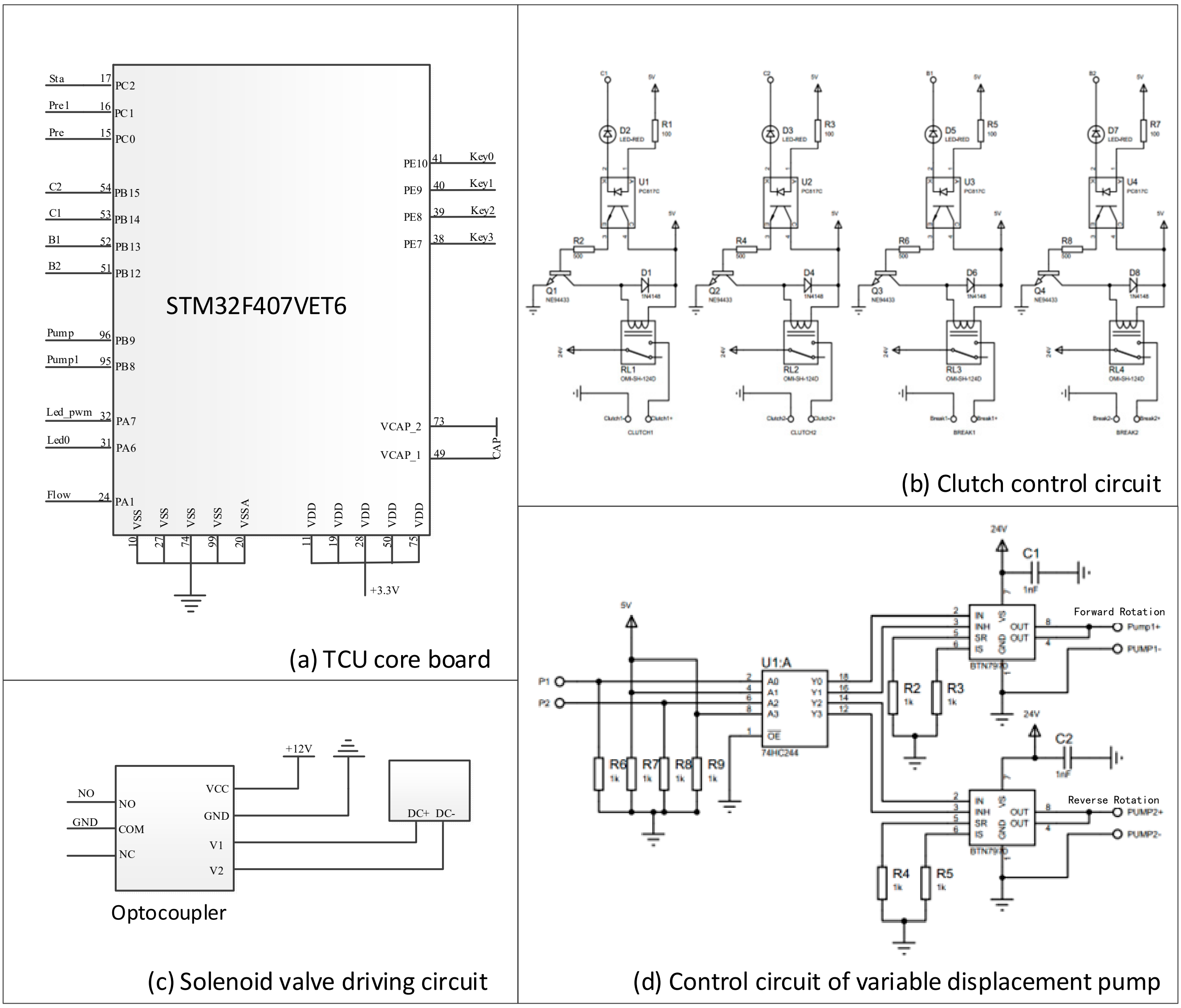

Figure 6. Partial control circuit diagram of the control system.

The clutch control affects the filling and discharging process of hydraulic oil through the transposition of an electromagnetic reversing valve and then realizes the combination and separation of the clutch [8]. The clutch control and drive circuit are shown in Figure 6b,c. Due to the complex working conditions of a cotton picker, it is necessary to switch gears frequently, and the on-off of current frequently reduces the accuracy of the TCU control signal. The TCU is protected and isolated by the action of the photoelectric coupler. When the input signal is high, the photoelectric coupler has no potential difference, the electromagnetic reversing valve is disconnected, and the clutch is separated. When the input signal is at a low level, the potential difference is formed, the valve core of the reversing valve is displaced, and the clutch is combined so that the transmission system can change sections.

The continuous adjustment of the speed ratio of the cotton picker is controlled by the change in the displacement ratio of the variable pump. A Linde HPV-055-E2 variable pump is selected as the transmission system, and the single-chip microcomputer cannot control the voltage change of the variable pump. The control circuit of the pump control motor is shown in Figure 6d. BTN7970 is selected to control the variable pump voltage, the voltage ranIe is 8–45 V, the pulse width modulation (PWM) signal is used to control the displacement ratio of the variable pump, and the average voltage power of the load is changed from 0–100% by changing the duty cycle of the output square wave. There is no photoelectric isolation in the chip, so the 74HC244 driver chip needs to be connected in series at the input end to avoid interference and damage to the circuit caused by overload.

Based on the TCU control module, clutch control module, and pump control motor control module, the hardware construction of the total control module of the HMCVT system of the cotton picker is carried out, as shown in Figure 7.

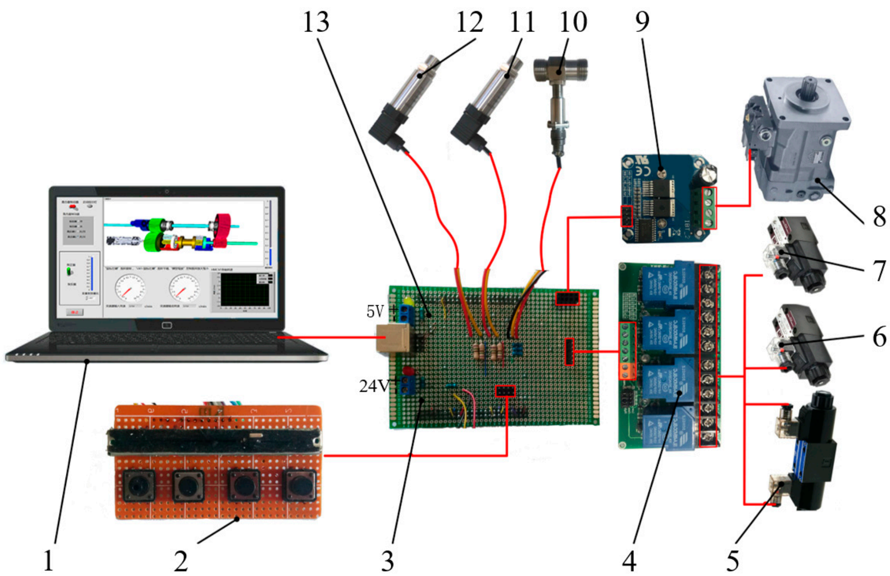

Figure 7. Physical diagram of a general control module. 1. Host computer; 2. Joystick circuit; 3. Lower computer controller; 4. Clutch circuit; 5. Electromagnetic reversing valve 1; 6. Electromagnetic reversing valve 2; 7. Electromagnetic reversing valve 3; 8. Variable displacement pump; 9. PWM amplifier; 10. Flowmeter; 11. Pressure gauge 1; 12. Pressure gauge 2; 13. Single-chip microcomputer and circuit board.

2.5.2. Software Design of HMCVT Measurement and Control System

(1) Composition of measurement and control software

According to the data communication and human-machine interaction between the upper computer and the lower computer control module, the HMCVT measurement and control software system developed by LabVIEW is adopted to ensure the data processing and analysis of the HMCVT test-bed. The RS232 serial Modbus protocol is used for data communication, with a baud rate of 9600. Its human-computer interaction system interface is simple and easy to understand, which mainly includes a system landing interface, a basic parameter-setting main interface, an HMCVT regulation and detection interface, a clutch hydraulic oil circuit (low-pressure oil circuit) control module, a pump-motor hydraulic oil circuit (high-pressure oil circuit) control module, a speed torque and magnetic particle braking debugging and correction interface, and a system alarm module.

(2) Control strategy

According to the best matching between the hydraulic transmission system and the cotton-picker operational situation, a suitable control method is put forward to adapt to the operational speed requirement of the cotton picker under complex working conditions. Figure 8 is the adaptive control principle. The HMCVT system control is complex, nonlinear, and multi-coupling control. In order to ensure the response characteristics and matching characteristics of the system, an adaptive control method combining gray prediction with fuzzy PID control is adopted [32]. According to the data of each sampling period, the behavior trend of the system can be predicted, and the cotton picker has the ability to adjust in advance so that the cotton picker has a strong adaptive ability in the working process.

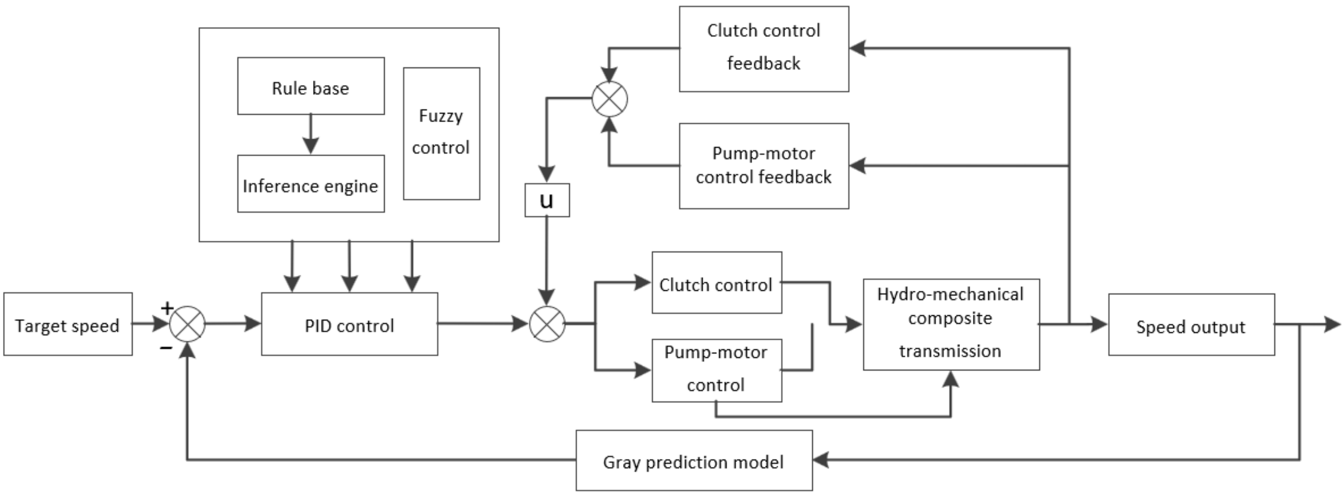

Figure 8. Schematic diagram of adaptive control.

The adaptive control system is realized by inputting deviation e and deviation change rate *ec* and by adjusting parameters according to fuzzy control rules to achieve system control. The set speed and output speed of the HMCVT system are accurate values, which can't be directly used as system control variables, so the values need to be quantized.

$$\begin{cases} e_0(i) = v_{set} - v_{out} \\ ec_0(i) = e(i-1) - e(i) \end{cases} \tag{6}$$

where v_{out} is the output speed of the HMCVT system, r/min; v_{set} is the target speed set by the HMCVT system of a cotton picker, r/min; e_0 is the deviation between the target value and the actual output value; and ec_0 is the rate of change of deviation e_0.

According to the input data of the system, the range is determined. In this paper, linear quantization is adopted, and the expression is:

$$\begin{cases} e = \frac{3e_0}{v_{\max} - v_{\min}} \\ ec_0 = \frac{3ec_0}{2(v_{\max} - v_{\min})} \end{cases} \tag{7}$$

where e is the deviation between the target value and the actual output value; and ec is the rate of change of deviation e.

The e and ec are fuzzified according to the quantization results, and corresponding universes {−3, −2, −1, 0, 1, 2, 3} in the quantization function and fuzzy subsets {NB, NM, NS, ZO, PS, PM, PB} defining e and ec are determined. The HMCVT system is fuzzified by a triangular membership function, and a fuzzy inference rule base is established for inference. In this controller, it is necessary to speed up the response speed of the system and reduce the overshoot to improve the control accuracy. According to the analysis, fuzzy rules use the coefficient weighting method:

$$u = \frac{\sum (k_i \cdot x_i)}{\sum k_i} \tag{8}$$

where u is the output value; k_i is the membership degree; and x_i is the fuzzy quantization value.

The feedback circuit of gray prediction to the HMCVT system can adjust the speed of the cotton picker online adaptively through gray prediction. The model is based on GM (1, 1), and its input and output time series are as follows:

$$u^{(0)}(1), u^{(0)}(2), \ldots, u^{(0)}(n)\ (n \geq 4) \tag{9}$$

$$y^{(0)}(1), y^{(0)}(2), \ldots, y^{(0)}(n)\ (n \geq 4) \tag{10}$$

The system is affected by external interference, and the time series is accumulated by gray data series, which can weaken the random interference. The accumulated data series is as follows:

$$u^{(1)}(i) = \sum_m^i 1^{u^{(0)}(m)},\ (i = 1, 2, \ldots, n) \tag{11}$$

$$y^{(1)}(i) = \sum_m^i 1^{y^{(0)}(m)},\ (i = 1, 2, \ldots, n) \tag{12}$$

The gray differential equation model is defined by linear fitting with accumulated sequence data:

$$y^{(0)}(i) + a_g z^{(1)}(i) = b_g \tag{13}$$

where $z^{(1)}(i)$ is the whitening background value; a_g is the development coefficient; b_g is the ash action amount, where e $z^{(1)}(i)$ is:

$$z^{(1)}(i) = \frac{1}{2}\left[y^{(1)}(i) + y^{(1)}(i-1)\right] \tag{14}$$

Substitute time i = 2, 3, . . ., n into the Formula (13):

$$\begin{cases} y^{(0)}(2) + a_g z^{(1)}(2) = b_g \\ y^{(0)}(3) + a_g z^{(1)}(3) = b_g \\ y^{(0)}(4) + a_g z^{(1)}(4) = b_g \\ \qquad \cdots \\ y^{(0)}(n) + a_g z^{(1)}(n) = b_g \end{cases} \tag{15}$$

Introducing vector-matrix notation:

$$Y = \left[y^{(0)}(2) \quad y^{(0)}(3) \quad \ldots \quad y^{(0)}(n)\right]^{\mathrm{T}} \tag{16}$$

$$B = \begin{bmatrix} -z^{(1)}(2) & 1 \\ -z^{(1)}(3) & 1 \\ \ldots & \ldots \\ -z^{(1)}(n) & 1 \end{bmatrix} \tag{17}$$

Thus, the GM (1, 1) model can be expressed as:

$$Y = B\begin{bmatrix} a_g \\ b_g \end{bmatrix} \tag{18}$$

The least square method is used to estimate:

$$\begin{bmatrix} a_g \\ b_g \end{bmatrix} = \left(B^T B\right)^{-1} B^T Y \tag{19}$$

The estimated value of a_g and b_g were obtained by regression analysis, and the corresponding whitening model was obtained:

$$\frac{dy^{(1)}(t)}{dt} + a_g y^{(1)}(t) = b_g \tag{20}$$

Works out to:

$$y^{(1)}(t) = (y^{(0)}(1) - \frac{b_g}{a_g})e^{a_g(t-1)} + \frac{b_g}{a_g} \tag{21}$$

According to the whitening equation, $y^{(1)}(t)$ obtains the predicted value at moment k:

$$y^{(1)}(k+1) = (y^{(0)}(1) - \frac{b_g}{a_g})e^{a_g k} + \frac{b_g}{a_g} \tag{22}$$

From this, the prediction at moment $k + m$ is carried out as follows:

$$y^{(0)}(k+m) = (-\frac{b_g}{a_g})e^{a_g m}(1 - e^{-a_g}) \tag{23}$$

Gray predictive control feedback can predict the speed change of the HMCVT system in advance, improve the accuracy and real-time performance of the control, and improve the response speed of the system. Using the established gray prediction model, when the input speed is 2000 r/min, the target speed is set to 1780 r/min, and some data in the process of taking and changing segments are used to predict the output of the HMCVT system, as shown in Figure 9. In the figure, before 0.5 s is the data acquisition stage, and 0.5–0.6 s is the partial gray prediction result of the system section change process. It can be seen from the figure that the gray prediction has a high fitting degree of the collected data before the section change speed of 300 r/min, a slight prediction gap appears at 320 r/min, and the fitting degree difference is small, which shows that the gray prediction control method can be used for experimental tests.

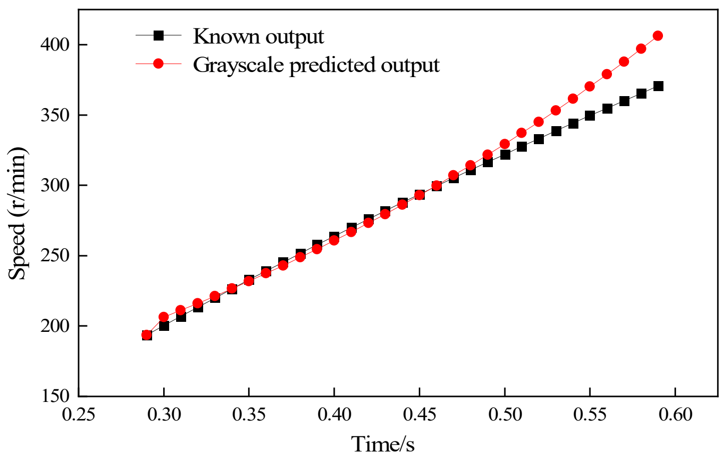

Figure 9. Gray prediction model.

3. Test Results and Analysis

This study tests the HMCVT adaptive test of the cotton picker, builds the HMCVT test bench, completes the debugging of measurement and control software, and carries out dynamic tests on the HMCVT system of a cotton picker, including a coupling transmission continuity test, an input and output transmission efficiency test, and a control strategy test, and obtains enough data for processing and analysis.

3.1. Continuity Testing

When the system control method is tested to verify the correctness of the HMCVT system, the change of the pump-motor system with displacement ratio and motor output speed at different input speeds is obtained, as shown in Figure 10a. As shown in this diagram, pump output speed varies in a nearly sinusoidal manner, and as input speed increases, pump output speed peak time becomes longer and overall speed control becomes smoother. Figure 10b shows the continuity test of the output speed of the HMCVT system of a cotton picker when the displacement ratio of the variable pump ranges from −1 to 1. The results show that the output speed process of the HMCVT transmission system of the cotton picker is continuous, which is suitable for the working state of the cotton picker.

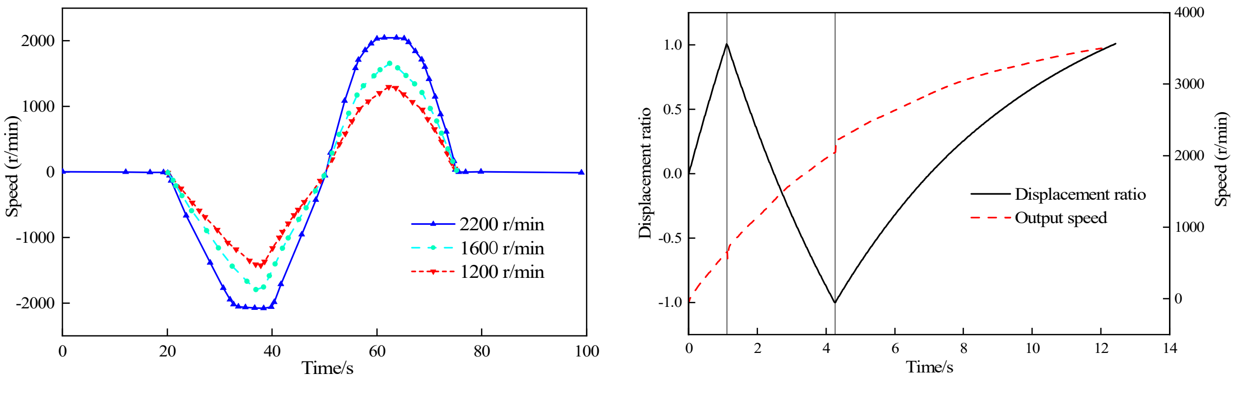

Figure 10. Transmission continuity test of cotton picker HMCVT. (**a**) Pump motor output speed; (**b**) Drive train continuity output speed.

3.2. Transmission Efficiency Test

When the engine speed is 1200 r/min, 1600 r/min, and 2200 r/min, the transmission efficiency of the hydraulic system in the cotton picker's transmission system is tested and verified. As shown in Figure 11a, the test results show that with an increase in the displacement ratio of the variable displacement pump, the transmission efficiency of the hydraulic system increases correspondingly, but the highest efficiency is about 0.8. According to the different working speeds and loads of the cotton picker under complex working conditions, the input and output speed transmission efficiency of the hydraulic-mechanical coupling system of the cotton picker is tested, as shown in Figure 11b. The test results show that under different engine speeds, the transmission efficiency of the HMCVT system of the cotton picker is over 80% at the working speed of 10 km/h, and the high efficiency of the mechanical system in the whole system makes up for the low efficiency of the hydraulic system. The transmission efficiency of cotton pickers is the highest at 15–25 km/h, which provides power for cotton pickers and ensures the economy of cotton pickers.

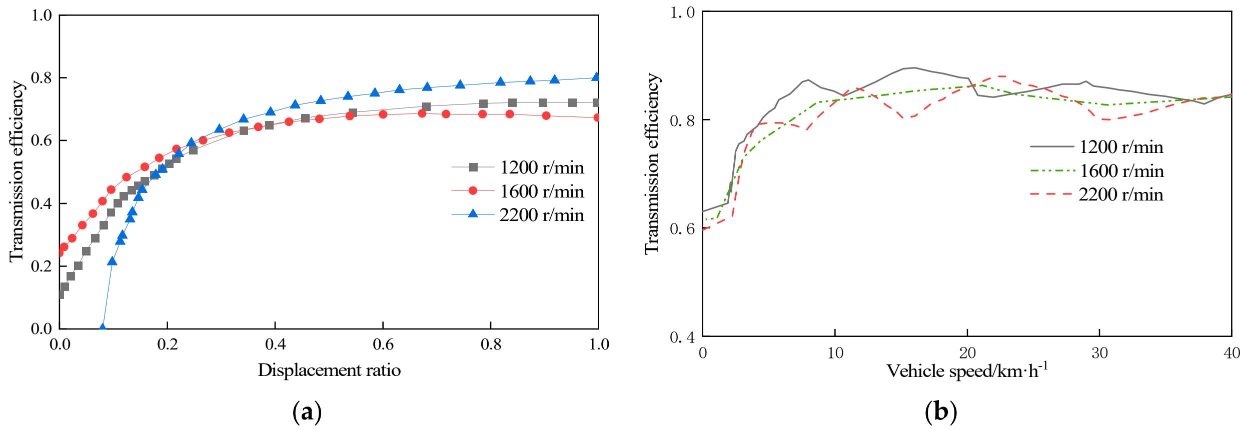

Figure 11. Transmission efficiency test of cotton picker HMCVT. (**a**)Transmission efficiency of pump motor; (**b**) Transmission efficiency of the drive system.

3.3. Adaptive Testing

When picking cotton, the picker needs to adjust its driving speed adaptively according to the picking environment. According to the fact that the picking speed of the cotton picker is 5.6 km/h and the output speed of the cotton picker's HMCVT system is 400 r/min, the adaptive control algorithm combining gray prediction with fuzzy PID is used to simulate and verify the starting process of the cotton picker. As shown in Figure 12a, the speed following the performance of the transmission system of the cotton picker is better.

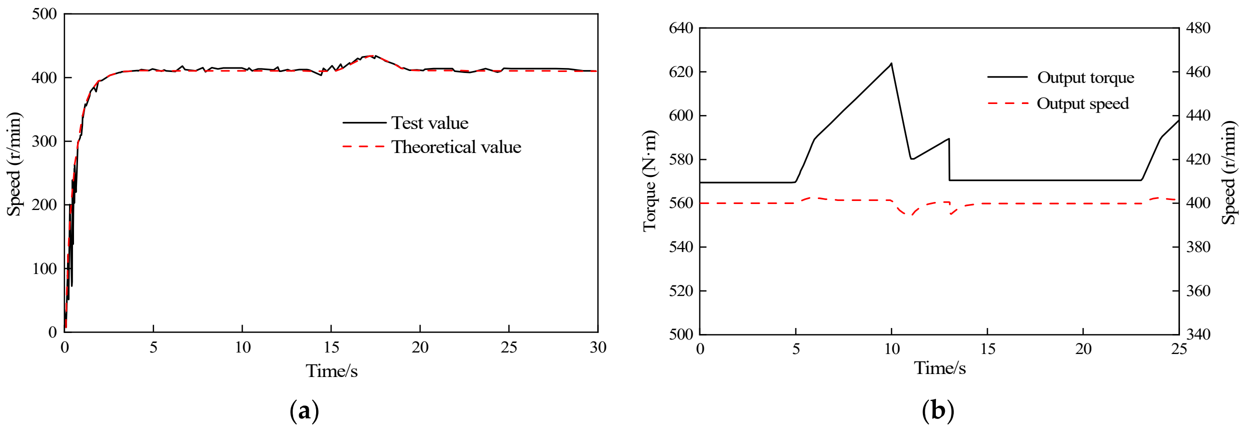

Figure 12. Adaptive test of HMCVT transmission system. (**a**) Drive train following output speed; (**b**) Drive train adaptive output.

During cotton-picker operation, the driving resistance will change due to the changing soil, the weight of the cotton entering the cotton box will increase during the harvesting process, and the poor working environment in the field will lead to a sharp change of output torque of the cotton picker. As shown in Figure 12b, the 5th s applies a randomly changing load to the HMCVT system, which leads to a sharp change in the output torque of the gearbox. The output speed of the transmission system only fluctuates within 0.0125%, which verifies that the adaptive control has good robustness.

4. Discussion

On the basis of the transmission composition of the cotton harvester and the HMCVT transmission scheme, the HMCVT test bench was built, including a mechanical system, hydraulic system, control module, testing unit, etc., to simulate the loading process in the traveling state of the cotton harvester and provide a practical basis for the loading of the gearbox. The dynamic test bench of the HMCVT of the cotton picker was built, and the adaptive control strategy of the HMCVT of the cotton picker based on grayscale prediction combined with fuzzy PID control was proposed, and the transmission continuity test, efficiency test, and adaptive test for the adaptive control strategy were carried out through the bench test.

In comparison with the existing research, the study of the HMCVT adaptive control strategy based on the RBF neural network has been proposed in the literature [31], which compared and analyzed the speed output of PID control and PIDNN methods, but only conducted system speed testing experiments. However, this article adopts an adaptive control method combining grayscale prediction and fuzzy PID for speed testing, efficiency testing, and adaptive testing verification of hydraulic modules, which has promotional and reference significance for the literature [32]. In the literature [34], an adaptive control method based on error symbol robustness was used to study the trajectory tracking control of autonomous tracked vehicles. Through driving at a speed of 5 m/s in this experimental environment, compared with traditional PID control methods, it can control tracked vehicles to accurately track the expected trajectory, with good tracking performance, and can suppress various model uncertainties and external interference effects. Compared to this article, the adaptive control method in [30] has better robustness, but the control theory and process are complex, which can be used as a direction for future research. In future research, by conducting simulations and experiments, further improving the adaptive control strategies, and comparing and analyzing different control methods, the adaptive control effect of the cotton picker during operation and the driving process will be improved, which can provide adaptive control reference for other agricultural vehicles meanwhile.

5. Conclusions

The conclusions of the study are as follows:

(1) As the input speed increases, the peak time of the pump motor output speed is prolonged, while the overall speed regulation process is smoother and the output speed process of the HMCVT system is continuous.
(2) As the displacement ratio of the variable pump increases, the transmission efficiency of the hydraulic system increases accordingly, but the highest efficiency is around 0.8. At a working speed of 10 km/h, the cotton picker's HMCVT system transmission efficiency is more than 80%. The mechanical system's high efficiency makes up for the lower efficiency of the hydraulic system, and the cotton picker in the 15–25 km/h transmission efficiency is the highest.
(3) When the picking speed of the cotton picker is set at 5.6 km/h, the speed following under the adaptive control strategy is good. Meanwhile, the output speed of the cotton picker drive system fluctuates only 0.0125% under the sudden change of external load torque, which verifies that the adaptive control has good robustness.

The test verified the speed continuity of the cotton picker's transmission system, transmission efficiency at different traveling speeds, and adaptive control strategy. It proves the rationale for the adaptive control strategy of the HMCVT transmission of the cotton picker. It can be used as a reference for the adaptive control of transmission output speed of heavy vehicles and construction machinery in the future.

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References

1. Shen, S.; Wang, L. Research on China's cotton industry security under open conditions. *China Cotton* **2022**, *49*, 1–6.
2. Li, H.; Fu, X.; Wang, H.; Zhang, H.; Gu, Y.; Du, X.; Tao, Y.; Li, J. Research on the Wear Characteristics of the Hook Teeth of Cotton Pickers. *Coatings* **2022**, *12*, 762. [CrossRef]
3. Zhang, R.; Chen, Y.; Zhao, D. Development status and suggestions of the cotton industry in Xinjiang. *J. Smart Agric.* **2023**, *3*, 5.
4. Gu, Y.; Zhang, H.; Fu, X.; Wang, L.; Shen, Z.; Wang, J.; Song, Z.; Zhang, L. Experimental Wear Behavior Analysis of Coated Spindle Hook Teeth under Real Harvesting Work Conditions. *Materials* **2021**, *14*, 2487. [CrossRef] [PubMed]
5. Wang, L.; Yin, C.; Zhang, L.; Zhang, H.; Li, H. Analysis and Experiment on the Impact of Various Hook Angle Factors on Spindle Picking Performance. *Agriculture* **2022**, *12*, 768. [CrossRef]
6. Miao, Z.; Li, C.; Han, K.; Hao, F.; Han, Z.; Zeng, L. Optimal Control Algorithm and Experiment of Working Speed of Cotton-picking Machine Based on Fuzzy PID. *Trans. Chin. Soc. Agric. Mach.* **2013**, *46*, 9–14.
7. Yuan, Y.; Bai, S.; Niu, K.; Zhou, L.; Zhao, B.; Wei, L.; Liu, L. Research progress in the key technologies and equipment for cotton planting mechanization. *Trans. Chin. Soc. Agric. Eng.* **2023**, *39*, 11.
8. Shao, W.; Feng, J.; Zhang, F.; Wang, S.; Li, Y.; Lv, J. Aerodynamic Performance Optimization of Centrifugal Fan Blade for Air System of Self-Propelled Cotton-Picking Machine. *Agriculture* **2023**, *13*, 1579. [CrossRef]
9. Wu, J.; Chen, X. Present situation, problems and countermeasures of cotton production mechanization development in Xinjiang Production and Constuction Corps. *Trans. Chin. Soc. Agric. Eng.* **2015**, *31*, 6.
10. Niu, G.; Li, B.; Liu, Y.; Li, Y.; Wang, T.; Wang, S. Development and research status of cotton picker in China. *J. Chin. Agric. Mech.* **2020**, *41*, 7.
11. Zhao, X.; Ni, X.; Bao, M.; Li, S.; Han, S. Coordinated Control of Picking and Walking Constant Speed of New Cotton Picker Based on AMESim-Simulink. *Chin. Hydraul. Pneum.* **2020**, *5*, 6.
12. Miao, Z.; Lu, M.; Hu, X.; Zou, Z. Development and application of intelligent monitoring and controlling system of cotton-picking machine based on virtual instrument technology. *Trans. Chin. Soc. Agric. Eng.* **2014**, *30*, 35–42.
13. Zhao, J.; Xiao, M.; Bartos, P.; Bohata, A. Dynamic engagement characteristics of wet clutch based on hydro-mechanical continuously variable transmission. *J. Cent. South Univ.* **2021**, *28*, 13. [CrossRef]
14. Wang, G.; Zhang, X.; Zhu, S.; Zhang, H.; Ma, R.; Ti, J. Dynamic simulation on shift process of tractor hydraulic power split continuously variable transmission during acceleration. *Trans. Chin. Soc. Agric. Eng.* **2016**, *32*, 30–39.
15. Yildiz, A.; Piccininni, A.; Bottiglione, F.; Carbone, G. Modeling chain continuously variable transmission for direct implementation in transmission control. *Mech. Mach. Theory* **2016**, *105*, 428–440. [CrossRef]
16. Yildiz, A.; Kopmaz, O. Control-oriented modelling with experimental verification and design of the appropriate gains of a PI speed ratio controller of chain CVTs. *Stroj. Vestn.-J. Mech. Eng.* **2017**, *63*, 374–382. [CrossRef]
17. Cheng, Z.; Chen, Y.; Li, W.; Liu, J.; Li, L.; Zhou, P.; Chang, W.; Lu, Z. Full Factorial Simulation Test Analysis and I-GA Based Piecewise Model Comparison for Efficiency Characteristics of Hydro Mechanical CVT. *Machines* **2022**, *10*, 358. [CrossRef]
18. Cheng, Z.; Chen, Y.; Li, W.; Zhou, P.; Liu, J.; Li, L.; Chang, W.; Qian, Y. Optimization Design Based on I-GA and Simulation Test Verification of 5-Stage Hydraulic Mechanical Continuously Variable Transmission Used for Tractor. *Agriculture* **2022**, *12*, 807. [CrossRef]
19. Xia, Y.; Sun, D. Characteristic analysis on a new hydro-mechanical continuously variable transmission system. *Mech. Mach. Theory* **2018**, *126*, 457–467. [CrossRef]
20. Qian, Y.; Cheng, Z.; Lu, Z. Study on stepwise regression optimization of shift quality of heavy-duty tractor HMCVT based on five factors. *J. Nanjing Agric. Univ.* **2020**, *43*, 10.
21. Wang, G.; Zhang, X.; Li, X.; Fan, G.; Zhang, H.; Sun, R. Analysis of shift quality of power split continuously variable transmission for tractor equipped with steel belt. *Trans. Chin. Soc. Agric. Eng.* **2019**, *35*, 11.
22. Fu, S.; Yang, Z.; Du, Y.; Li, Z.; Mao, E.; Zhu, Z. Starting Control Method for Power Shift Tractor Employing Time—Varying Disturbance Rejection. *Trans. Chin. Soc. Agric. Mach.* **2021**, *52*, 371–380.
23. Liu, Y.; Zhang, J.; Wan, Y.; Sun, D.; Qin, D. Adaptive Shifting Control for Data Driven Dual Clutch Transmission. *Automot. Eng.* **2021**, *43*, 9.
24. Wang, G.; Song, Y.; Wang, J.; Chen, W.; Wang, J. Study on the Shifting Quality of the CVT Tractor under Hydraulic System Failure. *Appl. Sci.* **2020**, *10*, 681. [CrossRef]

25. Li, X.; Zhang, L.; Yang, S.; Liu, N. Analysis and experiment of HMT stationary shift control considering the effect of oil bulk modulus. *Adv. Mech. Eng.* **2020**, *12*, 727–739. [CrossRef]
26. Cheng, Z.; Lu, Z. System response modeling of HMCVT for tractors and the comparative research on system identification methods. *Comput. Electron. Agric.* **2022**, *202*, 11. [CrossRef]
27. Cheng, Z.; Lu, Z.; Qian, J. A new non-geometric transmission parameter optimization design method for HMCVT based on improved GA and maximum transmission efficiency. *Comput. Electron. Agric.* **2019**, *167*, 9. [CrossRef]
28. Wang, Q. Design and Study on Control Strategy of Cotton-Picking Machine Hydro-Mechanical CVT. Master′s Thesis, Shihezi University, Shihezi, China, 2019.
29. Zhao, X. Design and Research on Control System of Hydro-Mechanical Continuously Variable Transmission for Cotton Picker. Master′s Thesis, Shihezi University, Shihezi, China, 2021.
30. Bao, M.; Ni, X.; Zhao, X.; Li, S. Research on the HMCVT gear shifting smoothness of the four-speed self-propelled cotton picker. *Mech. Sci.* **2020**, *11*, 267–283. [CrossRef]
31. Bao, M.; Ni, X.; Zhao, X.; Han, S. Research on Adaptive Fuzzy PID Joint Simulation of HMCVT Hydraulic System. *Mach. Tool Hydraul.* **2020**, *48*, 7.
32. Zhao, X.; Ni, X.; Wang, Q.; Bao, M.; Li, S.; Han, S. Research on adaptive control strategy of hydraulic mechanical continuously variable transmission of a cotton picker. *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.* **2020**, *234*, 3335–3345. [CrossRef]
33. Yildiz, A.; Kopmaz, O.; Cetin, S.T. Dynamic modeling and analysis of a four-bar mechanism coupled with a CVT for obtaining variable input speeds. *J. Mech. Sci. Technol.* **2015**, *29*, 1001–1006. [CrossRef]
34. Li, R.; Xiang, C.; Wang, C.; Fang, J.; Liu, C. Robust Adaptive Trajectory Tracking Control Approach for Autonomous Tracked Vehicles. *Acta Armamenta RII* **2021**, *42*, 1128–1137.