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DESIGN OF TEST TURNTABLE BASED ON FUZZY PID ALGORITHM AND ITS ERROR CORRECTION

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Abstract. In order to meet the requirements of antenna for high bearing capacity, high positioning accuracy and speed stability of the test turntable, a test turntable with simple operation is designed. First of all, the structure of the turntable is introduced. The turntable adopts the form of gear transmission and multi-turn absolute encoder angle measurement. The mechanical simulation analysis of the turntable table is carried out, and the static performance and modal characteristics of the turntable are analyzed. Then, the servo control system of the turntable is introduced. The multi-turn absolute encoder is used as the detection element of the actual position of the turntable. The target position is sent to the controller by the upper computer through the serial port. The controller uses the field programmable logic gate array (FPGA) as the core, and the encoder, controller and control object constitute the position loop; In the software design, the fuzzy PID algorithm is used to replace the traditional PID algorithm. Finally, the turntable accuracy test platform is built, and the autocollimator and polyhedral prism are used to obtain the angle measurement error. The test results show that the control accuracy is better than $\pm 0.01°$, the system position accuracy is better than 2.5', and the turntable positioning accuracy and rotational speed stability have been effectively improved.

Key words: Servo; Turntable; Fuzzy control; FPGA.

1. Introduction. In the design of high-precision turntables, commonly used forms of power transmission include direct drive, worm gear transmission, and gear transmission [6]. The worm gear transmission has the advantages of large reduction ratio, smooth transmission, low noise, and large bearing capacity; Gear transmission has the advantages of accurate transmission ratio, stability, high efficiency, high working reliability, and long service life. The load-bearing capacity, position accuracy, smoothness of speed, and system stability of the test turntable will directly affect the testing effect of the test turntable. Therefore, the control strategy for the motor in the control system of the test turntable is crucial. At present, there are various control algorithms for motors [13, 21]. Le K M [8] proposes an algorithm based on improved PI control current to improve the performance of the motor. It determines the control parameters through the parameters of the motor and the speed of operation; Tran H N [15] proposed a method based on an effective phase compensator to improve the accuracy of the motor; Zhai Yan [20] and Changjun Zhao [22] propose an algorithm based on fuzzy adaptive control, which performs fuzzy control on classical PID and adjusts the control parameters according to different situations automatically. Sliding mode variable structure control algorithms have good control effects on nonlinear factors. [12, 1, 4]

The author has designed a high-precision gear transmission turntable and conducted mechanical analysis on the turntable using ANSYS software. The maximum deformation of the loading table is 0.026mm, and the maximum stress is 0.95MPa, both of which are far less than the strength limit of the material; At the same time, a control strategy based on the fuzzy PID algorithm is adopted. Fuzzy control can formulate control strategies based on engineering experience, which is suitable for nonlinear and uncertain systems such as turntable control systems. Fuzzy control is used to adjust the proportional integral derivative coefficients of PID online, which not only has the advantages of simple and reliable PID control, but also enables the turntable to better cope with sudden disturbances and has excellent control performance. And the error effect was verified using a polyhedron prism, with a control accuracy better than $\pm 0.01°$ and a system position accuracy better than 2.2', meeting the requirement of antenna testing 3'. At the same time, the speed stability of the turntable was

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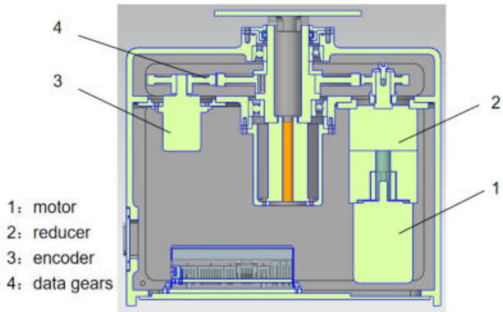


Fig. 2.1: Turntable structure

Table 2.1: Main parameters of encoder

Shaft diameter	Lines per revolution	revolution	resolution ratio	repeatability
10 × 19 mm	262144	4096	4.9”	0.002°

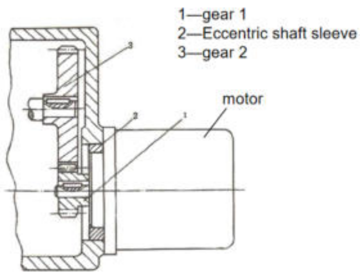


Fig. 2.2: Adjusting the backlash of the eccentric shaft sleeve

effectively improved.

2. Turntable structure design. The turntable mainly consists of a pair of transmission gears, data gears, reducer, absolute multi-turn encoder, motor, etc. The structural diagram of the turntable is shown in Figure 2.1.

According to the load requirements of the turntable, through analysis and calculation, combined with the Mechanical Design Manual, the gear module is determined, in which the gear ratio is 23:181, the data gear ratio is 1:8, and the speed ratio of the reducer is 100.The large total deceleration ratio ensures the load-bearing capacity of the turntable.

The absolute multi-turn encoder is used to measure the actual position of the turntable, and the main technical parameters of the encoder are shown in Table 2.1.

The encoder is installed coaxially with the data gear, and the data gear is installed parallel to the output gear, with a data gear ratio of 1:8, So compared to the spindle, the encoder resolution reaches 4.9”/8=0.62”, However, the backlash of gears can affect the positioning accuracy and stability of the system, so it needs to be effectively overcome. There are different methods for adjusting the backlash of different types of gear transmission pairs. The eccentric shaft sleeve adjustment method is used here, as shown in Figure 2.2. By adjusting the eccentric shaft sleeve, the center distance between the input and output gears can be changed.

Considering the requirements of matching the torque, rated speed, and inertia of the motor, a three-phase synchronous servo motor is chosen here.

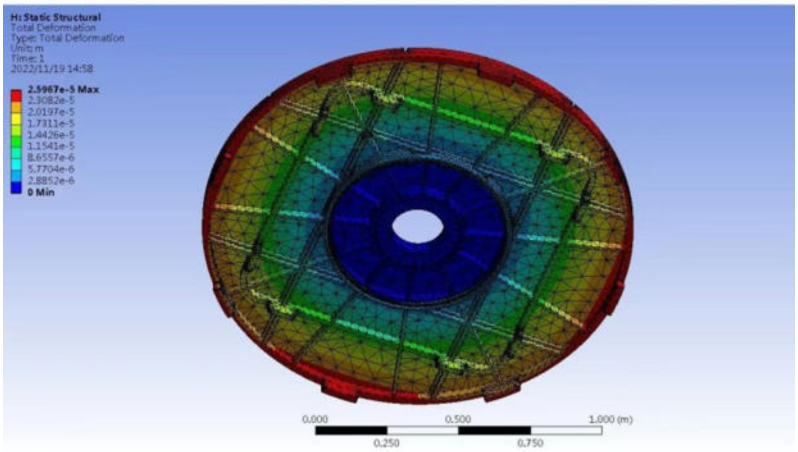


Fig. 3.1: Table deformation analysis

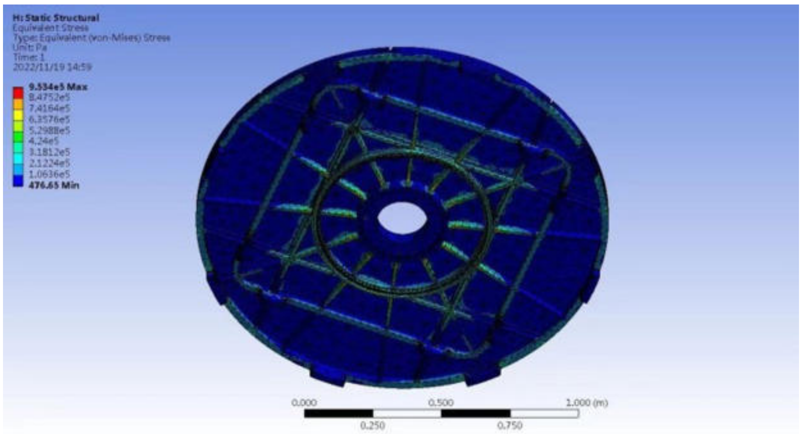


Fig. 3.2: Turntable stress analysis

3. Mechanical simulation analysis. The flatness and end face runout of the turntable' table determine the installation accuracy of the antenna load and have a significant impact on the testing effect. Under load, the deformation and vibration of the table also have an impact on the turntable, which cannot be ignored. Therefore, mechanical analysis of the table top is necessary. This article uses ANSYS software for mechanical analysis of the turntable. [23, 11, 9]

The load table of the turntable is made of aluminum alloy material, with a density of 2770 kg/m^3, a tensile yield strength of 280Mpa, a comprehensive yield strength of 280Mpa, and a tensile ultimate strength of 310Mpa. The analysis results are shown in Figures 3.1 to 3.3. Figure 3.1 shows the deformation analysis results of the table after applying load, Figure 3.2 shows the stress analysis results of the turntable, and Figure 3.3 shows the modal analysis results of the turntable.

According to the design requirements, the turntable needs to meet the load requirement of a maximum load of 50 kg. With the turntable as the center, a distributed load is added and a force of 500 N is applied to the turntable surface. Through the analysis of the above simulation results, it can be seen that the maximum deformation of the loading platform is 0.026mm, and the maximum stress is 0.95MPa. Both parameters are

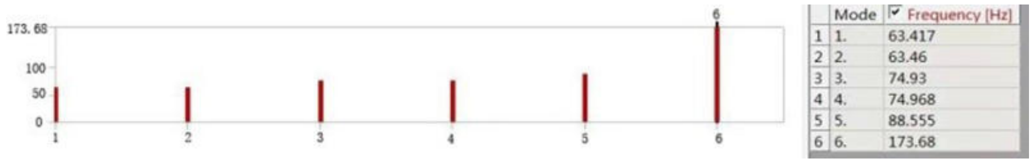


Fig. 3.3: Turntable modal analysis

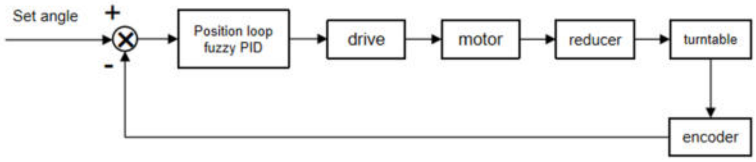


Fig. 4.1: Servo system control block diagram

far less than the strength limit of the material.

4. System hardware composition. The servo control system of the testing turntable mainly consists of an upper computer, a controller, a driver, an encoder, and a motor. The servo system receives control commands from the upper computer through the RS-422 serial port, and reports information such as position, speed, and fault codes. The servo controller is implemented using the Cyclone series FPGA, which is responsible for receiving feedback angle from the encoder. Its NIOS II core completes the calculation of the guidance command, and the calculation results are sent to the driver through the CAN bus. The speed and current loops are calculated in the driver, and finally the driver generates a sinusoidal pulse width modulation (SPWM) signal to drive the motor to move [14]. The system is shown in Figure 4.1.

5. System software design.

5.1. Fuzzy PID control strategy. In this system, the load is large and the inertia is large. Under the action of step response, the deviation is usually not eliminated in a short time, and the integral term can cause significant overshoot, even causing system oscillation and reducing system stability [5, 18, 10]. At the same time, in order to meet the control quantity changes caused by the quality differences of different testing equipment, it is necessary to use control methods with good adaptability.Fuzzy control modifies PID parameters based on fuzzy reasoning, obtaining different correction values based on the size of the deviation, thereby affecting the original PID parameters and accelerating the system response time while ensuring control accuracy. [3, 7] This article adopts a fuzzy PID control strategy to achieve the requirements of precise position control and fast response of the testing turntable. This article designs the algorithm for the position loop of the system. The speed loop and current loop are completed by the selected driver. Effective control of the testing turntable is achieved through position loop control combined with driver parameter settings.

5.2. Design and Simulation of Fuzzy PID Controller. In this turntable control system, the angular position deviation e and the variation of angular position deviation ec are selected as input variables to complete fuzzy control. Adopting a second-order fuzzy controller, the deviation signal and the variation of the deviation signal are used as the control signals of the entire control system.The ΔK_P, ΔK_I, ΔK_D derived from fuzzy reasoning principles and PID parameters (K_P, K_I, K_D) work together on the controlled object, and θ_{in} represents the target angle issued by the upper computer, θ_{out} represents the current actual angle output by the encoder, the structural flow of the fuzzy PID controller is shown in Figure 5.1.

Establish a fuzzy domain for the control signal, select an appropriate membership function curve for fuzzification processing, and obtain the fuzzy output according to the control rules [16, 2, 17]. Set the basic universe of input variables e, e_c and output variables ΔK_P, ΔK_I, ΔK_D to $[-6, +6]$. Input variablese and e_c correspond to language variables E and E_C,the output variable ΔK_P, ΔK_I, ΔK_D corresponds to the language variable

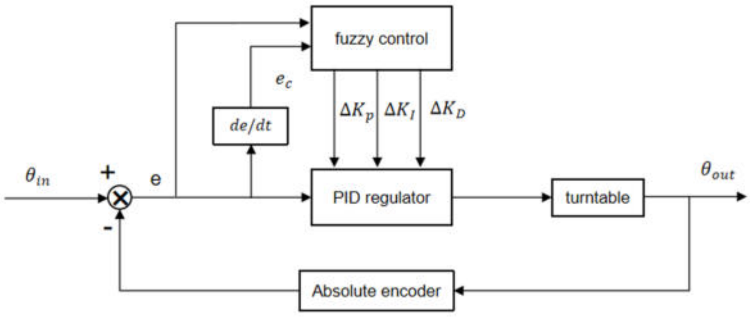


Fig. 5.1: The Structural Process of Fuzzy PID Controller

Table 5.1: Fuzzy rules of ΔK_P, ΔK_I, ΔK_D

ΔKp/ΔKi/ΔKd Ec / E	NB	NM	NS	ZO	PS	PM	PB
NB	PB/NB /PS	PB/NB /NS	PM/NM /NB	PM/NM /NB	PS/NS /NB	ZO/ZO /NM	ZO/ZO /PS
NM	PB/NB /PS	PB/NB /NS	PM/NM /NB	PS/NS /NM	PS/NS /NM	ZO/ZO /NS	NS/ZO /ZO
NS	PM/NB /ZO	PM/NM /NS	PM/NS /NM	PS/NS /NM	ZO/ZO /NS	NS/PS /NS	NS/PS /ZO
ZO	PM/NM /ZO	PM/NM /NS	PS/NS /NS	ZO/ZO /NS	NS/PS /NS	NM/PM /NS	NM/PM /ZO
PS	PS/NM /ZO	PS/NS /ZO	ZO/ZO /ZO	NS/PS /ZO	NS/PS /ZO	NM/PM /ZO	NM/PB /ZO
PM	PS/ZO /PB	ZO/ZO /PS	NS/PS /PS	NM/PS /PS	NM/PM /PS	NM/PB /PS	NB/PB /PB
PB	ZO/ZO /PB	ZO/ZO /PM	NM/PS /PM	NM/PM /PM	NM/PM /PS	NB/PB /PS	NB/PB /PB

ΔK_P, ΔK_I, ΔK_D. The fuzzy quantization levels of the input and output language variables E, E_C, ΔK_P, ΔK_I, ΔK_D are [NB (negative large), NM (negative weight), NS (negative small), O (zero), PS (positive small), PM (positive middle), PB (positive large)].

According to the membership function of variable E, E_C, ΔK_P, ΔK_I, ΔK_D, the fuzzy control rules formulated are shown in Table 5.1.

The mathematical model G (s) of the turntable motor is a second-order system, and the relationship between the input and output of the controller is:

$$\omega = \mathbf{K_p e} + \int_{\mathbf{0}}^{\mathbf{t}} \mathbf{e(t)dt} + \mathbf{K_D}\frac{\mathbf{de(t)}}{\mathbf{dt}}$$

After discrete processing:

$$\omega(\mathbf{k}) = \mathbf{K_p e(k)} + \mathbf{K_I}\sum_{\mathbf{j=0}}^{\mathbf{k}} \mathbf{e(j)} + \mathbf{K_D}[\mathbf{e(k)} - \mathbf{e(k-1)}]$$

In the equation: $\omega\,(\mathbf{k})$ and $\mathbf{e}\,(\mathbf{k})$ are the output values and deviation values at the k-th sampling time, using a step signal as the excitation signal of the system. After multiple experiments, the initial PID value of the algorithm is determined.

Obtaining Actual PID Controller Parameters through Demystification:

$$\mathbf{K_p} = \mathbf{k_p} + \Delta K_P, \mathbf{K_I} = \mathbf{k_I} + \Delta K_I, \mathbf{K_D} = \mathbf{k_D} + \Delta K_D,$$

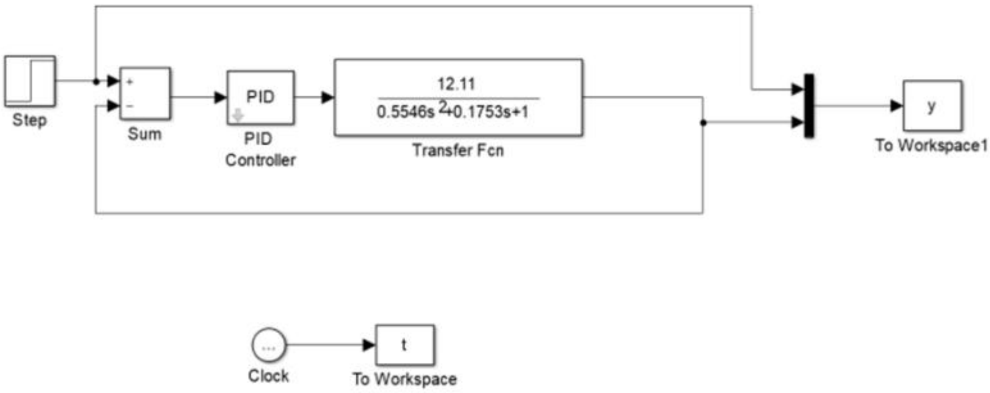
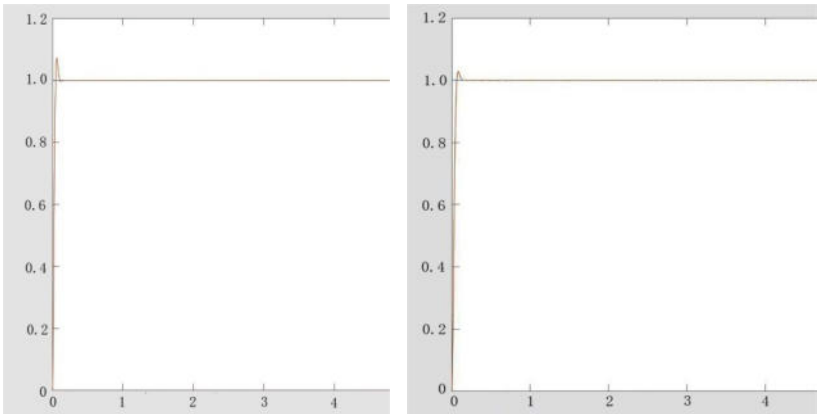


Fig. 5.2: Modeling of Fuzzy PID Control System



(a) traditional PID control (b) fuzzy PID control

Fig. 5.3: Comparison of Two PID Effects

Among them, $\mathbf{k_p}$, $\mathbf{k_I}$ and $\mathbf{k_D}$ are conventional PID parameters.

Input fuzzy rules into the fuzzy controller and make relevant settings to establish a simulation model of the turntable control system based on fuzzy PID, as shown in Figure 5.2. In the figure, the sum of the input step signal and feedback signal is inputted into a PID controller, and then output through a transfer function.

Through the SIMULINK modeling and simulation environment of MATLAB simulation software, a comparison was made between fuzzy PID control and traditional PID control. Figure 5.3(a) shows the simulation results of ordinary PID and Figure 5.3(b) shows the simulation results of fuzzy PID. The comparison shows that the entire process output of the fuzzy PID controller is smoother, with less speed oscillation. At the same time, due to strong control adaptability and high control accuracy, it can meet the requirements of motion control for this test turntable.

5.3. Software design. The system software mainly consists of FPGA based controller software for the lower computer. The software design includes functions such as controlling motor operation, adjusting fuzzy PID parameters, and processing relevant data to achieve precise positioning of the turntable. The controller has an RS422 interface for communication with the upper computer. The upper computer sends control instructions based on custom messages through the RS422 serial port, while the lower computer controller constantly reports

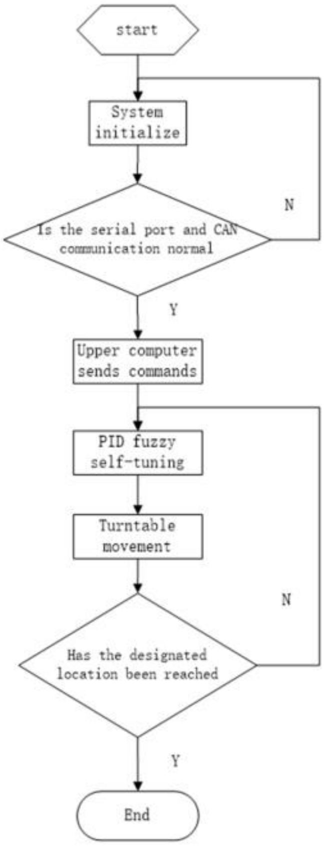


Fig. 5.4: System software structure diagram

information such as system angle, speed, and self status. The system software structure diagram is shown in Figure 5.4.

The system first initializes itself, checks whether the serial port and can communication are normal, and constantly reports the current angle and system status to the upper computer. After normal operation, the controller receives instructions from the upper computer, judges the validity of the instructions, and then completes PID fuzzy self-tuning. The driver drives the turntable to move until the turntable reaches the designated position, ending the control process.

6. Error analysis. In order to test the accuracy of the turntable, according to the *Main Performance Testing Methods for Inertial Technology Testing Equipment*, an angular position measurement test is adopted [19]. The measurement principle is shown in Figure 6.1, and the testing system includes a testing turntable, a 24 sided prism, an autocollimator, and an adjustable tripod. The actual test turntable is shown in Figure 6.2.

The experiment adopts a 24 sided prism. Firstly, from the angle feedback of the measured axis to display the 0 position, record the initial reading of the theodolite θ_1, Then rotate the measured axis by 15° in sequence based on the angle feedback display value, and record the corresponding readings of the theodolite $\theta_2 \ldots \theta_{24}$, at last Calculate the error at each point using the following formula:

$e_i = \theta_i - \theta_1 (i = 2, \ldots\ldots 24)$, The test data is shown in Table 6.1.

In Table 6.1, the system measured significant errors at positions 30°, 70°, 225°, and 270°, exceeding 100". This is mainly due to structural machining accuracy errors and transmission errors, resulting in significant errors at several fixed positions throughout the system. According to national standards, take the maximum positive error in the calculation results $e^+ = 152$", the maximum negative error $e^- = -118$", $\frac{e^+ - e^-}{2} = 2.25$'.

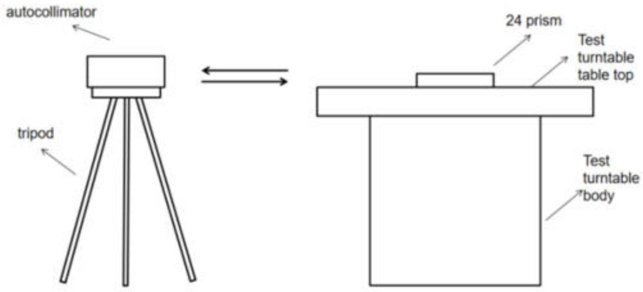


Fig. 6.1: Principle of Position Measurement Test

Fig. 6.2: device detection

Table 6.1: Test turntable error of fuzzy PID algorithm

Set Angle(°)	Measurement value(")	error value(")	Set Angle(°)	Measurement value(")	error value(")
0	228				
15	291	63	360	230	2
30	390	152	345	321	93
45	259	31	330	301	73
60	270	42	315	241	13
75	365	137	300	267	39
90	219	−9	285	163	−65
105	218	−10	270	122	−106
120	263	35	255	209	−19
135	212	−16	240	198	−30
150	199	−29	225	100	−118
165	324	96	210	254	26
180	181	−47	195	240	12

After multiple measurements and taking the average value, it is found that the positioning accuracy of the turntable is better than 2.2'.

During the testing process, the rotational speed of the turntable (1-10°/s) is set, and after considering the total system deceleration ratio, it is converted into the motor speed (rpm). By reading the speed of the motor during operation, the maximum and minimum values of the motor speed during stable operation are recorded. Table 6.2 shows the speed stability of the fuzzy PID algorithm.

The relative error of the turntable measured by this control strategy is 1.9%, which is better than 3.2% of the ordinary PID. Meanwhile, the lower the rotational speed of the turntable, the poorer its speed stability.

Table 6.2: Speed error during fuzzy PID control

Serial Number	Set speed(°/s) (motor speed)	Motor speed range(rpm)	Relative error (%)	Overall relative error(%)
1	1(92.7rpm)	88∼97	4.6	1.9
2	2(185.5rpm)	178-191	2.9	
3	4(371.0rpm)	365-380	1.6	
4	6(556.5rpm)	550-562	1.1	
5	8(742.0rpm)	737-746	0.7	
6	10(927.5rpm)	923-931	0.5	

7. Conclusion. This article designs a single axis electric turntable based on the requirements of high positioning accuracy and speed stability of the testing turntable. The system adopts a three-phase synchronous servo motor+reducer+gear transmission method, and the table is made of aluminum alloy material; The control system adopts a fuzzy PID control strategy to achieve the requirements of precise position control and fast response of the testing turntable. The equipment has the characteristics of large load-bearing capacity, high accuracy, and stable speed. Research has shown that:

(1) The turntable adopts gear transmission and multi turn absolute encoder angle measurement, with high transmission torque. The static and modal analysis of the turntable was conducted using ANSYS simulation software, verified that the testing turntable can meet the requirements of high load-bearing, high precision, and smooth operation;

(2) The fuzzy PID algorithm is used to replace the traditional PID algorithm, and an autocollimator is used to measure the positioning error of the turntable. The accuracy of the turntable system can reach 2.2', which is better than 2.6' of ordinary PID, and the running speed is more stable.

In future research and design of the turntable, in terms of machinery, we will consider reducing the clearance between gears from the perspective of improving part machining accuracy and assembly accuracy, or eliminating the clearance through coordinated work of dual motors, in order to achieve the goal of smaller system errors; In terms of control strategy, modern control methods such as sliding mode variable structure control algorithm that have good control effects on nonlinear factors can be used to control the turntable.

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