

SIMULATION OF CUTTING ERROR OF CRADLE CNC MACHINE TOOL UTILIZING THREE-LOOP PID CONTROL MODEL

Shujuan Gao

School of Mechatronics Engineering, Zibo Vocational Institute, Zibo, 255000, China

Email: gaoshujuan611@163.com

Abstract: The purpose of this work is to study the error of the three-loop PID (Packet Identifier) control model of cradle CNC (Computer Numerical Control) machine tool in the cutting process through simulation. Here, the milling and hobbing process are controlled through the vertical feed servo system of the cradle CNC machine tool. At the same time, the model is established in the ADAMS (Automatic Dynamic Analysis of Mechanical Systems) and MATLAB (Matrix Laboratory) software, including the servo motor, the complete control system, and the mechanical operation system. Then, the parameters of the three-loop PID are re-tuned. The gain parameters are adjusted from small to large, and the integral time constant is adjusted from large to small following the general experience of the external load. The steady-state value without vibration overshoot is set as the optimal value. Finally, the cradle CNC machine tool and the hobbing model are constructed, and the milling and hobbing are simulated through experiment. The pitch deviation and accumulation deviation of the simulated gear are measured through the VGMC (Virtual Gear Measurement Centre). The simulation experiment shows that the initial values set through the PID controller can shorten the system instability that arose from random values and shorten the intelligent algorithm and optimization time. Therefore, the error of the cradle CNC machine tool is significantly smaller than that of the ordinary CNC machine tool in the gear cutting process when controlled by a servo drive system with more accuracy, rapidity, and stability. It provides a more effective method to reduce the error in future precision machining. This can improve the accuracy requirements for products in the machining of CNC machine tools in China and lays a foundation for future intelligent control research.

Keywords: Simulation Experiment; Three-Loop PID Controller; Gear Measurement Centre; Cradle CNC Machine Tool.

1. Introduction

Modern CNC (Computer Numerical Control) manufacturing is developing in many directions, such as precision manufacturing and rapid manufacturing. Therefore, the machine feed servo system needs to achieve a faster response speed and higher control accuracy. The control of the CNC machine tool feed servo system is an error control, and the traditional PID (Packet Identifier) control method is generally adopted [1]. PID controller has been the first industrial controller used in practice for almost a century, and PID controller is still most widely used in industrial control.

The principle and structure of traditional PID control are very simple, which is only composed of three parts: proportion, integral, and differential. The basis of control adjustment is proportional control. The integral control can reduce the steady-state error, but it will increase the overshoot of the system response, and the differential control can reduce the response time of the inertial system and suppress the overshoot trend of the system [2]. The

traditional PID controller has the advantages of high precision, fast response, easy operation, and no steady-state static error. It is mainly used in linear systems with deterministic models. But the system model is not easily determined for the complex servo system with time-varying parameters, and meanwhile, the drive motor is also a complex multivariable nonlinear coupling system. The end load and the disturbance generated by the system will also make the control of the feed servo system complex and changeable.

Therefore, the traditional PID linear controller with fixed parameters cannot adapt to the complex nonlinear feed servo system, which often leads to poor parameter tuning, poor control performance, and poor adaptability to operating conditions [3,4]. An AFLC (Adaptive Fuzzy Logic Control) method for precision contour machining is studied. The fuzzy and NN (Neural Network) APID (Adaptive PID) controllers are designed for the feed servo system of CNC machine tools. Based on the theory of coordinate rotation, the coordinate rotation PID controller is designed, and the three control systems

composed of three controllers are simulated, respectively. For the CNC machine tool feed servo system, a fuzzy immune APID control method is proposed based on the immune feedback system and fuzzy control theory. The parameters of the three-loop PID controller are set and simulated through the control simulation software. Based on the standard GA (Genetic Algorithm) theory, an adaptive genetic control algorithm is proposed with crossover and mutation probability as the core [5]. The mathematical model is established and simplified for the feed servo system of CNC machine tools, and the PID control method can control and simulate the established model [6].

At present, to improve the machining accuracy of CNC gear hobbing machines, many scholars have done a lot of research on error prevention and error compensation. Error prevention can improve the machining accuracy through the improvement of design, manufacturing, and assembly of machine parts [7]. Most of the gear hobbing machining error compensation is to compensate for the error of the gear hobbing machine tool, and the geometric error is generally compensated through offline methods. It is necessary to measure the geometric error of the gear hobbing machine in advance. The dynamic errors caused by cutting force and cutting heat need to be monitored and measured in real-time. The offline compensation can compensate for the geometric error of the gear hobbing machine, while the online compensation can compensate for the cutting force and cutting the heat of the gear hobbing machine. These compensation methods are both highly costly and technically difficult to implement [8]. The proposed method here can reduce the error and improve the accuracy in the subsequent machine tool processing (such as turning teeth, slotting teeth, and grinding teeth). It reduces the error caused by traditional machining and is of great significance to improve the machining accuracy of domestic CNC gear hobbing machines.

2. Error Source Analysis and Modelling of CNC Gear Hobbing Machine

The basic components of CNC machine tools include processing program carrier, CNC device, servo system device, machine tool body, and other auxiliary devices. The ideal trajectory is interpolated according to the input data, and then output to the execution part for the processing of the required parts. Therefore, the NC device is mainly composed of three basic parts: input, processing, and output. All these tasks are reasonably organized through the computer system program so that the whole system can work harmoniously [9].

Compared with traditional machine tools, the structure of CNC machine tools has the following characteristics.

(1) A new machine tool structure with high stiffness, high seismic resistance, and small thermal deformation is adopted. Usually, the stiffness and seismic resistance of the machine tool host are improved through the static stiffness of the structural system, damping, quality, and natural frequency of the structural components, so that the machine tool host can adapt to the needs of continuous and automatic machining of CNC machine tools. Measures such as improvement on machine tool structure layout, heat reduction, temperature control, and thermal displacement compensation can reduce the influence of thermal deformation on machine tool host [10].

(2) High-performance spindle servo system and feed servo system can shorten the transmission chain of CNC machine tools and simplify the structure of machine tool mechanical transmission system.

(3) High efficiency, high precision, and no-clearance transmission device and moving parts are adopted, such as ball screw nut pair, plastic slide guide, linear rolling guide, and hydrostatic guide.

Here, the cutting error of the cradle CNC machine tool is analysed through simulation. Consequently, the accuracy is improved and the error is reduced through the PID controller.

2.1 Mechanical System

The structure of the CNC milling hobbing machine tool is shown in figure 1, which includes one spindle motion and three feed motions. The horizontal feed system is fixed during machining, and the vertical feed system and the rotary feed system are controlled through the CNC system for the milling and rolling of large modulus gears. The vertical feed system is analysed below.



Figure 1: Cradle CNC machine tool

Figure 2 shows that the vertical feed system is driven by a screw nut and an AC (Alternative Current) servo motor. The mechanical dynamics module of the electromechanical coupling system is established in ADAMS (Automatic Dynamic Analysis of Mechanical System).

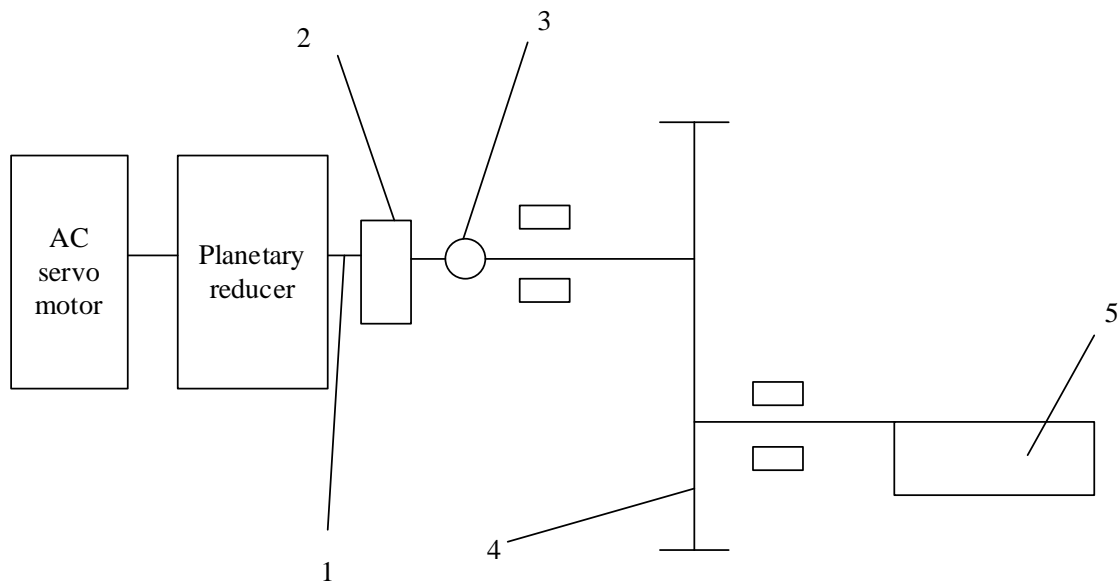


Figure 2: Feed servo system model (1: Screw; 2: Spindle box; 3: Cutting tools; 4: Gears to be processed; 5: Turntable)

The cutting process is discontinuous and strong, and the influencing factors of transient cutting load are complex and they vary tremendously in amplitude, so the response and stability for the electromechanical coupling system are required

higher [11,12]. The feed component model of milling tooth cutting load $F_z(t)$ can be expressed as in equation (1), considering the milling period and instantaneous milling depth.

$$F_z(t) = 9.2 * 10^3 * k_p * d_0^{-1.1} a_e(t)^{0.9} a_f^{0.8} \bullet a_p^{1.1} z n_0^{-0.1} \tag{1}$$

$$a_p = k + \tan 20^\circ \tag{2}$$

In equations (1) and (2), k_p represents the milling power correction factor, d_0 stands for the diameter of the milling cutter, and a_e denotes the milling depth. t represents the time, a_f denotes the feed per tooth, a_p stands for the milling width, and z represents the number of milling cutter blades. n_0 is milling cutter speed, k represents the top width of the disc cutter, and k is full tooth height.

The torque of the cutting load of milling teeth interferes with the electromechanical coupling system through the screw. The cutting load model of the milling tooth is expressed as a step function and sawtooth wave function, and the cutting load of the milling tooth is transformed into the corresponding screw torque.

2.2 Semi-closed Loop Servo System

The semi-closed loop control mode is adopted in the feed servo system of the cradle CNC machine tool. The electromechanical coupling relationship is shown in figure 3.

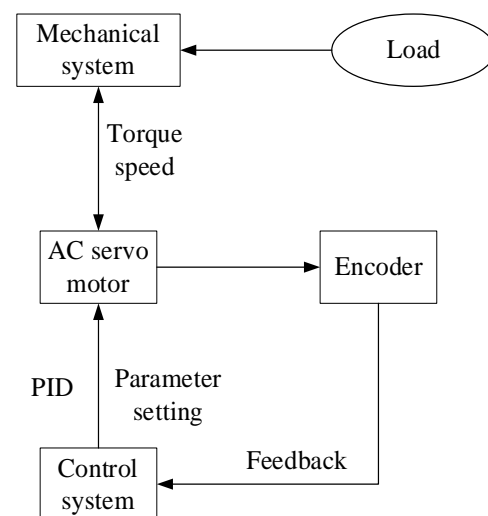


Figure 3: Electromechanical coupling process of the semi-closed-loop servo system

The control system is contour control, which requires accurate positioning, and the motor speed and steering should be controlled at any time. The common control methods of the three-phase PMSM (Permanent Magnet Synchronous Servo Motor) include vector control, direct torque control, fuzzy control, NN control, robust control, active disturbance rejection control, and compound control.

The position control of the AC servo motor is the vector transformation control of the magnetic field, which is composed of a current loop, speed loop, and position loop. The control model of the vertical feed servo system with servo motor is established in MATLAB/Simulink. Since the mechanical transmission link has a great influence on the control system, the PID parameters of the three-loop control of the system must be reset.

2.3 Electromechanical Coupling Dynamic Model

The three-loop response of the electromechanical coupling system is simulated in MATLAB/Simulink, and its dynamic performance is evaluated through the unit step response of the electromechanical coupling system. In actual working conditions, when uniform acceleration and deceleration or S curve acceleration and deceleration control mode are adopted, the dynamic performance will be better. The system is driven by a 1FK7101 Siemens AC servo motor. The reduction ratio of the planetary reducer is 1:26 and the pitch of the ball screw is 14 mm. The three-dimensional solid model of the vertical feed system is established in CAXA (Computer-Aided X Alliance) and imported into ADAMS/View through IGES (Initial Graphics Exchange Specification) standard data interface. The mechanical model is shown in figure 4.



Figure 4: The mechanical model of the feed servo system

The kinematic pair constraints are established in ADAMS/View: the column is connected to the ground through a fixed pair. The planetary reducer and bearing seat are connected to the column through a fixed pair. The motor and the screw are connected to the earth through the rotating pair, and the coupling pair is established. The coupling speed ratio is 26:1. The screw is connected to the screw base through the screw pair, and the guide is set to

14 mm. The screw seat is connected to the trailer through a fixed pair. The drag plate is connected to the column through the moving pair, the sliding static friction coefficient is set to 0.2, and the dynamic friction coefficient is set to 0.1. Finally, the rotary drive is added to the motor. The system dynamics simulation model is established through the addition of driving torque to the kinematics simulation model.

2.4 Error Source Analysis and Modelling

The components of the cradle CNC machine tools include rack slide, hob spindle, and rotary table, and these components may produce errors in manufacturing and assembly, reducing the accuracy of gear processing [13]. The errors are classified into many types based on the formation mechanisms, such as geometric error, force error of cutting force, the thermal error of cutting heat. Domestic and international research shows that various error sources influence the accuracy of CNC gear hobbing machines differently. The specific error types and their respective proportions are shown in table 1.

Table 1 Error and proportion distribution of cradle CNC machine tools

Error type		Proportion (Unit%)	
A	Geometric	22	65
	Force	10	
	Thermal	33	
B	Cutting tool	8	25
	Fixture	9	
	Other	8	
C	Random	5	10
	Installation	5	

(A: Machine tool error B: Machine processing error C: Detection error)

According to the meshing principle of hobbing machining, the meshing relationship between hob and worktable can be obtained, as shown in equation (3).

$$\omega_c = i_{cb}\omega_b + i''v_{oc} \quad (3)$$

In equation (3), w_c denotes the angular velocity of the workpiece, w_b stands for the acceleration of the hob, and i_{cb} represents the tooth number ratio between the hob and the workpiece. i'' represents the ratio of the axial velocity of the hob along the workpiece, and v_{oc} denotes the speed of the hob moving along the axial direction of the workpiece.

In the gear hobbing process, the workpiece goes through forced-hobbing periodically according to the meshing law [14]. When the gear is being hobbled, if the gear blank and hob contain errors, the errors will be reflected periodically in the tooth pitch error of the workpiece. Therefore, the gear hobbing error has

periodicity, which is a function of the gear blank rotation angle. Therefore, the error in the cumulative deviation of tooth pitch can be decomposed by the harmonic decomposition method. The harmonics with a period less than $27c$, a period equal to 2π , and a period greater than 2π can be obtained [15]. Figure 5 shows the classification of gear machining errors.

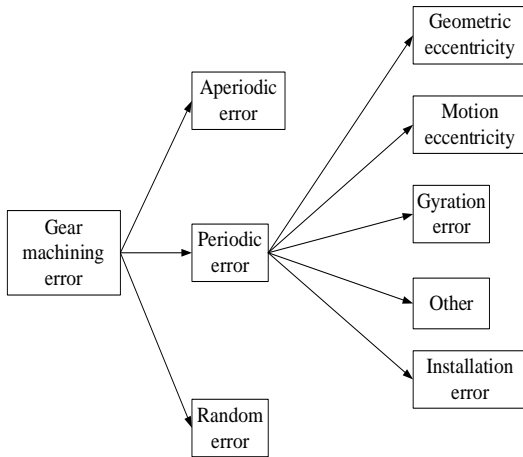


Figure 5: Classification of gear machining errors

A: Research on the error of hob

In the gear hobbing process, the relationship between the meshing line error of the hob and the meshing error of the workpiece is can be summarized as follows: the meshing line error of the hob is an important index for studying the hob error, including the tooth profile error and the helix error of the hob. The relationship between the meshing line error of hob and the meshing error of the workpiece can be expressed as in equations (4) and (5).

$$\Delta f_L = -e_{left} \sin\left(\frac{z}{k} \varphi + \theta_{left}\right) \tag{4}$$

$$\Delta f_R = -e_{right} \sin\left(\frac{z}{k} \varphi + \theta_{right}\right) \tag{5}$$

In equations (4) and (5), e denotes the meshing of the cutter, θ represents the phase angle relative to e , z is the number of teeth, and k stands for the number of graded worm heads.

The influence of meshing line error on cumulative tooth pitch deviation can be expressed as follows.

$$\Delta f_L = -e_{left} \sin\left(\frac{z}{k} \varphi + \theta_{left}\right) / \cos a \tag{6}$$

$$\Delta f_R = -e_{right} \sin\left(\frac{z}{k} \varphi + \theta_{right}\right) / \cos a \tag{7}$$

In equations (6) and (7), Δf represents the cumulative deviation of the tooth pitch of the radial jump of the hob, and α stands for the pressure angle of the gear.

In the hob error, the gear tooth pitch is influenced by the hob radial runout and axial runout. According to the meshing principle, the influence of hob radial runout P tool diameter on the workpiece meshing line error can be solved as follows.

$$\Delta f = \pm e \sin \alpha \sin\left(\frac{z}{k} \varphi + \theta\right) \tag{8}$$

In equation (8), e_1 denotes the radial eccentricity of the hob, and θ_1 represents the phase angle relative to e .

The influence of radial runout e , namely the tool diameter, on the cumulative deviation of workpiece tooth pitch can be expressed as follows.

$$\Delta f = -e_1 \sin a \sin\left(\frac{z}{k} \varphi + \theta_1\right) / \cos \alpha \tag{9}$$

In equation (9), $\Delta_3 F$ denotes the cumulative deviation of the tooth pitch of the radial runout, and α stands for the pressure angle of the gear.

Similarly, the relationship between the hob axial beating axis and the machining workpiece meshing line error can be deduced as follows.

$$\Delta f = \pm e \sin a \sin\left(\frac{z}{k} \varphi + \theta\right) \tag{10}$$

Then, the influence of axial jump $e_{hob - radius}$ on the cumulative deviation of workpiece tooth pitch can be expressed as in equation

$$\Delta_4 f = \pm e \sin \alpha \sin\left(\frac{z}{k} \varphi + \theta\right) / \cos \alpha \tag{11}$$

In equation (11), $\Delta_4 F$ denotes the cumulative deviation of the tooth pitch caused by the axial jump of the hob, and α stands for the pressure angle of the gear.

B: Research and analysis on the high-frequency rotary error of rotary table

The cumulative deviation of tooth pitch can effectively reflect the periodic error of the high-frequency error signal when the rotary table rotates, which is mainly manifested as the unevenness of gear indexing [16]. The degree of reaction mainly depends on the number of teeth Z of the machined gear and the rotation progress of the spindle. This is because the meshing line of the short period error is

a continuous curve, and the measurement point is the discrete point on the curve. Therefore, the position of the measuring point is related to the rotation accuracy, and the meshing line error can be expressed as in equation (12).

$$\Delta f_i' = \pm \frac{\Delta f_{i1}'}{2} (\sin(\varphi - \frac{z}{k} + \psi)) \quad (12)$$

The influence of cumulative deviation of workpiece pitch is expressed as in equation (13).

$$\Delta_5 F = \pm \frac{\frac{\Delta f'}{2} (\sin(\varphi - \frac{z}{k} + \psi))}{\cos \alpha} \quad (13)$$

C: Periodic error simulation experiment research

The periodic error is simulated through the compensation of high-order harmonic error caused by the manufacturing and installation errors of the hob. The periodic errors also include the machining errors of the spindle and rotary table whose period is less than 2π in the rotary process. Afterward, the machine tool data are initialized through the PID control model, and the periodic error is simulated and studied.

The CNC machining code is added to the cradle CNC machine tool. When the period $T = (1/2)\pi$, the amplitude of the superimposed small period error is $1.9\mu\text{m}$, and the phase is 0. The machining program is added to the virtual CNC simulation gear hobbing machine to start the virtual CNC gear hobbing machine and complete the machining of gear with the eccentric error.

The processed gear model is saved and imported into the VGMC (Virtual Gear Measurement Centre) for the measurement of gear pitch deviation and pitch cumulative deviation.

3. Simulation Analysis and Error Analysis

3.1 Electromechanical Coupling Dynamic Model and Simulation Analysis

A. Simulation of servo system without mechanical part

The dimensionless function is input and can analyse the current loop response, speed loop response, and position loop response of the servo system without mechanical part. The simulation results are shown in figure 6.

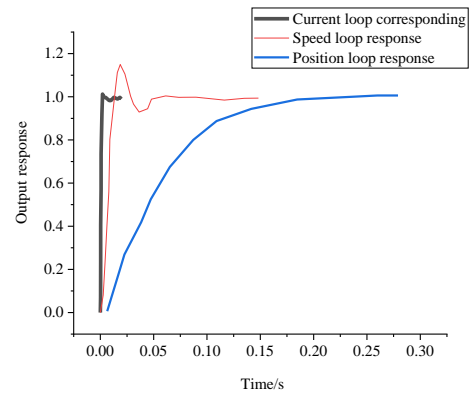


Figure 6: Simulation results of the unit step function

The simulation results show that the response speed of the current loop is fast, the position loop has no overshoot and steady-state error, and the overshoot of the speed loop is large (13.2%). In practical application, the acceleration and deceleration control can greatly reduce overshoot, so the dynamic response of the electromechanical coupling system can be stable.

B: Semi-closed-loop electromechanical coupling simulation of the servo system

The servo system with vertical feed is simulated through the electromechanical coupling model. The input signal is a step function of the motor angular displacement 1rad, and the output signal includes the angular displacement of the motor and the linear displacement of the spindle box, as shown in figure 7.

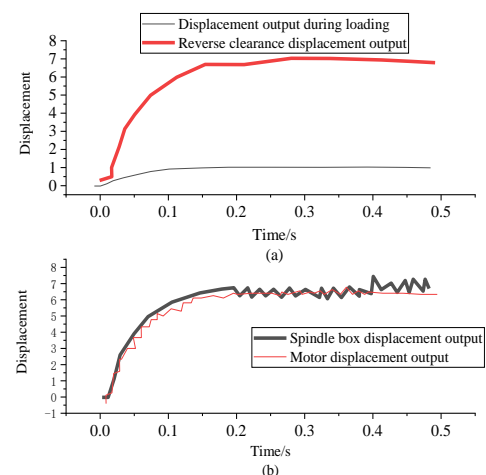


Figure 7: Simulation results of semi-closed-loop electromechanical coupling (a: The displacement output of spindle box during loading and the reverse clearance displacement output of spindle box; b: Displacement output of servo motor and displacement output of non-load spindle box)

The simulation results show that the servo system has no overshoot and good stability. Figures 7a and 7b illustrate that the servo motor angular displacement output can easily resist cutting load impact, and the steady-state error is caused by the mechanical system.

When the load is removed at 0.4s, the steady-state error can be eliminated. Figure 7a shows that the ring adjustment time of the spindle box without load-displacement is 0.3s, and there is no overshoot, but there are displacement fluctuations. Figures 8b and 8c show that the impact of cutting load will increase the resonance of the spindle box displacement, and the resonance frequency is the natural frequency of the mechanical system of the vertical feed system (92.7 Hz).

Meanwhile, the steady-state error will occur. Figure 7a demonstrates that the reverse gap can feedback an impact to the system the moment the

motor starts, and the step function can simulate the impact load. The reverse gap can be compensated in the CNC system, but it will cause system oscillation. Since it can be quickly stabilized, the servo feed system is stable and has little influence in the milling and hobbing process. Besides, the frequency of the periodic milling load has little effect on the resonance of the displacement ring of the spindle box, because the frequency of the milling load is 16Hz, far lower than the natural frequency of the mechanical system.

3.2 Experimental Study on Periodic Error Simulation

The data curve after periodic error simulation measurement is shown in figure 8.

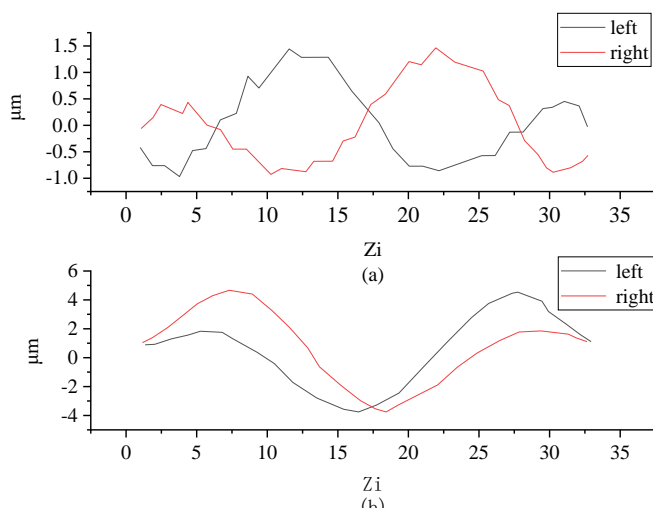


Figure 8: Tooth pitch error curve of actual hobbing error

(a: Tooth pitch deviation under actual hobbing error; b: Cumulative deviation of tooth pitch in actual hobbing)

According to the measured cumulative tooth pitch deviation data, the DFT (Discrete Fourier Transform)

can calculate the amplitude-frequency curve and phase-frequency curve, as shown in figure 9.

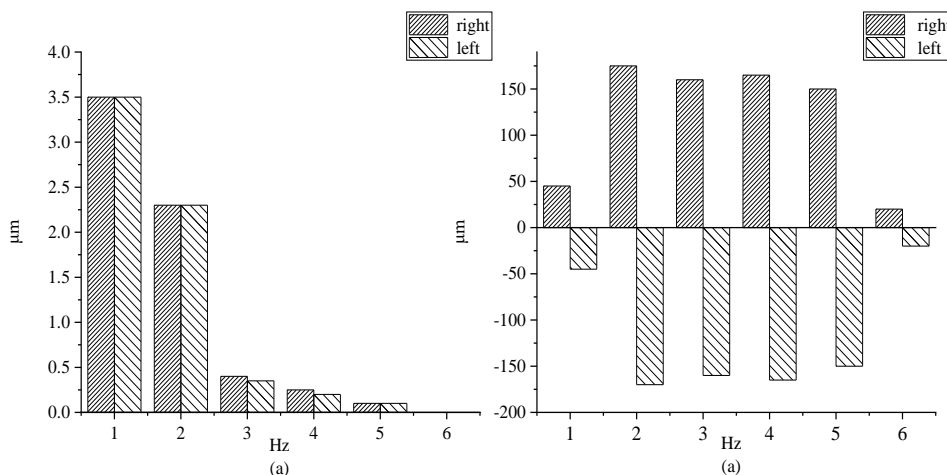


Figure 9: DFT variation diagram of cumulative deviation of gear tooth distance in actual gear rolling (a: Amplitude-frequency characteristic; b: Phase-frequency characteristic)

The data obtained through the three-loop PID control system is added to the hobbing shaft, and the meshing ratio is changed during the hobbing process after the rotation angle of the hob is controlled.

As a result, the eccentric error can be process-compensated. The compensation results are shown in figure 10.

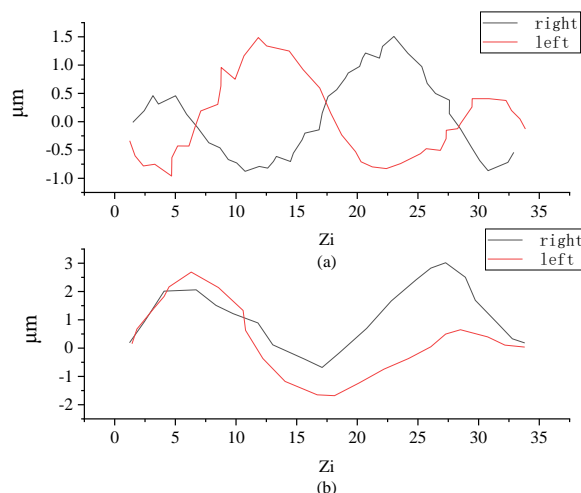


Figure 10: Initialization curve of tooth pitch error in actual hobbing tJDT error (a: Pitch deviation; b Cumulative pitch deviation)

The cumulative total deviation of left and right tooth pitch after initialization is $LF_p=3.6\mu m$ and $RF_p=5.3\mu m$, respectively.

Then, the pitch deviation and pitch cumulative deviation curves before and after initialization are compared, as shown in figure 11.

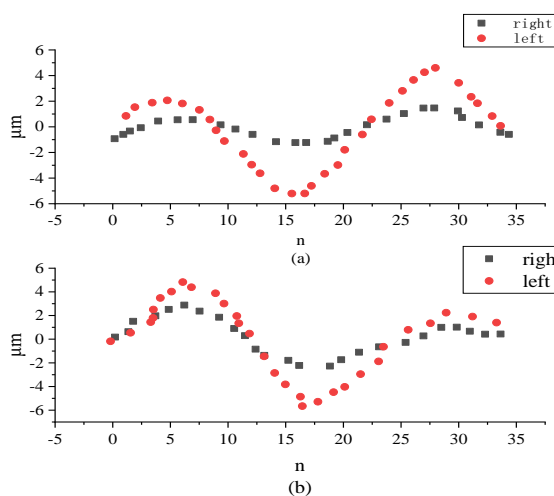


Figure 11: Comparison of cumulative pitch deviation before and after initialization (a: Cumulative deviation of left tooth pitch; b: Cumulative deviation of right tooth pitch)

Figure 11 shows that comparison results of simulation experiment data before and after initialization, and accuracy standard of involute cylindrical gear can be consulted.

The accuracy indexes and analysis results of gears before and after initialization are shown in table 2.

Table 2 Precision index and analysis data of gear before and after initialization

Item	Accuracy comparison	Accuracy before initialization		Accuracy after initialization		Initialization effect	
		Results	Accuracy grade	Results	Accuracy grade	Efficiency	Improve accuracy
F_p (μm)	Left flank	9.7	Grade 4	3.5	Grade 2	62.8%	Grade 2
	Right flank	10.3	Grade 4	5.4	Grade 3	49.2%	Grade 1

(Efficiency= (error before initialization–error after initialization)/error before initialization)

In the proposed PID control system, the data obtained through PID is taken as the initialization data of the machine tool, which can effectively optimize the accuracy of the gear after machining. Compared with the previous error effect, the optimization reaches over 50%.

4. Discussion

Generally, the CNC machine tool feed servo system adopts a kind of error control through the traditional PID control method. It has been almost a century since the first usage of the PID controller as an industrial controller, and the PID controller is still most widely used in industrial controls [17]. The principle and structure of traditional PID control are very simple, which is only composed of three parts: proportion control, integral control, and differential control.

The basis of control adjustment is proportion control. The integral control can reduce the steady-state error, but it will increase the overshoot of the system response. The differential control can reduce the response time of the inertial system and suppress the overshoot. The traditional PID controller has many advantages, such as high adjustment accuracy, fast response speed, easy operation, and no steady-state static error, which is mainly used in the linear system with a specific model [18]. But the system model is not easily determined for the complex servo system with time-varying parameters, and meanwhile, the drive motor is also a complex multivariable nonlinear coupling system. The end load and the system disturbance will complicate the control process of the feed servo system.

Therefore, the traditional PID linear controller with fixed parameters cannot adapt to the complex nonlinear feed servo system, which often leads to poor parameter tuning, poor control performance, and poor adaptability to operating conditions [19]. An APID method for precision contour machining is studied. A three-loop PID controller is designed for the feed servo system of cradle CNC machine tools. A fuzzy immune adaptive three-loop PID control method is proposed for the feed servo system of CNC machine tools based on the immune feedback system and fuzzy control theory. In the three-loop control, the proportional gain of the position loop is set. When the position loop needs adjustment, the speed loop should be adjusted first. There is no fixed value for the parameter adjustment of the position loop and the speed loop. Instead, they are determined by many conditions, such as the mechanical transmission connection mode of the external load, the motion mode of the load, the load inertia, the speed and acceleration requirements, and the rotor inertia and output inertia of the motor. It is most easy to adjust the gain parameters from small to large and adjust the integral time constant from

large to small within the scope of general experience according to the external load. The steady-state value without vibration overshoot is set as the optimal value.

The parameters of the three-loop PID controller are set and simulated through the control simulation software. Based on the standard genetic algorithm theory, an adaptive genetic control algorithm is proposed, with crossover and mutation probability as the core [20]. The mathematical model of the feed servo system of CNC machine tools is established and simplified, and the fuzzy PID control method can control and simulate the proposed system.

5. Conclusion

(1) The parameters are tuned for the three-loop PID controller of the vertical feed servo system of the cradle CNC machine tool. The electromechanical coupling dynamic model is established through ADAMS and MATLAB. The simulation results show that the servo drive system using the three-loop PID control has accuracy, rapidity, and stability.

(2) The mechanical part of CNC machine tools has a great influence on the dynamic performance of electromechanical coupling systems. The periodic load of milling tooth cutting will increase the vertical feed, which will resonance with the position loop of the servo system and produce the steady-state error. The resonance frequency is the natural frequency of the mechanical system.

(3) The intelligent controller with stronger robustness is needed due to the disturbance of mechanical system rigidity and cutting load. The influence of P, I, D parameters in the control model are analysed on the control effect, and the optimal PID parameters are selected for the proposed model. The proposed control system can reduce the system instability caused by the random selection of initial values and shorten the intelligent algorithm and optimization time. The proposed system can lay a good foundation for future intelligent control research.

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