Research on Servo Transmission Control System of Laser Micro-Texture Machining Machine

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Abstract. In the process of laser surface micro-texture processing, the instantaneous speed and instantaneous acceleration of the moving machine tool are high, the positioning error and repeated positioning error are difficult to control, and the precision of laser micro-texturing processing cannot be guaranteed. The dynamic model of the machine tool servo system is established. Based on the model, the error compensation scheme of the control system is designed. A speed and acceleration composite feedforward compensation PID control strategy is proposed. In order to illustrate the superiority of the proposed position accuracy compensation method, the PID control effects before and after compensation were compared. The results show that the position error of the system is reduced from 4μm to 1μm before compensation, and the repeat positioning accuracy is improved by 50%. Experiments show that this kind of control strategy can effectively reduce the position error of laser micro-texturing processing system, and has higher position tracking accuracy and repeat positioning accuracy, which satisfies the system's demand for high-precision positioning, and is the surface micro-texture morphology. Performance studies provide more sophisticated machine tool servo control strategies and higher laser surface micro-texture machining accuracy.

1. Introduction

Laser processing technology has been widely used in various fields such as laser micro-texturing processing because of its low processing conditions, small processing area, and ability to accurately process complex micro-morphological structures. The quality of laser-machined workpieces is closely related to the positioning accuracy of moving machine tools, so the selection of ideal mechanical transmission components is essential. Among them, the ball screw pair is widely used in laser processing motion control systems due to its reliable work, high transmission precision and good dynamic performance of mechanical structure [1]. In order to meet the requirements of high-speed and high-precision positioning systems in the precision machining process of sports machine tools [2], many scholars at home and abroad have carried out a lot of research on improving the positioning accuracy and repeat positioning accuracy of ball screw pairs.

Zhang Wenkai [2] analyzed the large lead ball screw feed system, and established the lumped parameter dynamics model by using the D'Alembert principle. The correctness of the theoretical analysis of the system was verified by the vibration noise test module, but it was not improved. Tian Liangang et al [3] took the high-speed bed machining center as the research object. Through the parametric modeling of the ball screw feed system, the influence of the system dynamics parameters on the dynamic characteristics was analyzed, and the solution to improve the dynamic performance of the system was proposed. Wang Yongqiang et al [4] considered the viscous friction and transmission
stiffness, established the model reference adaptive system simulation model, and derived the second-order mathematical model of the ball screw feed system. Qian Rongrong [5] carried out theoretical analysis and experimental research on the vibration and positioning accuracy of the servo motor with ball screw during the working process, and the closed-loop control algorithm and dynamic characteristics of the ball screw positioning system. Yang Xiaotong et al [6] used the double-drive feed system of the dynamic beam-free ram vertical milling and machining center as the research object, established the system synchronization control model, and obtained the main factors affecting the system out-of-synchronization error and its error. Dan J. Gordon et al [7] adopted a ball screw servo system controller based on the pole placement algorithm to achieve active damping of the ball screw in the transmission, high-bandwidth interference suppression and positioning, and improved tracking performance of the drive system.

In summary, with the problems of low positioning accuracy, reciprocating focus misalignment, and low repeatability in the research on the ball screw. In this paper, the research of high performance laser micro-texture processing system is carried out, and the dynamic model of machine tool servo system is established for the ball screw servo motion system. Based on this, the error compensation scheme of the control system is designed and the speed is proposed. Combined with the acceleration feedforward compensation PID control model, and through MATLAB simulation experiments, the effectiveness of the servo control strategy of the ball screw machine tool is verified, which has a significant effect on improving the position tracking accuracy and reciprocating processing repeat positioning accuracy.

2. Laser Processing System Structure and Working Principle
The basic structure of the laser processing system is shown in Figure 1. The system consists of two subsystems: servo motion control and laser control. The machine servo motion subsystem takes the multi-axis motion controller as the core, receives and processes the feedback signals of the grating scale and other position sensors, and combines the received PC-side host computer commands to output the motion control signals to X, Y, Z, The θ four-axis servo driver accurately controls the movement of the machining table; the laser control subsystem outputs the specified laser Q signal to the Q-switching driver according to the upper machine machining instruction, and controls the YAG solid-state laser (output wavelength is 532 nm) and the fiber laser. The laser opens and closes and starts the water cooling system to work.

![Figure 1. Schematic diagram of laser processing system](image)

3. Dynamics Modeling of the Ball Screw Servo Drive System

3.1 Force Analysis of the Mechanical Transmission Mechanism of the Ball Screw Servo Drive System
Through the structural analysis of the ball screw servo drive system, the system generally consists of two mechanical transmission mechanisms and a servo control system. Most of the composition. The mechanical transmission mechanism is shown in Figure 2. The two ends of the ball screw are
supported by bearings, one end is connected with the servo motor, the motor drives the ball screw to rotate, and then the ball screw nut drives the slider and the table moves along the linear guide pair. The rotary motion of the transmission component is converted into a linear motion of the table. The grating scale detects the real-time position of the workbench, and the feedback signal is used for servo system position tracking.

According to the calculation and analysis of the mechanical transmission structure, the axial total stiffness of the system is set to remain unchanged, and the influence of the torsional deformation of the ball screw and the Coulomb friction on the axial displacement of the slider is not considered. According to Figure 3, the mechanical analysis of the mechanical structure of the ball screw servo system is carried out, and the mathematical model of the transmission part can be expressed as equations (1)–(4):

\[
T = J_M \ddot{\theta}_M + k_b \dot{\theta}_M + k_s k_i (X_M - X_i) + k_s c_i (\dot{X}_M - \dot{X}_i) \quad (1)
\]

\[
M_s \ddot{X}_i = -k_f \dot{X}_i + k_s (X_M - X_i) + c_i (\dot{X}_M - \dot{X}_i) \quad (2)
\]

\[
k_i = L/2\pi \quad (3)
\]

\[
X_w = k \theta_M \quad (4)
\]

Where \(k_b\) is the viscous friction coefficient between the servo motor shaft and the coupling, \(c_i\) is the viscous friction coefficient between the ball screw and the bearing, \(k_f\) is the dynamic friction coefficient between the table and the guide rail, \(J_M\) and \(T\) are moment of inertia and driving torque, \(X_M\) and \(\theta_M\) are the rotational displacement of the motor, \(X_i\) is the axial displacement of the servo motor and the angular displacement of the motor, \(M_s\) is the mass of the table, \(L\) is the lead of the ball screw, \(k\) is the angle of rotation of the screw. Conversion factor between displacement and linear displacement. The transfer function of the mechanical transmission structure model can be obtained from equations (5) to (6):

\[
G_1(s) = \frac{X_M}{T} = \frac{M_s s^2 + (k_f + c_i) s + k_i}{a_s s^4 + a_s s^3 + a_i s^2 + a_i s} \quad (5)
\]

\[
G_2(s) = \frac{X_i}{T} = \frac{c_i s + k_i}{a_s s^4 + a_s s^3 + a_i s^2 + a_i s} \quad (6)
\]

3.2 Speed Acceleration Composite feed forward Compensation

In the ball screw servo system, the measurement of the system disturbance error is difficult. It is not wise to compensate the disturbance directly under unknown conditions; It is caused by the input signal,
and it is considered that in the laser processing process, the movement trajectory, velocity and acceleration of the control object are usually predicted according to the processing requirements. Therefore, the input and signal compensation are compensated by the composite feedforward compensation method of speed and acceleration. The feedforward control method can not only reduce the tracking error of the system, but also improve the trajectory tracking accuracy of the controller and the control precision of the system while ensuring the rapidity of the system. The principle block diagram of the feedforward compensation PID controller is shown in Figure 3.

### 3.3 Servo Control System Modeling

Starting from the integrity of the system, the mechanical dynamics model of the ball screw servo motion control system is linked with the motor control part to establish the theoretical transfer function model of the above system, combined with the speed and acceleration of the design. The feedforward compensation PID controller establishes a simulation model of the servo system of the ball screw machine shown in Fig. 4. Where \( k_{pw} \) and \( T_{pw} \) are the amplification factor and time constant of the inverter respectively, \( L_a \) and \( R_a \) are the armature inductance and resistance, \( k_s \) and \( k_c \) are the feedback gain of the speed loop and the current loop, \( k_t \) is the torque current coefficient. The servo motor adopts a position loop, a speed loop, and a current loop three-loop control, wherein the transfer functions of the speed regulator, the current regulator, and the position regulator are respectively shown in equations (7) to (9):

\[
G_p(s) = k_p \tag{7}
\]

\[
G_v(s) = \frac{k_v(s + \frac{k_c}{k_s})}{s} \tag{8}
\]

\[
G_c(s) = \frac{k_c(s + \frac{k_v}{k_c})}{s} \tag{9}
\]

![Figure 4. Simulation model of the servo system of the ball screw machine](image)

### 4. Machine tool simulation results and analysis

#### 4.1 Compensation Scheme Verification

![Figure 5. Feed forward compensation PID and system step response under traditional PID control](image)
In order to verify the effectiveness and superiority of the proposed composite feedforward compensation PID control algorithm, the feedforward compensation PID controller and the traditional PID controller are used to test the step response to test the two. Control performance. Figure 5 shows the step response of the system under the effects of feedforward compensation PID control and traditional PID control, respectively.

| Control algorithm              | Traditional PID control | Feedforward compensation PID |
|-------------------------------|-------------------------|------------------------------|
| Rise Time /ms                 | 3.2                     | 1.8                          |
| Adjustment time /ms           | 5.4                     | 3                            |
| Overshoot \(\sigma/\%\)       | \(\leq 1\%\)           | \(\leq 1\%\)                |
| Maximum error ratio           | 0.03\%                 | 0.01\%                       |

Table 1 reflects the performance metrics of the system step response for the two control algorithms tests in Figure 8. It can be seen from Fig. 8 and Table 2 that from the oscillation situation, the two control algorithms have almost no oscillation and the overshoot is small; but from the response speed, compared with the conventional PID controller, the system rise time of the feedforward compensation PID controller is used. It is shortened by 78\%, and its adjustment time is only 56\% of the former; from the control accuracy, the error ratio of the feedforward compensation PID controller is also smaller, so the feedforward compensation PID controller has better transient response performance and The higher control precision can prove the effectiveness and superiority of the combined feedforward compensation scheme of speed and acceleration proposed in this paper.

4.2 Experimental results and analysis

The MATLAB simulation is carried out by using the continuous-speed continuous feed motion trajectory curve. The axial speed of the motor is reciprocated with an acceleration of 0.5 s. The acceleration and speed of the motor after each cycle is completed. In the initial state, the table of the ball screw also returns to the initial origin. The acceleration (A), speed (V) and position (X) settings of the motor motion are shown in Figure 6.

![Command curve](image)

Figure 6 Command curve

Figure 7(a) shows the position tracking curve of the system using composite feedforward compensation PID control. It can be seen from the figure that the system has good position tracking accuracy and response performance without considering the ball screw torsion deformation and Coulomb friction.
Figure 7 Result curve (From left to right are (a) position tracking curve, (b) Position error curve before and after PID and feedforward compensation, (c) Repeat positioning error curve)

Figure 7(b) shows the position error curve of the system before and after PID and feedforward compensation. The system position error is compared in three cases. Among them, it can be seen from the original error curve that the position error will also generate a large oscillation whenever the motor acceleration transient occurs; and as the acceleration tends to be stable, the error will return to stability; The change and the displacement curve are basically synchronized, and the maximum error range is 57-63 $\mu m$. Firstly, the PID adjustment is adopted for the system. As can be seen from the figure, the oscillation of the error curve is greatly improved, the overshoot is reduced, the error range is controlled within 4 $\mu m$, the error accuracy is improved by 14 times compared with the original state, and the stability of the system is better. Then, based on the existing basis, the composite feedforward compensation of speed and acceleration is added, and the error range is reduced again, which is reduced to less than 1 $\mu m$, and the error precision is reduced to the nanometer level. In this paper, the reciprocating motion method is used to investigate the origin return and repeat positioning accuracy of the ball screw. As shown in Fig 7(c), the repeated positioning error of the ball screw cycle motion before and after compensation is compared. It can be seen from the figure that After 500 cycles of the system reciprocating motion, the error curve without feedforward compensation is shifted by about 2 $\mu m$ in the negative direction of motion, while the error curve with feedforward compensation has almost no offset, and the repeat positioning accuracy is increased by 50% compared with no compensation. Therefore, the composite feedforward compensation PID control method has a great improvement on the system repeat positioning accuracy, and has better position tracking accuracy and repeat positioning accuracy.

5. Conclusion
In this paper, the laser micro-texture processing system is researched based on improving the precision of laser surface micro-texture processing. The model compares the performance of the system position error by comparing the feedforward compensation PID control method with the traditional PID control method. It verifies the superiority of the composite feedforward compensation PID control strategy and effectively reduces the position error and repeated positioning error of the servo system. From the diversity of processing, whether the control strategy has universality under other processing conditions besides laser processing needs further investigation. The laser micro-texture processing system provides an experimental platform for the study of the surface texture performance of the laser surface micro-texture process. The control strategy will be further tested and optimized according to the diversification of the processing requirements.

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