Key Engineering Materials
ISSN: 1662-9795, Vol. 339, pp 163-167
doi:10.4028/www.scientific.net/KEM.339.163

Online: 2007-05-15

Research on Low Speed Servo Control Technology of Ultra-precision Machine Tool

X.W. Sun[1,a], F.H. Zhang[1,b], S. Dong[2,a] and L.J. Zhang[2,b]

[1]Harbin Engineering University, Harbin,heilongjiang, china

[2]Harbin Institute of Technology, China

[a]sun_xiwei@163.com,zhangfh@hit.edu.cn

Keywords: Ultra-precision machine tool , Low speed feed, Servo control , KDP crystal

Abstract. An ultra-precision machine is developed by Precision Engineering Research Institute of Harbin Institute of Technology to machine components made of KDP crystal with single point diamond fly cutting technique . A stable ultra-low speed feed of worktable is necessary in the machining process inasmuch as the KDP crystal components to be machined must be high form accuracy, low surface roughness and low surface waveness . This paper analyses the effect on speed stability and positioning accuracy under the control of semi-closed loop and full-closed loop based on the experimental data, and also present a compensating control algorithm of error disturbance feed-forward which enhances the stability of ultra-low speed motion of the semi-closed loop feed control servo system of the machine. The simulation results indicate that the values of the steady-state tracking error decreased to 1/10 after using compensating control algorithm. The P-V value of the aluminum specimen machined by the ultra-precision machine tool was 0.27 wavelengths.

Introduction

An ultra-precision machine is developed by Precision Engineering Research Institute of Harbin Institute of Technology to machine components made of KDP (Potassium dihydrogen phosphate) crystal with single point diamond fly cutting technique. A stable ultra-low speed feed of worktable is necessary in the machining process inasmuch as the KDP crystal components to be machined must be high form accuracy, low surface roughness and low surface waveness . As the ultra-precision machine adopting semi-closed loop feed servo control system, an appropriate compensating control algorithm is needed for the feed servo system to hold the stability of ultra-low speed motion .

Configuration and System Dynamic Characteristic

In the servo control system of the ultra-precision machine, an AC servo motor and a ball screw are used to implement the feed of the worktable. An aerostatic slideway is used to reduce the friction generated during the feed. In order to keep thermal stability, the bed piece of the machine is made by granite which has low coefficient of dilatation and high dimensional stability.

In the AC servo unit, a closed loop of speed regulation is used, in which a proportional regulator is adopted. The dynamic model of the position servo system is shown in Figure 1, where K_T is a moment constant, which equals to 3.92N·m/v. $D(s)$ is a position controller. The proportionality coefficient of the tachometer C_S equals to 0.796V/Rad/s. K_d is the circuit enlargement factor of the encoder. T_d is the disturbance moment of the system mainly caused by the friction and fluctuation of the motor's torque. $G_j(s)$ is the transfer function of the mechanical transmission link. R is the input signal and x is the position output of the table. θ is the output of the rotating angle of the motor.

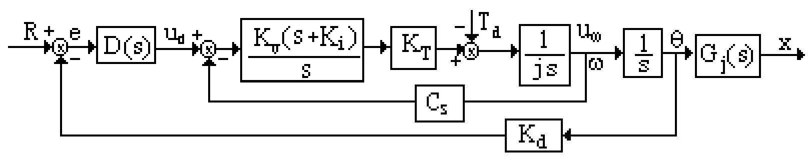


Fig.1 Dynamic model of the position servo system

From Figure 1, the transfer function of the driving unit can be obtained

$$G_u(s)=\frac{u_w(s)}{u_d(s)}=\frac{\dfrac{1}{C_S K_i}s+\dfrac{1}{C_s}}{\dfrac{J}{K_V K_T C_S K_i}s^2+\dfrac{1}{K_i}s+1} \tag{1}$$

With the FFT analysis, the transfer function is obtained as follows

$$G_u(s)=\frac{u_w(s)}{u_d(s)}=\frac{0.001s+1.256}{0.0000085s^2+0.0008s+1} \tag{2}$$

The open loop transfer function of the servo system is

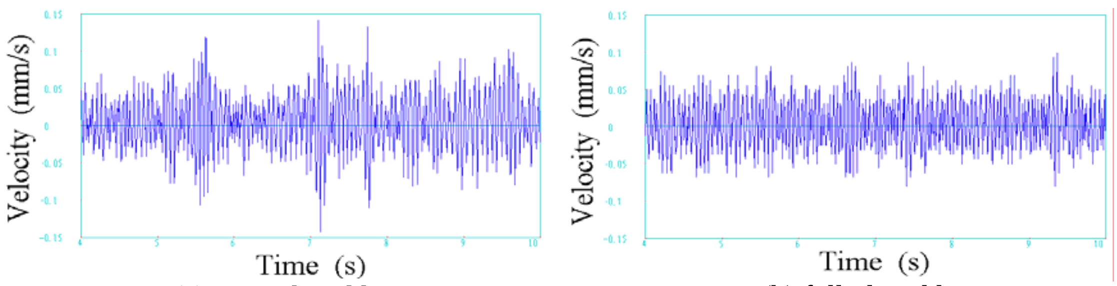
$$G_0(s)=\frac{x(s)}{R(s)}=\frac{K_p(0.001s+1.256)G_j(s)}{s(0.0000085s^2+0.0008s+1)} \tag{3}$$

The Effect on Speed Stability and Positioning Accuracy under Control of Semi-closed Loop and Full-closed Loop

Typical advantage of semi-closed loop is to obtain high servo gain[1]. As the feedback signals are generated by encoder integrated with the motors, there is only minimum time delay between motion command and actual feedback signal, thus, higher servo gain can be obtained .On the other hand, typical advantage of full-closed loop is to obtain positioning accuracy with minimizing influence of ball screw's thermal growth/shrink[2]. However, there is certain time delay between motion command and actual feedback signal because of motion transmission and motor shaft - coupling - ball screw - scales.

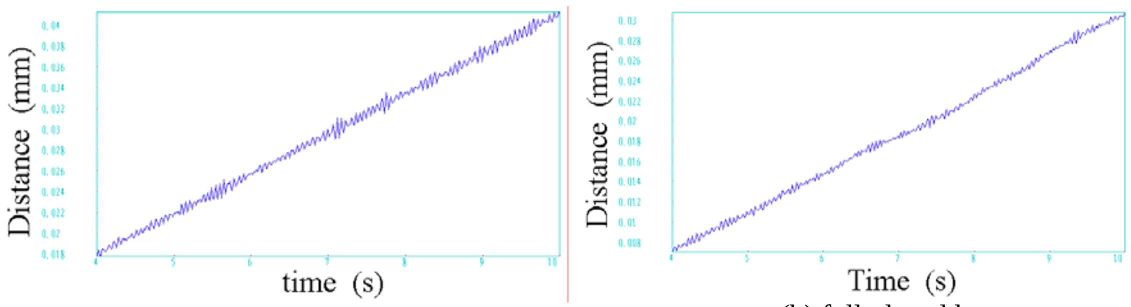
Two experiments separately under control of semi-closed loop and full-closed loop were made to analyze and research effect on low-speed stability and positioning accuracy. The semi-closed loop feedback signal came from the encoder of servo motor , and full-closed loop feedback signal came from the grating ruler which resolution was 0.001mm. The measuring device was laser-interferometer which resolution was 5nm. The pitch of lead screw was 4mm .

The experiment result indicated in Figure 2~3 drew a conclusion that the low-speed stability under control of full-closed loop was better than under control of semi-closed loop.



(a) semi-closed loop (b) full-closed loop

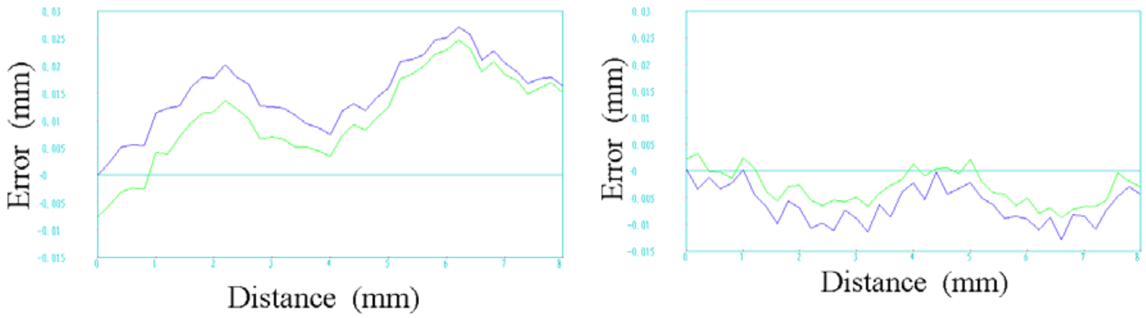
Fig.2 The velocity-time curve when feed was 0.004mm/s



(a) semi-closed loop (b) full-closed loop

Fig.3 The position-time curve when feed was 0.004mm/s

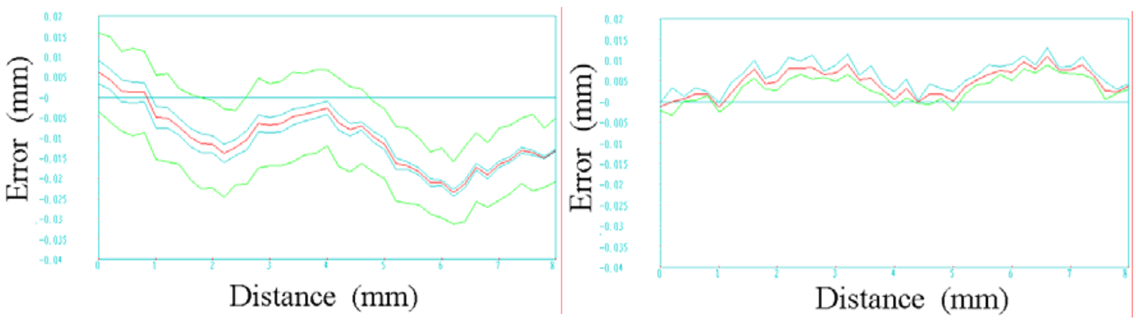
The effect of pitch on positioning accuracy was depressed in full-closed loop control as indicated in Figure 4.



(a) semi-closed loop (b) full-closed loop

Fig.4 The position error curve

The positioning accuracy was 0.047056mm and position error was 0.029825mm in semi-closed loop control, but these two parameters were separately decreased to 0.016200mm and 0.012200mm in full-closed loop control as indicated in Figure 5.



(a) semi-closed loop (b) full-closed loop

Fig.5 The positioning accuracy curve

The Error Disturbance Feed-forward Compensator Algorithm

The disturbing signals in the servo system of the ultra-precision machine have two modes: step disturbance and sine disturbance[3]. The frequency of the sine disturbance signal varies with the rotating speed of the motor. The friction moment causes tracking error, dead zone, limit loop and stick-slip movement. The low-speed negative slope characteristic of the friction model is the vital reason that causes the table creeping in low speed[4]. This corresponds to a positive feedback is added into the control system. The feedforward compensation is proved to be an useful method with which the disturbance of friction moment can be overcome[5].

In the cutting process the worktable of the ultra-precision machine moves at very low speed. The workaround of the control system is in low-frequency, but the disturbance signal is most significant in intermediate frequency and high frequency.

The dynamic model of the control system with error disturbance compensator indicated in Figure 6 includes PID controller, velocity feedforward controller, acceleration feedforward controller and error disturbance compensator which decreases the disturbance on speed signal. A trap filter is also used to cut down the interference of high frequency signal. The differential signal is added in the compensator loop, and a low-pass filter is used to eliminate the high frequency signal which is enlarged by the differential process.

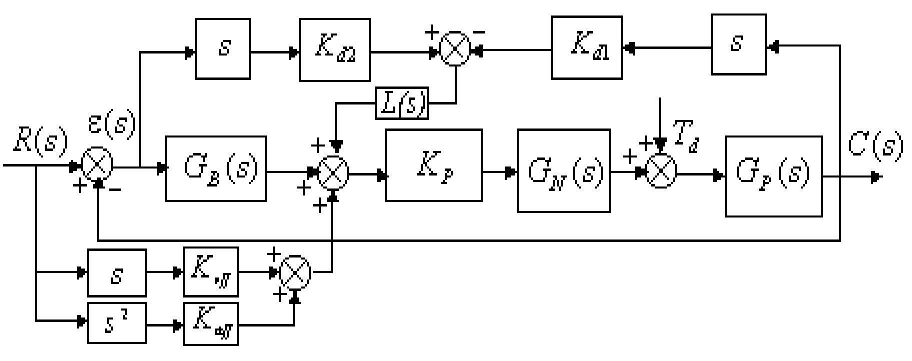


Fig.6 The dynamic model of the system with error disturbance compensator

Simulation and Experiment Result

In simulation, the speed signal used is a 0.04mm/s ramp signal. A 0.012mv disturbance signal with 6hz frequency and another 0.007mv disturbance signal with 7.1hz frequency are added into the control model. Figure 7 indicates the tracking error without disturbance compensator and feedforward controller. Figure 8 indicates the tracking error with disturbance compensator and feedforward controller which is decreased to 1/10 compared with that in Figure 7.

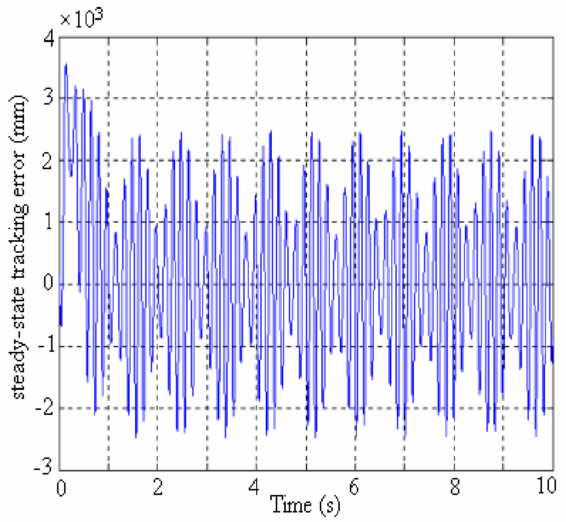


Fig.7 The steady-state tracking error without disturbance compensator

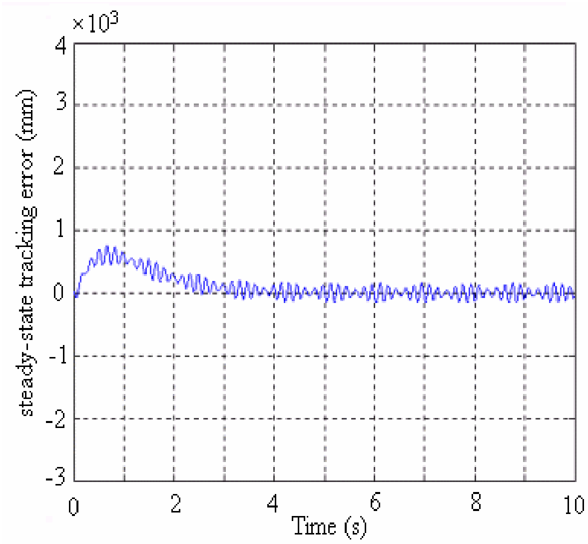


Fig.8 The steady-state tracking error with disturbance feed-forward compensator

Figure 9 shows the machining surface of KDP crystal which is measured by Atomic Force Microscope(AFM). The P-V value of the aluminum specimen machined by the ultra-precision machine tool was 0.27 wavelengths as shown in Figure 10.

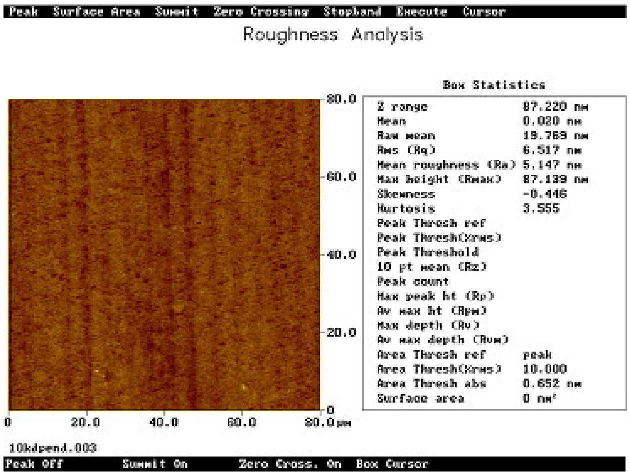


Fig.9 The surface roughness measured by scan probe microscope

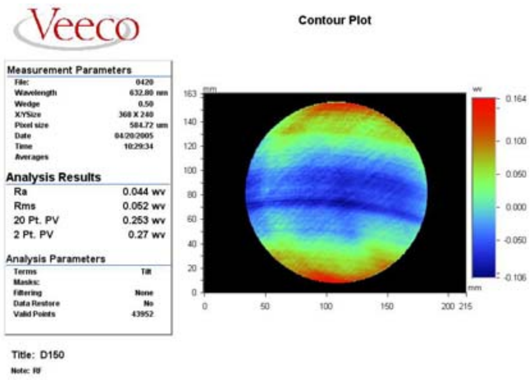


Fig.10 The surface shape accuracy measured by laser interferometer was 0.27λ p-v

Summary

An ultra-precision machine is developed to machine components made of KDP crystal with single point diamond fly cutting technique and a compensating control algorithm of error disturbance feed-forward is designed to enhances the stability of ultra-low speed motion of the semi-closed loop feed control servo system. This paper individually analyses the effect on speed stability and positioning accuracy under control of semi-closed loop and full-closed loop based on the experimental data .The simulation results indicate that the values of the steady-state tracking error decreases to 1/10 after using the compensating control algorithm. After adopting the strategy the feed was uniform and 0.27λ p-v was achieved .The machining experiment shows that the designed servo system meets the actual machining challenge.

References

[1] HoSeong Lee, Masayoshi and Tomizuka: IEEE Transactions on Mechatronics,Vol.43 (1996) No.1, pp.48255.

[2] Johan Eker and Jorgen Malonborg: IEEE Trans &Control Systems Society, Vol.19 (1999) No.4, pp.12221.

[3] Padma Sree, R. Srinivas, M.N. Chidambaram: Computers and Chemical Engineering, Vol.28 (2004) No.11, pp. 2201-2218.

[4] Keles, Omer, Ercan and Yucel: Control Engineering Practice, Vol.10 (2002) No.6, pp.645-654.

[5] F. Vassallo, Raquel, Schneebeli, J. Hans and Santos-Victor José: Visual servoing and appearance for navigation.Robotics and Autonomous Systems, Vol.31 (April 30, 2000) No.1-2, pp.87-97.