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Research on new software compensation method of static and quasi-static errors for precision motion controller*

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Abstract: To reduce mechanical vibrations induced by big errors compensation, a new software compensation method based on an improved digital differential analyzer (DDA) interpolator for static and quasi-static errors of machine tools is proposed. Based on principle of traditional DDA interpolator, a DDA interpolator is divided into command generator and command analyzer. There are three types of errors, considering the difference of positions between compensation points and interpolation segments. According to the classification, errors are distributed evenly in data processing and compensated to certain interpolation segments in machining. On-line implementation results show that the proposed approach greatly improves positioning accuracy of computer numerical control (CNC) machine tools.

Key words: Static and quasi-static errors, Positioning and machining accuracy, Digital differential analyzer (DDA) interpolator
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INTRODUCTION

Positioning accuracy is the most important factor deciding the machining quality of final product. But static and quasi-static error sources inducing positioning inaccuracy exist whenever a machine tool is built. The static and quasi-static error sources include lead screw pitch error, lead screw transmission backlash, servo system backlash, thermal deformation error, fixturing error, and so on. To obtain a high precision product, the influence of these static and quasi-static error sources on positioning accuracy should be minimized.

To address these problems, a significant amount of efforts from domestic and overseas researchers has been put in recent years. Look-up table is the most common method used in numerical control system nowadays based on right error calibration (You *et al.*, 2003). Through error mapping into look-up table in machining, static and quasi-static errors can be compensated with proper subroutines stored in controller (Zhang *et al.*, 1985). But to avoid the limitations of look-up table, such as hardware memory and time consumption, many parametric error models were proposed (Duffie and Malmberg, 1987; Sartori and Zhang, 1995; Tan *et al.*, 2000; 2003). In addition, many researchers concentrated on backlash compensation of servo system. Mathematical models (Tao and Kokotovic, 1993), neural networks (Selmic and Lewis, 2001) and rate loop control (Kwon *et al.*, 2004) methods were proposed. All above compensation methods are based on traditional command generation structures. So when big errors are compensated in a control loop in machining, harmful mechanical vibrations occur inevitably. To make ISR run more efficiently and obtain a higher machining velocity, a buffered DDA command generation method was proposed in (Chang, 2003). Combined improved DDA command generation structure with acceleration/ deceleration method (Kim and Jeon, 1994; Kim and Song, 1994; Jeon, 1994; Jeon, 2000a; 2000b) and

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data processing method in buffer (Ren *et al.*, 2006; 2007), reduction of harmful mechanical vibrations becomes possible.

In this paper a new software error compensation method is proposed. Using improved command generation generator, the static and quasi-static errors are merged into interpolation segments in data buffer by DDA analyzer and compensated evenly by DDA command generator in machining.

DDA WITH ERROR COMPENSATION

In a DDA interpolator, the adder is the basic device, and value in it changes at every DSP clock oscillation until overflows to generate pulses for axes moving. In Fig.1, a hardware structure of DDA interpolator is given. The principle of DDA is using summation of areas of many small rectangles to approximate the real area, which is the integration of a continuous curve. The integration can be expressed as follows:

$$A(t)=\int_0^t C(u)\mathrm{d}t \cong \sum_{i=1}^{k} C(u_i)\Delta t, \tag{1}$$

where, $A(t)$ is the integration of parametric curve $C(u)$ in time domain. $C(u_i)$ is a discrete point on parametric curve $C(u)$. Δt is the clock oscillation period, k is the total number of discrete points. If Δt is small enough, $A(t)$ can be approximated sufficiently. Then $A(t)$ can be expressed as follows:

$$A_k = A_{k-1} + \Delta A_k, \tag{2}$$

where

$$A_{k-1} = \sum_{i=1}^{k-1} C(u_i)\Delta t, \quad \Delta A_k = C(u_k)\Delta t.$$

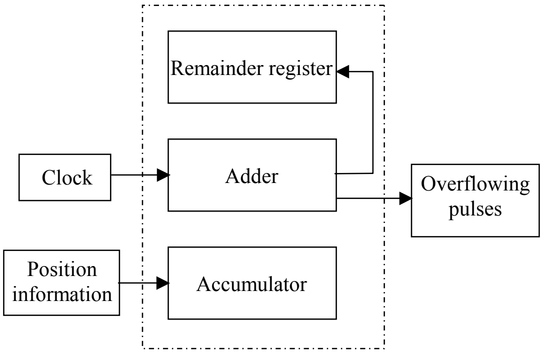

Fig.1 Hardware structure of DDA interpolator

When position information ΔA_k was sent into accumulator of DDA at every control loop, the value of A_k can be confirmed firstly. Secondly, the adder of DDA adds A_k and the value in remainder register

$$R_k = A_k + Q_{k-1}, \tag{3}$$

where, Q_{k-1} is the last value in remainder register. The value of R_k has two situations:

(1) $R_k>2^n$ (n is the bit number of the adder), the adder of DDA overflows and

$$Q_k = A_k + Q_{k-1} - overflows, \tag{4}$$

(2) $R_k \le 2^n$, R_k will be sent into the remainder register directly and

$$Q_k = R_k. \tag{5}$$

The integrator constant f_{cons} can be expressed as

$$f_{\mathrm{cons}} = \frac{1}{2^n \Delta t}. \tag{6}$$

The total overflowing pulses P_{t} can be written as

$$P_{\mathrm{t}} = \mathrm{mod}(C_k, 2^n), \tag{7}$$

and the average frequency f_{aver} of output pulses is

$$f_{\mathrm{aver}} = P_{\mathrm{t}}/\Delta t. \tag{8}$$

Based on the original DDA structure, a second adder was added (Fig.2). Another more pulse can be generated in an interpolation sample period when necessary.

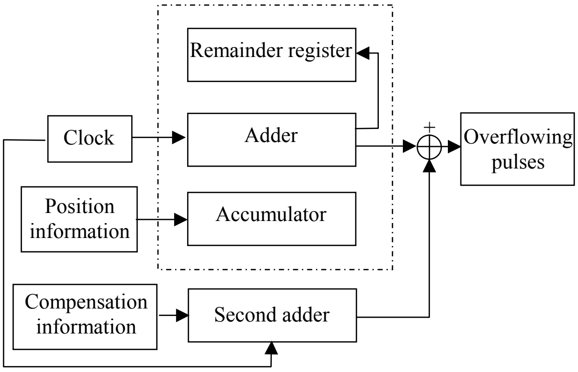

Fig.2 Hardware structure of DDA interpolator with compensator

EVEN ERROR COMPENSATION

Improved DDA command generation structure

In traditional control system, the error compensator is separate from the interpolator (Fig.3) and the linear compensation method is the main method to accomplish error compensation. The compensation is always inside the servo loop to obtain maximum speed and accuracy. So big errors will bring mechanical vibrations and machining accuracy will be degraded. To overcome this drawback, compensation should not be combined within machining but within data processing.

To improve compensation, a new DDA command generation structure is given (Fig.4). The DDA interpolator is divided into two parts (Chang, 2003): command analyzer and command generator. When interpolation data are input into buffer of control system, whatever linear segments or circle segments before the machining begins, the error compensation table will be projected to every interpolation segment accordingly. Command analyzer analyzes G-Code stored in rotary buffer and error information stored in error compensation table. The analyzing results will be saved in temporary register and used by command generator. This means that compensation and interpolation can be synchronized in machining. Based on the improved DDA command generation structure, the errors at calibration points can be distributed evenly to relevant interpolation segments. Higher machining accuracy and smaller mechanical vibrations can be guaranteed.

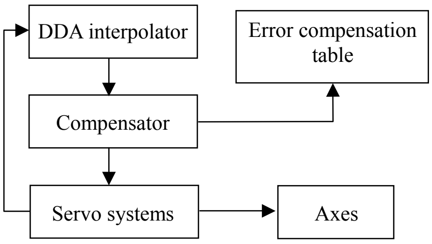

Fig.3 Traditional DDA command generation structure

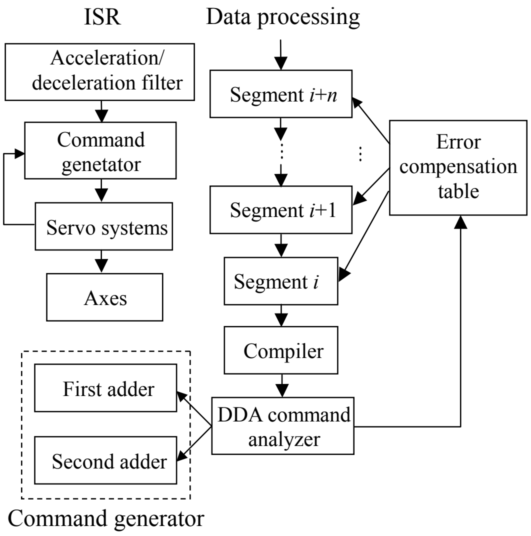

Fig.4 Improved DDA command generation structure

Relationship between compensation points and interpolation points

According to the travel length of each axis between two end-effectors and a certain interval, error compensation points are created. Before distributing errors segments, the relationship between compensation points and interpolation segments should be confirmed firstly. There are three categories as given below:

(1) Interpolation segment includes compensation points (see Fig.5a)

$$\overline{E_iE_{i+1}} \subset \overline{P_iP_{i+1}}, \tag{9}$$

where, P_i and P_{i+1} represent coordinates of interpolation points on an axis along the tool path to be machined. E_i and E_{i+1} represent coordinates of compensation points on an axis to be calibrated. The coordinates are all based on the same original point.

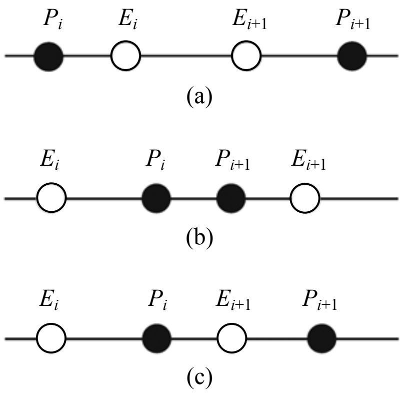

Fig.5 Three types of relationship between compensation points and interpolation segments. (a) Interpolation segment includes compensation points; (b) Compensation segment includes interpolation points; (c) Compensation segment and interpolation segment intersect

(2) Compensation segment includes interpolation points (see Fig.5b)

$$\overline{P_iP_{i+1}} \subset \overline{E_iE_{i+1}}, \tag{10}$$

(3) Compensation segment and interpolation segment intersect but are not subjected totally to each other (Fig.5c)

$$\overline{P_iP_{i+1}} \not\subset \overline{E_iE_{i+1}}, \quad \overline{E_iE_{i+1}} \not\subset \overline{P_iP_{i+1}}. \tag{11}$$

Error even distribution

According to the relationship between compensation points and interpolation points, errors can be projected to relevant interpolation segments. For the first situation (Fig.5a), the value of error projected to segment $\overline{P_iP_{i+1}}$ can be expressed as follows:

$$\begin{aligned} O_i = (e_i - e_{i-1}) \cdot \frac{|E_i - P_i|}{|E_i - E_{i-1}|} + (e_{i+1} - e_i) + \\ (e_{i+2} - e_{i+1}) \cdot \frac{|P_{i+1} - E_{i+1}|}{|E_{i+2} - E_{i+1}|}, \end{aligned} \tag{12}$$

where, e_i is the compensation value at the calibration point E_i.

For the second situation (Fig.5b):

$$O_i = |e_{i+1} - e_i| \cdot \frac{|P_{i+1} - P_i|}{|E_{i+1} - E_i|}. \tag{13}$$

And for case (3) (Fig.5c):

$$O_i = |e_{i+1} - e_i| \cdot \frac{|E_{i+1} - P_i|}{|E_{i+1} - E_i|} + |e_{i+2} - e_{i+1}| \cdot \frac{|P_{i+1} - E_{i+1}|}{|E_{i+2} - E_{i+1}|}. \tag{14}$$

In machining, O_i should be distributed evenly to its relevant interpolation segment $\overline{P_iP_{i+1}}$. The time of machining $\overline{P_iP_{i+1}}$ can be confirmed:

$$T_i = \left|\overline{P_iP_{i+1}}\right| \cdot B \cdot \Delta t, \tag{15}$$

and time for compensation of O_i

$$T_{ci} = |O_i| \cdot B \cdot \Delta t, \tag{16}$$

where, T_i is the machining time of segment $\overline{P_iP_{i+1}}$, T_{ci} is the time for compensation of O_i, B is the basic length unit. O_i can be distributed evenly and the interval of compensation is

$$T_{pi} = \Delta t \cdot T_i / T_{ci}, \tag{17}$$

where, T_{pi} is the interval of compensation when segment $\overline{P_iP_{i+1}}$ is machined.

RESULTS AND DISCUSSION

Hardware configuration

Fig.6 shows the hardware configuration for error compensation experiment. Controller is PC based and communicates with PC with 104 buses. DSP clock oscillation frequency is 40 MHz. The adder is 16-bit.

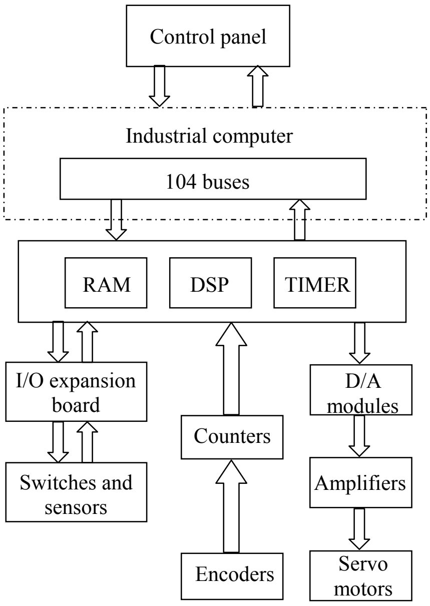

Fig.6 Hardware configuration of the controller

Error calibration

The experiment is based on a glass machining center of three axes (see Fig.7). The *X*, *Y* and *Z* axes travel together to span a 400 mm×270 mm×120 mm 3D space. The error to be calibrated is groove pitch error. The interpolation control period is 2 ms and BLU is 0.5 μm. *Y* axis is selected as an example to be calibrated and compensated. The interval of calibration is 10 mm. The errors at every calibration points were shown in Fig.8a.

Fig.7 The computer numerical control (CNC) for glass machining

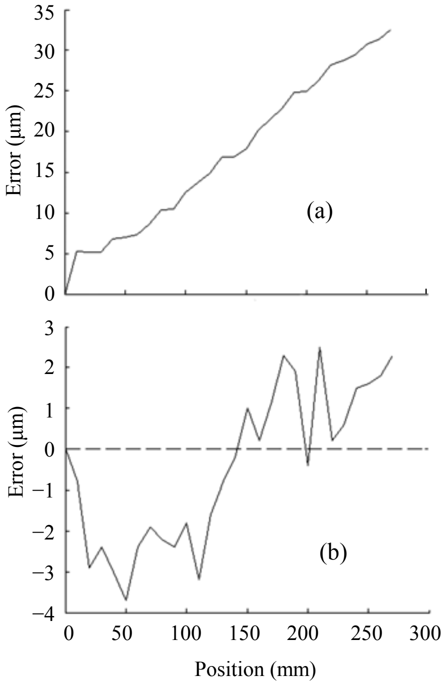

Fig.8 Groove error
(a) Before compensation; (b) After compensation

Error compensation

From calibration data, a segment from position 200 mm to position 210 mm of *Y* axis is selected at random and other segments on *Y* axis are the same. The pitch errors at positions 190 mm, 200 mm and 210 mm are 24.9 μm, 26.2 μm and 28.2 μm, respectively. The two G-Code commands such as G01 Y196.521 and G01 Y203.865 are given. When the machining begins, the error compensation table is projected to the segment (196.521, 203.865) automatically. Firstly compensation type can be confirmed according to Fig.5c and Eq.(11). The compensation value O_i for the machining segment (196.521, 203.865) is 1.22 μm according to Eq.(14). And the interval of compensation is 183.6 ms according to Eq.(17).

Based on calibration data and compensation method proposed by this paper, the compensation results for the whole *Y* travel length is shown as Fig.8b.

Result comparison

Under different control structures, a glass is machined with different compensation methods (Fig.9). Fig.10a is the grinding result under traditional control structure and Fig.10b is that under improved DDA control structure. It can be seen that the compensation method proposed in this paper makes glass edges smoother. The vibrations induced by big errors compensation have been greatly reduced.

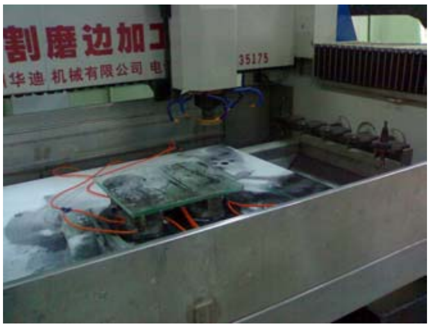

Fig.9 Grinding glasses under improved DDA control


(a) (b)

Fig.10 Grinding results of two ground glasses. (a) Under traditional control; (b) Under improved DDA control

CONCLUSION

By improving traditional DDA command generation structure, static and quasi-static errors can be compensated evenly to its relevant interpolation segments in real time:

(1) The improved DDA structure includes DDA command analyzer and command generator. The separation of traditional DDA structure makes it possible for interpolation segments and relevant compensation information to be unitized in data processing, and therefore avoids mechanical vibrations and guarantees higher positioning accuracy in machining.

(2) Compensator is eliminated from ISR. ISR efficiency will be improved.

(3) Compensation points are classified and based on the relevant interpolation segments. So compensation will not depend on calibration points but interpolation segments.

(4) The positioning accuracy is also based on the sufficient calibration points as usual. Therefore enough hardware memory is necessary.

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