International Journal of u- and e- Service, Science and Technology
Vol.9, No. 2 (2016), pp.195-206
http://dx.doi.org/10.14257/ijunesst.2016.9.2.20

A Software Method for Online Thermal Error Inspection and Compensation

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Abstract

In this paper, a new online method is proposed to measure and identify the spindle thermal error of the machining center. The method is firstly established by a comprehensive error identification model including geometric and thermal error. Then the multi-viewpoint modeling method based on stereo vision is adopted to obtain the solution of thermal deformation error without the influence of geometric error. A software is developed to online inspect and compensate the thermal error of machining center. The software is consisted by four modules, measurement module, error identification module, error compensation module and analysis module. It can not only be able to quickly identify the thermal error detection, but also can accurately predict thermal error, and effectively improve the machining accuracy. Finally, the experiment results show that the thermal error values of the machining center can be measured accurately and identified online quickly by the proposed software method.

Keywords: *Software, Online, Thermal error, Normal vector, Error compensation.*

1. Introduction

Thermal error is a kind of processing error due to the relative displacement changes between the tool tip and the work piece, which is caused by the thermal deformation of machine tool parts. There are two reasons for the thermal deformation: the friction of internal components and the influence of the external ambient temperature [1]. Studies have shown that thermal error accounted for about 40% ~ 70% of the total error of the machine [2-4]. Reasonable and effective control of thermal error is not only an important way to improve the accuracy of the machine, but also a key technology of current research in machine tools with high-speed and high-precision.

The thermal error control of machine tool is on the premise that thermal error can be detected and identified accurately and simply for the error compensation. The measurement accuracy determines the accuracy of the mathematical model of the subsequent error compensation and its final implementation effect [5-7]. Meanwhile the online measurement of the thermal error and thermal error processing online compensation has been brought to people’s attention, in order to improve the machining accuracy ,and ensure the reliability of the process, the online compensation software was been development, which control the thermal error at a reasonable range ,and improve the accuracy ,control quality ,reduction cost.

The current error measurement of machine tools research is mainly focused on offline measurement, there are many technical information and references on error detection [8-13]. Li [8] has measured thermal and geometric error in all directions by means of a ball-dimensional array. Chen [9] detected machine thermal error with machine probe and standard gauge block, in which the linear axis thermal error is obtained directly by the ruler measurement. Pahk and Lee [10] simultaneously measure five thermal error of the

ISSN: 2005-4246 IJUNESST

spindle by self-developed spindle thermal error detection device. In ISO [11] standard, the equipment composed of five non-contact sensors is used to detect the error of the spindle. Delbressine et al [12] has measured the machine tool error by the 1D ball array, which can quickly measure the values of thermal error. Zhang et al [13] have calculated the thermal error based on a model, and a laser interferometer to measure body diagonal sequent. Erkan [14-16] have used on-machine probe with non-calibration ball for detecting and identifying error of rotation axis of the machine. However, in these methods, gauge block or high accuracy equipment is needed to detect thermal error, which is complex to install and operate. Furthermore, most methods demand that the error must be measured on non-working state or under the condition that the geometric errors have been obtained before.

Recent researches on machine error detection and identification issues focused on how to detect geometric errors and identify the thermal errors and other issues. For the compensation research of the machine tool mainly focused on the thermal error prediction and compensation, and compensation method of the comprehensive error. The thermal error of machine tool is one of the major error sources. Online detection technology and real-time thermal error compensation research are insufficient. So, it is necessary to study on detecting error caused by heat. In this article, kinematic chain of machine has been analyzed. Comprehensive online detection model of the geometric and thermal error has been established based on multi-body system, which utilizes multi-viewpoint modeling method based on stereo vision to determine directly of thermal deformation error without considering geometric error. The human-computer interaction interface with the construction of functional module has been built based on Win7 platform, using MFC class library of VC. The software has developed based on object-oriented programming method and modularized program design. And it is improved accuracy of machine tool.

2. Error Identification Principle

2.1Error Analysis

A there-axis VMC650 machining center is taken as an example. There are two major error resources including the geometric error and the thermal error of the spindle are considered in this paper. Firstly, as shown in Fig.1, the geometric error model is built using the principle of multi-body system (MBS).

The workpiece coordinate system *B0* is set on the workbench, and the coordinate value in the global coordinate system is $P_0 = (X_W, Y_W, Z_W)$. Then, the other coordinate system of the other part is *B1* for Y-axis, *B0* for machine tool bed, *B3* for the spindle box and *B4* for the tool system. The origins of the four individual coordinates are all at the point *O* with coordinate value $O = (0,0,0)$. As tool *B4* is connected with the spindle box *B3*, the position of tool tip point in the coordinate system of the spindle box can be represented by $P_4=(0,0,r)$, where *r* is the tool length.

There are three linear axes X-axis, Y-axis and Z-axis. Each movement of the axis generates six basic geometric errors: three linear error $\delta_x(i)$, $\delta_y(i)$ and $\delta_z(i)$, and three rotation error $\varepsilon_x(i)$, $\varepsilon_y(i)$, $\varepsilon_z(i)$ for each axis, where *i* can be replace by *x* ,*y* and *z*. In addition, ε_{xy}, ε_{yz}, ε_{zx} is perpendicularity error between X-axis and Y-axis, Y-axis and Z-axis, Z-axis and X-axis respectively? Thus, there are totally 21 geometric errors [14].

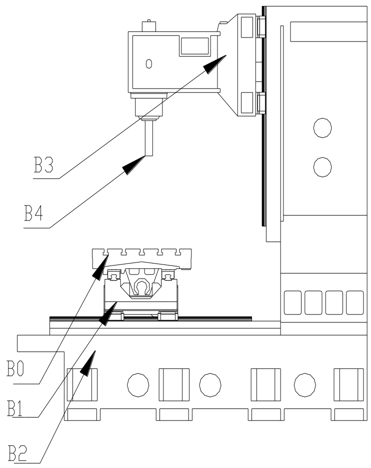

Figure 1. Three-axis Machining Center Model

According to MBS theory, transformation matrix between adjacent components can be expressed as follow.

$$ {}_{Y}^{B}T^{e}=\begin{bmatrix} 1 & -\varepsilon_z(y) & \varepsilon_y(y) & \delta_x(y) \\ \varepsilon_z(y) & 1 & -\varepsilon_x(y) & y+\delta_y(y) \\ -\varepsilon_y(y) & \varepsilon_x(y) & 1 & \delta_z(y) \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1} $$

Where ${}_{Y}^{B}T^{e}$ is the actual transform matrix of y-axis moving table relative to machine bed, superscript *B* is the original coordinates, subscript *Y* is the target coordinate and *e* is the actual transformation matrix. Similarly, considering the perpendicularity error, other coordinate transformation matrices of machine tool motion platform of *X, Y, Z* coordinates relative to the reference coordinate system ${}_{X}^{Y}T^{e}$, ${}_{Z}^{B}T^{e}$, ${}_{D}^{z}T^{e}$ are as follow

$$ {}_{X}^{Y}T^{e}=\begin{bmatrix} 1 & -\varepsilon_z(x) & \varepsilon_y(x) & x+\delta_x(x) \\ \varepsilon_z(x) & 1 & -\varepsilon_x(x) & \delta_y(x)-x\varepsilon_{xy} \\ -\varepsilon_y(x) & \varepsilon_x(x) & 1 & \delta_z(x) \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2} $$

$$ {}_{Z}^{B}T^{e}=\begin{bmatrix} 1 & -\varepsilon_z(z) & \varepsilon_y(z) & \delta_x(z)-z\varepsilon_{xz} \\ \varepsilon_z(z) & 1 & -\varepsilon_x(z) & \delta_y(z)-z\varepsilon_{yz} \\ -\varepsilon_y(z) & \varepsilon_x(z) & 1 & z+\delta_z(z) \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3} $$

$$ {}_{D}^{z}T^{e}=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & r \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4} $$

Furthermore, as well as the geometric errors, the thermal error can also influence the position error between ideal and actual position between the workpiece and tool tip. According to the recent research works, a close attention should be paid to the heat of the rotating friction of spindle bearings and conductivity of the spindle motor, which are two major heat sources for thermal deformation of the headstock. Therefore, the thermal error of the spindle is mainly considered in error analysis in this paper. Considering the actual affect of thermal error to the machine, thermal errors of spindle are attributed to linear error $\delta_x(t)$, $\delta_y(t)$, $\delta_z(t)$ and angular error $\varepsilon_x(t)$, $\varepsilon_y(t)$, $\varepsilon_z(t)$ to simply the calculation .

The transformation matrix of thermal error for the spindle box B_3 is determined as follow:

$$ {}^{z}T(t) = \begin{bmatrix} 1 & -\varepsilon_z(t) & \varepsilon_y(t) & \delta_x(t) \\ \varepsilon_z(t) & 1 & \varepsilon_x(t) & \delta_y(t) \\ -\varepsilon_y(t) & \varepsilon_x(t) & 1 & \delta_z(t) \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5} $$

2.2. Error Identification

Multi-viewpoint modeling method is a use of visual information to determine the position and orientation changes in vision systems [15]. The multi-viewpoint modeling method is introduced to identify spindle thermal error in this paper.

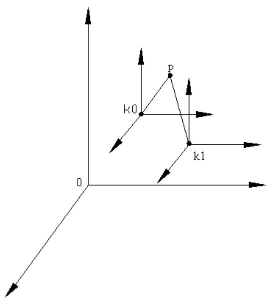

Figure 2. P-point in Different Coordinate System

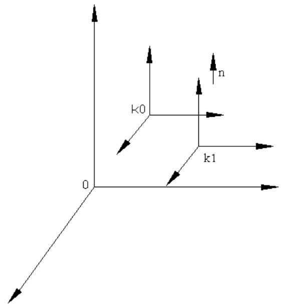

Figure 3. Vector of n in k_0、k_1

As shown in Fig.2, point P has different values in different coordinate systems. There are two coordinate systems k_0, k_1, and T_p is the transformation matrix between k_0 and k_1, which satisfies the following equation

$$ A' = T_p A \tag{6} $$

Where $A' = [x', y', z', 1]^T$ and $A = [x, y, z, 1]^T$ are coordinate values of point P in k_1 and k_0 respectively. T_p is the transformation matrix with a unique solution as follow

$$ T_p = \begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix} \tag{7} $$

As shown in Fig.3, assume a space vector $\vec{n}$ in the reference coordinate system, with vector $\vec{n}_1$、$\vec{n}_2$ representing the vector of $\vec{n}$ in the k_0, k_1 coordinate. $h = \vec{n}_1 / \|\vec{n}_1\|$, $H = \vec{n}_2 / \|\vec{n}_2\|$, and there is a rotational transformation matrix R of the vector between k_0 and k_1. When not considering displacement, we can get the following equation.

$$ H = Rh \tag{8} $$

By Rodrigues formula in rotation theory, there is a rotation vector $u = (u_x, u_y, u_z)$, which composes the relation matrix U .

$$ H - h = U(H + h) \tag{9} $$

Where, *h* and *H* are the vectors before and after the Coordinate changes respectively and *U* is a reverse skew symmetric matrix with matrix determinant values 0 as follow

$$U = Screw(u) = \begin{bmatrix} 0 & -u_z & u_y \\ u_z & 0 & -u_x \\ -u_y & u_x & 0 \end{bmatrix} \quad (10)$$

Which can be determined by the value of u. *R* and *U* have the following relationship

$$R = [I + U][I - U]^{-1} \quad (11)$$

As *U* is a singular matrix, $u = (u_x, u_y, u_z)$ cannot be solved by the formula (9) directly. But it can be solved by increasing variables. Assume that there is another space vector $\vec{m}$ in the coordinate system mentioned above, in which vector $\vec{m}_1$、$\vec{m}_2$ represent the vector of $\vec{m}$ in the k_0, k_1 coordinate respectively and $h_1 = \vec{m}_1 / \|\vec{m}_1\|$, $H_1 = \vec{m}_2 / \|\vec{m}_2\|$. Two space vector mentioned above are used to constitute augmented matrix as follow

$$\begin{bmatrix} H - h \\ H_1 - h_1 \end{bmatrix} = \begin{bmatrix} U(H + h) \\ U(H_1 + h_1) \end{bmatrix} \quad (12)$$

As shown in Fig.3, $u = (u_x, u_y, u_z)$ can be directly solved by formula (12).Then, formula (11) is substituted into formula(7) to solve *R* directly.

2.3Error Measurement Online

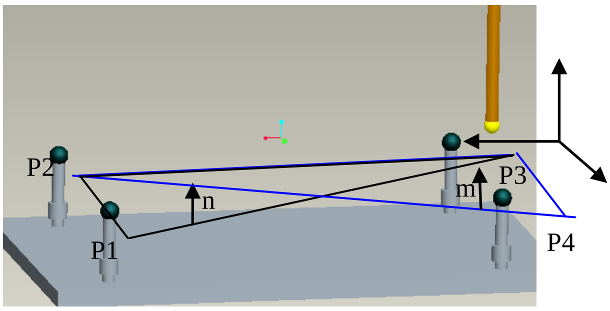

Figure 4. Online Measurement Schematics

As shown in Fig.4, there are 4 non-standard measuring balls distributed in the machine table, P1, P2, P3, P4 with the sphericity accuracy of 0.5μm-0.69μm. At time t_0, center coordinates of four balls can be obtained by machine probe in B0 coordinate system. A plane constituted by P1, P2, and P3 is used for seeking the normal vector $\vec{n}$ of the plane, and another plane constituted by P1, P2, and P4 is used for seeking the normal vector $\vec{m}$ of the plane. At time t after machine running, center coordinates of four balls become P1′, P2′, P3′, P4′, and the normal vector $\vec{n}$, $\vec{m}$ become $\vec{n}'$, $\vec{m}'$.

From Fig.1, we can get matrix transformation formula between the workpiece coordinate system B_0 and the principal axis system B_4 as follow

$$T = {}^{z}_{d}T\, {}^{y}_{z}T\, {}^{x}_{y}T\, {}^{w}_{x}T \quad (13)$$

And then, vector $\vec{n}$, $\vec{m}$, $\vec{n}'$, $\vec{m}'$ in the workpice coordinate system through the matrix transformation can be expressed in the spindle coordinates B_4 as

$$\begin{cases} \vec{n}^1 = {}^z_dT\,{}^y_zT\,{}^x_yT\,{}^w_xT\vec{n} \\ \vec{n}^2 = {}^z_dT\,{}^y_zT\,{}^x_yT\,{}^w_xT\vec{n}' \\ \vec{m}^1 = {}^z_dT\,{}^y_zT\,{}^x_yT\,{}^w_xT\vec{m} \\ \vec{m}^2 = {}^z_dT\,{}^y_zT\,{}^x_yT\,{}^w_xT\vec{m}' \end{cases} \tag{14}$$

Where $\vec{n}^1,\vec{m}^1$ is the vector in coordinates B_4 before thermal deformation, $\vec{n}^2,\vec{m}^2$ is the vector in coordinates B_4 after thermal deformation, ${}^z_dT\,{}^y_zT\,{}^x_yT\,{}^w_xT$ is the transformation matrix from B_0 to B_4, which can be simplified during solving process. According to the solution method of space vector, the spindle coordinates system B_4 before the thermal deformation is defined as k_0 and the spindle coordinates system B_4 after the thermal deformation is defined as k_t .We can get vectors $\vec{n}^1,\vec{m}^1$ in k_0 coordinate system, $\vec{n}^2,\vec{m}^2$ in k_t coordinate system. According to aforementioned theoretical equation, unit vectors of vector $\vec{n}^2,\vec{m}^2$ in B_4 coordinates can be expressed as

$$\begin{cases} M = \vec{m}^2 / \left|\vec{m}^2\right| \\ N = \vec{n}^2 / \left|\vec{n}^2\right| \end{cases} \tag{15}$$

The unit vectors are substituted into the formula (12), and we can get the $u=(u_x,u_y,u_z)$ and *U*. Then, formula (11) is substituted into formula (7) for solving R directly. The rotating coordinate transformation matrix *R* between the coordinates k0 and k1 can be solved in formula (6).*R* is substituted into formula (2) and formula (1) to obtain displacement variable T .

Finally, $T(t)$ is obtained by the transformation matrix before and after thermal deformation of spindle occurred. Transformation matrix of thermal error for reference coordinate should be

$$T_0(t) = {}^w_xT\,{}^x_yT\,{}^y_zTT(t) \tag{16}$$

$$T_0(t) = \begin{bmatrix} R_0 & T_0 \\ 0 & 1 \end{bmatrix} \tag{17}$$

Where $T_0 = \begin{bmatrix} \delta_{ox}(t) & \delta_{oy}(t) & \delta_{oz}(t) & 1 \end{bmatrix}^T$ is the compensation value for thermal error. The second order and higher infinitesimal parameter in equation (16) are ignored according to the characteristics value of thermal error.

$$\begin{aligned} \delta_{ox}(t) &= \delta_x(t) \\ \delta_{oy}(t) &= \delta_y(t) \\ \delta_{oz}(t) &= \delta_z(t) \end{aligned} \tag{18}$$

3. Analysis of Error Compensation Method

(1)Thermal error compensation method of external mechanical origin offset

The modern Open CNC system provides users with a method through origin of coordinates translation method to compensate the error of machine tool. The error compensation value was computed by compensation system, and sent to the control system. And the origin of reference coordinate system was controlled by the I/O port date, and the error compensation value was added to the control signal of servo loop. Finally error of machine tool was compensation. In this method the original processing program and interface display all kinds of coordinates does not be changed. The error compensation is completed by moving the origin of the coordinate.

(2)Feedback Interrupts Error Compensation Mode Analysis

In this method error compensation is completion by the phase signal inserting into the feedback loop of the servo system, which does not change the original coordinate and processing procedures. In order to achieve compensation purpose, the actual mechanical position was offset by operating an encoder or grating feedback pulse or sine wave. The method has low requirements for hardware, but need special electronic device inserted the phase signals in the servo loop. It is easy to generate interference to insert the signal into the feedback signal of machine tool. And it affect the accuracy of the compensation. When there is feedback sinusoidal voltage mode, the operation of feedback signal is difficult and prone to error signal and phase aberration. When the machine run fast, or sine wave pulse cycle shorter, operation in a quarter cycle feedback signal is harder.

(3)The Software Compensation Method based on Numerical Control Code Revision

Software error compensation method is to achieve the purpose of error compensation by modifying the NC program, which is an effective increase precision CNC machining cost-effective way. This method has two technical approaches, an error compensation model is integrated into CAM software post-processing module, the geometric error model predicted tool position superimposed on the reverse bias cutter location file, use post-processing module output NC program to achieve error compensation, but the interface differences between different CAM post-processing software module is large, the development of high difficulty. Another is through the identification of NC code generation NC machining trajectory, and then using geometric error model to forecast trajectory point position and pose error of a tool, by decoupling model calculation error compensation value, finally accomplished the software error compensation by means of modify the NC machining program. This method need not change CNC system hardware structure, to meet the needs of various types of machine tool error compensation, to reduce the difficulty of the application of error compensation.

4. Error Real-time Compensation Software Research

4.1Error Compensation System Hardware Structure

In this paper, the development of thermal error compensation software is based on the hardware platform structures, which includes three parts: the temperature real time acquisition unit, the machine data acquisition unit, the external drive machine tool control unit, as shown in Fig.5.

Temperature acquisition system is a key point of machining center of real-time temperature detection, which gets the data with the computer through RS232 serial port into the database. The combination of PCMCIA Ethernet card gets operation parameters when the machining center of machine tool is in processing. The compensation value of thermal error is obtained with the calculation model of software. Finally, the process of thermal error compensation is achieved by translating machine tools coordinate of reference point through external CNC control unit.

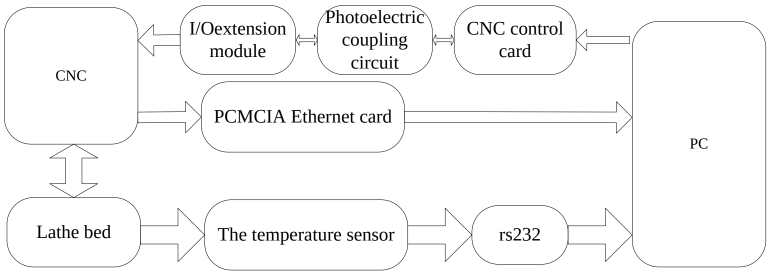

Figure 5. Structure Diagram Hard Hardware

4.2 Error Compensation System Software Platform

The error compensation software platform is developed based on Windows software platform with hardware. The main interface is shown in Fig 6.

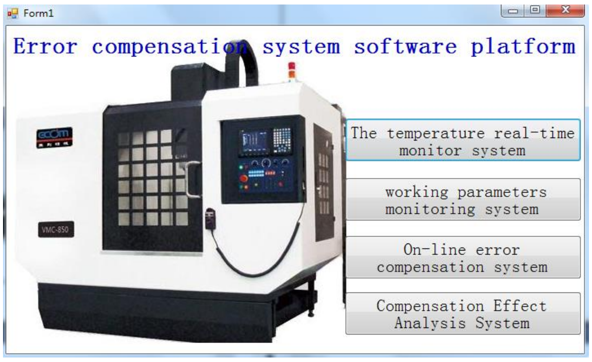

Figure 6. Main Interface of Software Platform

The software includes four modules: the temperature real-time monitor system, working parameter monitoring system, on-line dynamic compensation system, compensation effect analysis system. Click on the corresponding module to get into the human interface module.

(1) The temperature real-time monitor system

Temperature real-time monitoring module can monitor the temperature change at each measuring point in machine tool and record the time of temperature measurement for the basis data of modeling. The temperature monitoring interface can be shown in Fig.7.

The temperature real-time monitor system

A piont	B point	C point	D piont	E piont
22	20	21.5	23.7	20.1
F piont	G piont	H piont	I piont	G piont
24.8	26.1	23.6	27.2	25.4

Figure 7. The Temperature Real-time Monitor System

(2) Working parameters of CNC machining center monitoring system

The spindle speed and feed rate of machine tool can be monitored and recorded by working parameters monitoring module system, and the system parameters can be adjusted according to the operating condition of which working parameter monitoring interface can be shown in Fig.8.

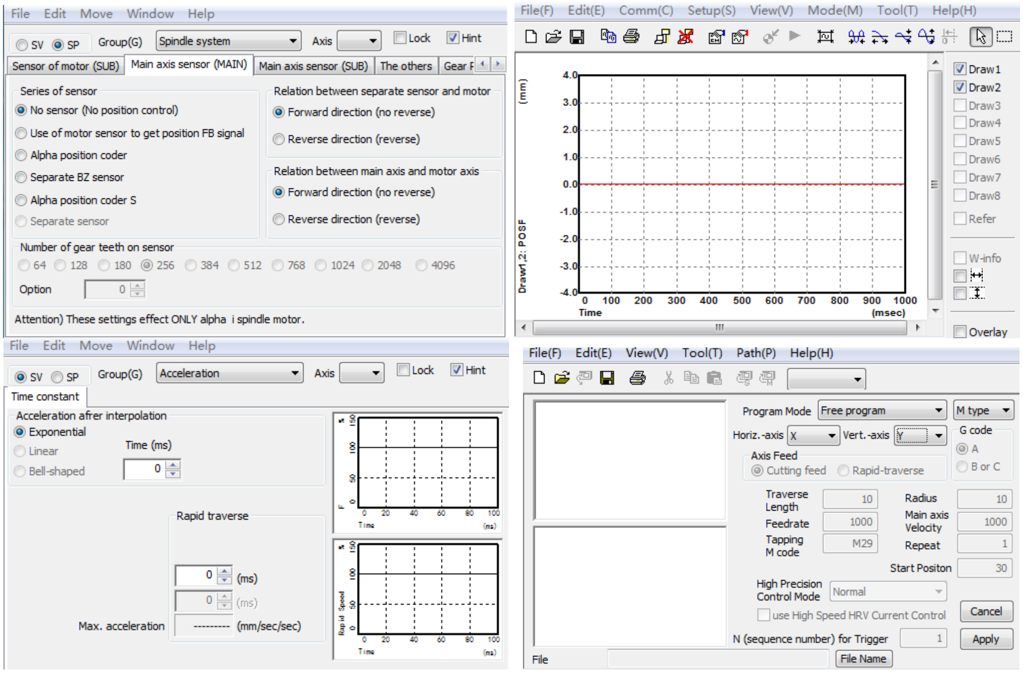

Figure 8.CNC Machining Center Working Parameters Monitoring System

(3) On-line error compensation system

In processing, the distribution changes of machine tool temperature are caused by the heat source, which causes thermal deformation. The module is a mathematical model of thermal error based on motion parameters and temperature change of key point, which predicts the value of the thermal error. Error online compensation system is to compensate the thermal error of each axis through error modeling techniques. In the compensation process of thermal error, machine coordinate data are obtained by the PCMCIA card and compensation for thermal error is completed with an external control module for offsetting the machine reference point coordinates. The interface is shown in Fig.9.

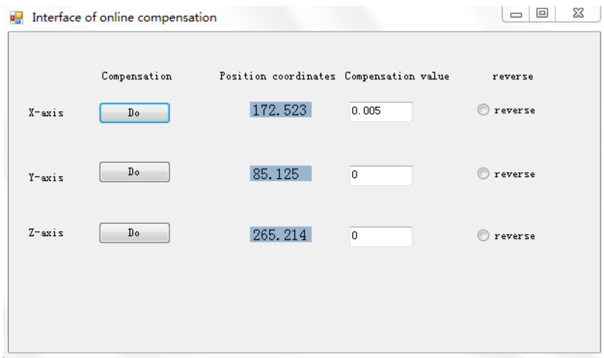

Figure 9. Interface of Online Compensation

(4) Compensation Effect Analysis System

Compensation effect analysis system interface can be shown in Fig.10. Select the date before and after compensation and click ok button. Then, the data will be displayed in the waveform diagram. In addition, the machine software can also process the corresponding calculation formula with national standards before and after compensation for positioning accuracy. It can show the compensation effect.

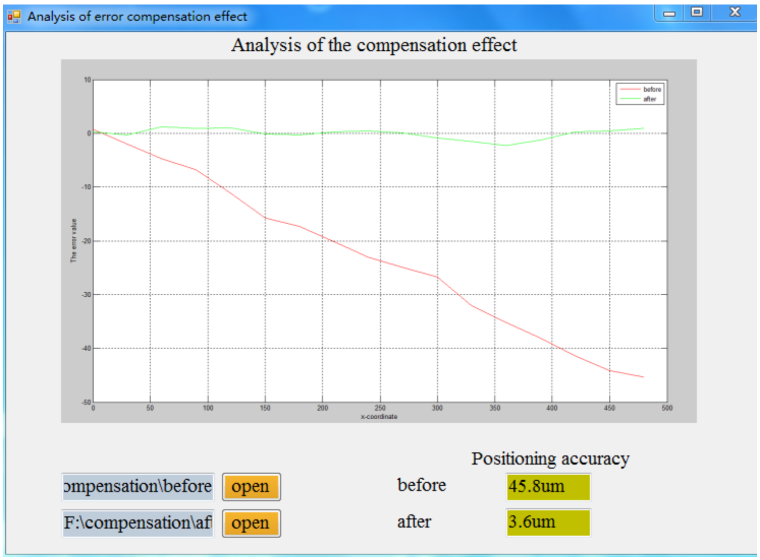

Figure 10. Compensation Effect Analysis System

5. Conclusion

Online measurement method of thermal error uses on-machine probe to measure coordinates of the balls which layout on the workbench. And, the normal vector of plane consisted of coordinates of the three ball center is used for reflecting the changes of the thermal error. Mathematical model of thermal error is established with the normal vector corresponding to the changes of thermal error. In solving process, the space visual model is built based on the normal vector without considering the geometric error, and the rotation matrix of the thermal error can be solved. Finally, the thermal error can be obtained. This method can quickly and easily solve the thermal error which does not affect the processing of the machine. It provides a very important way of the real-time compensation for thermal error.

In order to achieve real-time compensation value for thermal error, this paper has developed a software interface for thermal error compensation combining with hardware. Key point temperature of machine tool is detected by real-time temperature detection system. Operation parameters of machine tool are obtained by hardware PCMCIA Ethernet card. The thermal error is calculated by the mathematical model and the coordinates of reference points are adjusted by the external CNC control system. To reduce the influence of thermal error on the accuracy of machining center, compensation can be compensated in the processing effectively and accurately.

Acknowledgement

The author would like to acknowledge the support of the special subject of the national Nature Science Foundation of China. (No.51405085 and No.51175086).

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