A Novel Non-contact Method for Circular Path Test of NC Machine Tool

Zhenya He[1], **Jianzhong Fu**[1,#], **Xinhua Yao**[1], and **Zichen Chen**[1]

1 State Key Laboratory of Fluid Power Transmission and Control, Zhejiang University, Hangzhou, Zhejiang, China, 310027
Corresponding Author / E-mail: fjz@zju.edu.cn. TEL: +86-571-87952418, FAX: +86-571-87952418

KEYWORDS : NC Machine Tool, Non-contact Measurement, Circular Path, Error Modeling, Deviation

The movement of circular path is one of the most common machining methods. In recent years, with the rapid development of modern manufacturing technology, it requires more and more precise circular path. Thus, this paper presents a non-contact two-dimensional measurement method for the circular path of NC machine tool. First, the theory of the measurement method was introduced and the error modeling of the circular path for the NC machine tool was established. Then through further analyzing the influence of the geometric errors to circular path deviations, the error resources were identified, such as the displacement errors, backlashes and squareness errors. Finally measurement and compensation experiment of circular path based on the non-contact laser measurement method was conducted. The experimental results show that the presented method can be set up easily and rapidly, even can be used to measure smaller radius circular path under a high feed rate condition. After compensation, the accuracy of the circular path of the machine tool is improved by 57%. Therefore, the method can be used to rapidly evaluate the accuracy of machine tool and lay the reliable foundation of the error compensation for NC machine tool.

Manuscript received: January XX, 2011 / Accepted: January XX, 2011

NOMENCLATURE

x_i = measurement data in the x-direction
y_i = measurement data in the y-direction
i = number of points
N = number of the points in one period
R = radius of nominal path
X_o = center coordinate of the circle in x direction
Y_o = center coordinate of the circle in y direction
$\Delta\theta$ = incremental angle
θ_i = polar angle in the i point
R_i = polar radius, actual value of radius in the i point
dR_i = circular deviation
F = feed rate of the machine tool
$O_0X_0Y_0Z_0$ = coordinate frames on the machine body
$O_1X_1Y_1Z_1$ = coordinate frames on the x-slide
$O_2X_2Y_2Z_2$ = coordinate frames on the y-slide
$O_3X_3Y_3Z_3$ = coordinate frames on the z-slide
T_0^1 = transformation matrix between coordinate frames on the machine body and x-slide
T_1^2 = transformation matrix between coordinate frames on the x-slide and y-slide
T_0^3 = transformation matrix between coordinate frames on the machine body and z-slide
$\vec{E}$ = geometric error vector
$\vec{E}_{x-y}$ = error vector of the x-y plane
$\vec{P}_{t\,ideal}$ = position coordinate of the tool under ideal condition
$\vec{P}_{w\,ideal}$ = position coordinate of the workpiece under ideal condition
δ_{xx}, δ_{yy}, δ_{zz} = linear displacement errors
δ_{yx}, δ_{zy}, δ_{xz} = vertical straightness errors
δ_{zx}, δ_{xy}, δ_{yz} = horizontal straightness errors
ε_{xx}, ε_{yy}, ε_{zz} = roll angular errors
ε_{yx}, ε_{zy}, ε_{xz} = pitch angular errors
ε_{zx}, ε_{xy}, ε_{yz} = yaw angular errors
s_{xy}, s_{yz}, s_{xz} = squareness errors
$\vec{X}$, $\vec{Y}$, $\vec{Z}$, $\vec{T}$, $\vec{W}$ = position vector of x-axis, y-axis, z-axis, tool, and workpiece, respectively

1. Introduction

With increasing requirements on the accuracy of machined parts, various approaches have been proposed to increase the circular accuracy of NC machine tool.[1,2] ISO 230-4[3] specified the standard of the circular test for NC machine tools. Circular test technology can largely be divided into contact methods and non-contact methods.[4]

Ball bar is widely used to measure circular test of the machine tool. In 1982, Bryan[5] presented the testing method of the Telescoping

Ball Bar (TBB) to measure the errors of circular movements. And in 1994, Ziegert et al.[6] presented using the Laser Ball Bar (LBB) to measure the circular deviation. However, they are contact measurement methods, which are limited by the standard precision balls. That is, the contact measurement method could not be used to measure a radius smaller than the standard ball of the ball bars, also can not be used under the high feed rate condition. At present, Charles Wang[7,8] presented a non-contact measurement method and developed a measurement instrument, namely laser Doppler displacement measurement (LDDM). Jywe et al.[4] developed three nano-contouring measurement techniques for a nano-stage by employing laser interferometers, corner cubes and some developed fixture.

Many scholars have made researches on the error mapping modeling of machine tool. Schultschik[9] presented the components of the volumetric accuracy and established the geometrical model of the machine tool. Zhanga et al.[10] proposed a displacement method of machine calibration and defined the 21 volumetric errors for three-axis machine tool. Jywe et al.[11] developed a dynamic circular measurement analysis system. And in 2003, M.Tsutsumi et al.[12,13] presented an algorithm for identifying particular deviations for 5-axis machining centers. In 2009, Uchiyama et al.[14] proposed a contouring controller for three-dimensional machining based on coordinate transformation.

In this paper, a non-contact two-dimensional measurement method using the LDDM was presented to measure the circular path of NC machine tool. The remainder of the paper is organized as follows: Section 2 introduces the theory of the non-contact measurement method. Section 3 establishes the mapping modeling of the volumetric errors. Section 4 presents an experimental validation by testing and compensating the circular errors of a Vertical NC Machining Center. Finally, the paper ends with a brief conclusion as presented in Section 5.

2. Theory of the Non-contact Method

The non-contact laser measurement technique for circular path test of NC machine tool is shown in Fig. 1. Use the two single-aperture LDDM as the optical sources and two flat mirrors as targets. Take testing the circular path of x-y plane as example, one laser beam pointing in the x-direction and the other pointing in the y-direction,

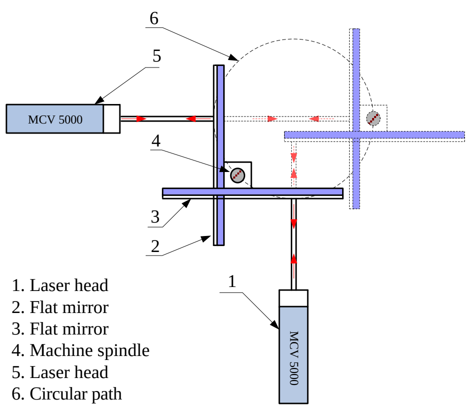

Fig. 1 Schematic of the non-contact method testing the circular path

both of them are mounted in the working table of the machine tool. And two flat mirrors were installed on the spindle. Make sure that the flat mirrors are perpendicular to the x-direction laser beam and y-direction laser beam, respectively. Therefore, it can respectively measure the displacement of the x-direction and y-direction. As shown in Fig. 2, the measured displacement is a sin curve or cosine curve.

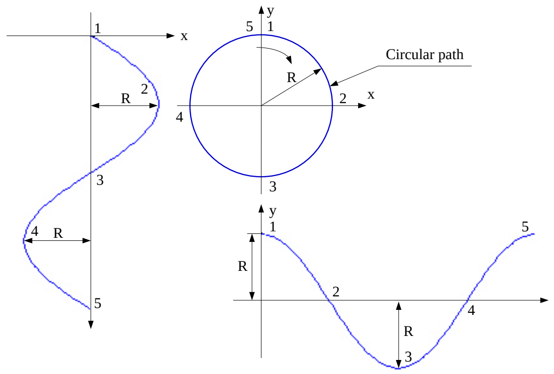

Fig. 2 Schematic of mapping relationship among the spindle circular path, x-axis displacement and y-axis displacement

2.1 Circular Deviation

Assuming that the measurement data in the x-direction and y-direction are x_i and y_i, respectively, where i (=0,1,2…) is the number of points. Under ideal condition, the deviation of the radial direction dR_i can be expressed as follow.

$$dR_i = \sqrt{(x_i - X_o)^2 + (y_i - Y_o)^2} - R \tag{1}$$

where, X_o, Y_o and R are constants. (X_o , Y_o) is the center coordinate of the circle, R is the radius of the nominal path. The incremental angle $\Delta\theta$ can be expressed as

$$\Delta\theta = \frac{360^0}{N} \tag{2}$$

where, N is the number of the points in one period. The angle θ_i of the circular path can be express as

$$\theta_i = i \cdot \Delta\theta = \frac{360^0 \cdot i}{N} \tag{3}$$

Therefore, we can gain the polar diagram of the circular deviations.

2.2 Straightness Errors

The circular accuracy of NC machine tool is affected by many factors, such as linear displacement errors, vertical straightness errors, angular errors and squareness errors. Assuming the x-axis is not perpendicular to y-axis (When the angle between the x-axis and y-axis is greater than 90 degrees, the squareness errors $s_{xy} > 0$). Fig. 3 shows the schematic of squareness errors, the actual value of radius R_i can be expressed as

$$\begin{aligned} R_i &= \sqrt{(R\cos\theta_i - R\sin\theta_i \sin s_{xy})^2 + (R\sin\theta_i \cos s_{xy})^2} \\ &= R\sqrt{1 - \sin s_{xy} \sin 2\theta_i} \end{aligned} \tag{4}$$

$$dR_i = R_i - R \tag{5}$$

when $\theta_i = 45^0$ or $\theta_i = 135^0$, the minimum value or maximum value of R_i can be obtained. Therefore, squareness errors can be evaluated by

$$s_{xy} = \arcsin[1 - (1 - \frac{dR}{R})^2] \tag{6}$$

The schematic of the radial deviations of circular path is shown in Fig.4. The actual path is similar to an ellipse, the angle between x-axis and the semimajor axis of the ellipse is 45 or 135 degrees. Obviously, squareness errors will considerably affect the radial deviations of spindle circular path.

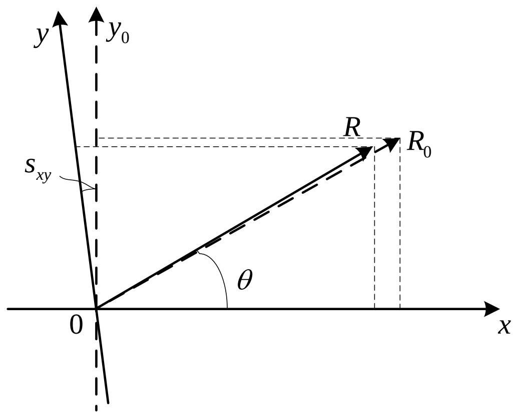

Fig. 3 Analysis of influence of squareness errors

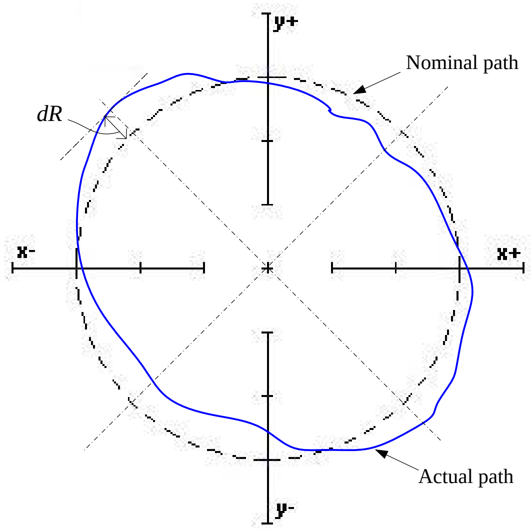

Fig. 4 Schematic of radial deviations of the spindle circular path

3. Error Modeling of Circular Path

Take three axis vertical XYFZ type machine as an example, its structure schematic diagram is shown as Fig. 5. The coordinate frames $O_0X_0Y_0Z_0$, $O_1X_1Y_1Z_1$, $O_2X_2Y_2Z_2$ and $O_3X_3Y_3Z_3$ are defined on the machine body, x-slide, y-slide and the spindle. Through analyzing the geometric characteristic of typical adjacent bodies, the homogeneous transformation matrixes of geometric errors are given as follows:[15]

$$T_0^1=\begin{bmatrix}1 & -\varepsilon_{zx} & \varepsilon_{yx} & \delta_{xx}\\ \varepsilon_{zx} & 1 & -\varepsilon_{xx} & \delta_{yx}\\ -\varepsilon_{yx} & \varepsilon_{xx} & 1 & \delta_{zx}\\ 0 & 0 & 0 & 1\end{bmatrix} \tag{7}$$

$$T_1^2=\begin{bmatrix}1 & -\varepsilon_{zy} & \varepsilon_{yy} & \delta_{xy}-S_{xy}y\\ \varepsilon_{zy} & 1 & -\varepsilon_{xy} & \delta_{yy}\\ -\varepsilon_{yy} & \varepsilon_{xy} & 1 & \delta_{zy}\\ 0 & 0 & 0 & 1\end{bmatrix} \tag{8}$$

$$T_0^3=\begin{bmatrix}1 & -\varepsilon_{zz} & \varepsilon_{yz} & \delta_{xz}-S_{xy}z\\ \varepsilon_{zz} & 1 & -\varepsilon_{xz} & \delta_{yz}-S_{yz}z\\ -\varepsilon_{yz} & \varepsilon_{xz} & 1 & \delta_{zz}\\ 0 & 0 & 0 & 1\end{bmatrix} \tag{9}$$

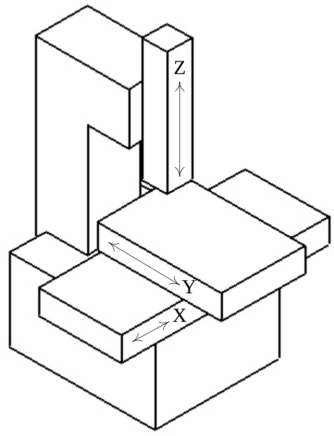

Fig. 5 Structure schematic of three axis vertical XYFZ type machine

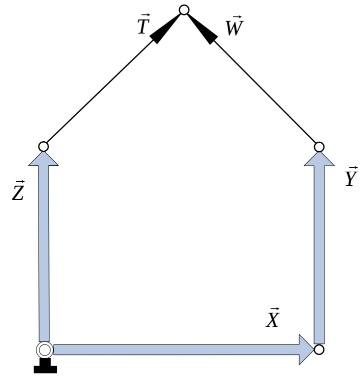

Fig. 6 Constraint condition of the machine structure

Under ideal conditions, the constraint condition of the machine structure is that the position coordinate of the tool is equal to that of workpiece in an inertial reference frame. Fig. 6 shows the schematic of constraint condition of the machine structure.

$$\vec{P}_{t\,ideal}=\vec{P}_{w\,ideal} \tag{10}$$

$$\vec{Z}+\vec{T}=\vec{X}+\vec{Y}+\vec{W} \tag{11}$$

However, actually we should take into account that there are some geometric errors transformed by moving between the typical adjacent bodies. The geometric errors can be expressed

$$\vec{E}=\vec{P}_{t\,\mathrm{actual}}-\vec{P}_{w\,\mathrm{actual}}=(\vec{Z}+\vec{T})-(\vec{X}+\vec{Y}+\vec{W}) \tag{12}$$

$$\vec{E}=\vec{P}_{t\,\mathrm{actual}}-\vec{P}_{w\,\mathrm{actual}}=\begin{bmatrix}1 & -\varepsilon_{zz} & \varepsilon_{yz} & \delta_{xz}-S_{xz}z\\ \varepsilon_{zz} & 1 & -\varepsilon_{xz} & \delta_{yz}-S_{yz}z\\ -\varepsilon_{yz} & \varepsilon_{xz} & 1 & \delta_{zz}\\ 0 & 0 & 0 & 1\end{bmatrix}\begin{bmatrix}x\\ y\\ z\\ 1\end{bmatrix} - \begin{bmatrix}1 & -\varepsilon_{zy} & \varepsilon_{yy} & \delta_{xy}-S_{xy}y\\ \varepsilon_{zy} & 1 & -\varepsilon_{xy} & \delta_{yy}\\ -\varepsilon_{yy} & \varepsilon_{xy} & 1 & \delta_{zy}\\ 0 & 0 & 0 & 1\end{bmatrix}\begin{bmatrix}1 & -\varepsilon_{zx} & \varepsilon_{yx} & \delta_{xx}\\ \varepsilon_{zx} & 1 & -\varepsilon_{xx} & \delta_{yx}\\ -\varepsilon_{yx} & \varepsilon_{xx} & 1 & \delta_{zx}\\ 0 & 0 & 0 & 1\end{bmatrix}\begin{bmatrix}x\\ y\\ z\\ 1\end{bmatrix} \tag{13}$$

When measuring the circular path based on the x-y plane, the z-axis is not moving, namely just 2D motion. Therefore the error mapping is as follows:

$$\vec{E}_{x-y}=\begin{bmatrix}Ex\\ Ey\end{bmatrix}=\begin{bmatrix}x\\ y\end{bmatrix}-\begin{bmatrix}x+\delta_{xx}+\delta_{xy}-S_{xy}y\\ y+\delta_{yx}+\delta_{yy}+\varepsilon_{zx}x\end{bmatrix}=\begin{bmatrix}-\delta_{xx}-\delta_{xy}+S_{xy}y\\ -\delta_{yx}-\delta_{yy}-\varepsilon_{zx}x\end{bmatrix} \tag{14}$$

4. Experiments and Discussions

In order to experimentally prove, the measurement and compensation experiments of circular path for the x-y plane of a XYFZ Type Vertical NC Machining Center were conducted. The

Table 1 Testing report of circular path for NC machine tool before compensation (R=15mm, F=2000mm/min, N=708, Clockwise)

Circular deviation	Optimum radius	Squareness error	X-axis backlash	Y-axis backlash	Min of circular deviation	Max of Circular deviation	Random vibration
13.8μm	14.9870mm	0.3μm/30mm	5.0μm	3.4μm	-4.9μm	9.6μm	3.4μm

Table 2 Testing report of circular path for NC machine tool after compensation (R=15mm, F=2000mm/min, N=708, Clockwise)

Circular deviation	Optimum radius	Squareness error	X-axis backlash	Y-axis backlash	Min of circular deviation	Max of Circular deviation	Random vibration
4.0μm	14.9968mm	-0.1μm/30mm	1.5μm	0.6μm	-2.1μm	1.9μm	1.9μm

testing region was $[0, 30]\times[0, 30]$mm on the x-y plane with $z=0$ mm, radius $R=15$ mm, the feed rate F = 2000mm/min, the number of one period $N=708$. The circular path was carried out by a clockwise motion.

Adopting the non-contact measurement method, the LDDM was used to measure the x-direction and y-direction, simultaneously. Fig. 7 shows the experiment of the circular path measurement.

Then according to the analyzing the measurement data, based on the above error modeling, the predictive value of displacement errors E_x, E_y, and squareness errors s_{xy}, and backlashes were calculated. The radial deviations of the circular path are shown in Fig. 8. The x-axis and y-axis displacement and displacement errors are shown in the Fig. 9-10. The testing report of circular path for NC machine tool before compensation is shown in Table 1.

Thirdly, the new compensation table was obtained based on the above results and activated in the NC control system.

Eventually, after compensation, the circular path was measured again, and the measurement data were analyzed based on the error modeling. The results are shown in Fig.11-13 and Table 2.

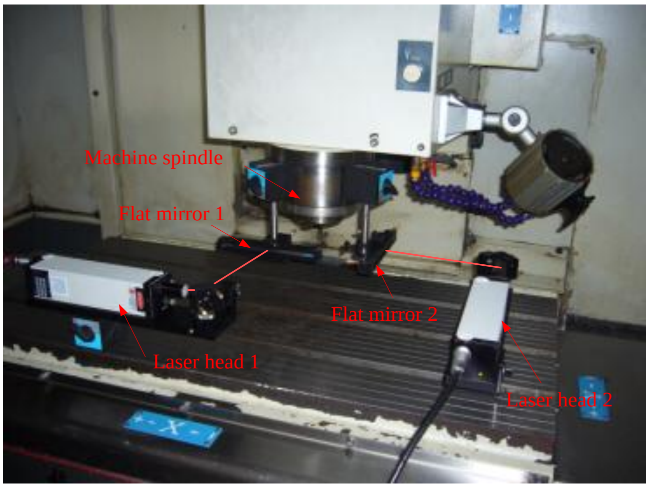

Fig. 7 The experiment of the circular path measurement

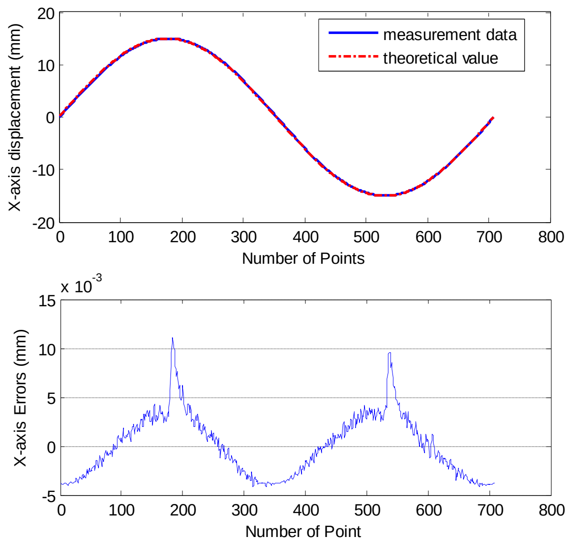

Fig. 9 The x-axis displacement and x-axis displacement errors

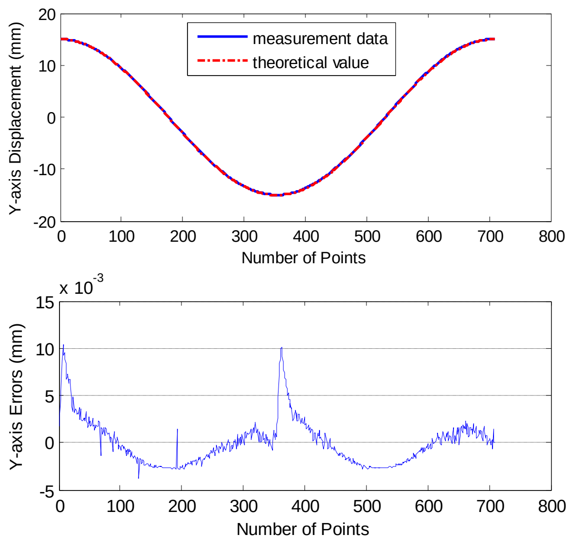

Fig. 10 The y-axis displacement and y-axis displacement errors

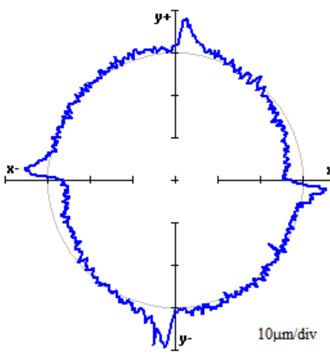

Fig. 8 The measurement radial deviations of the circular path before compensation

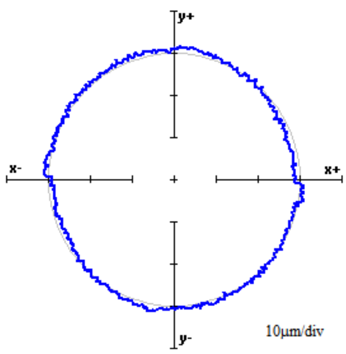

Fig. 11 The measurement radial deviations of the circular path after compensation

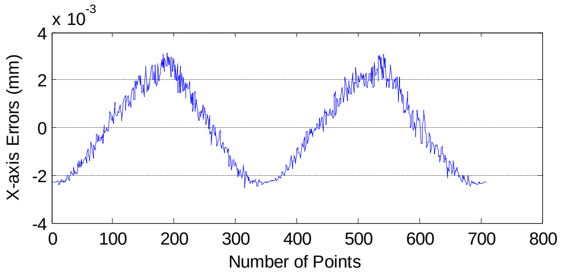

Fig. 12 The x-axis displacement errors after compensation

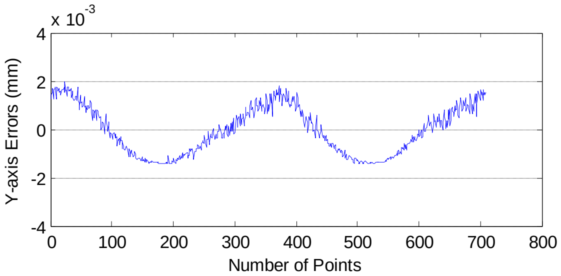

Fig. 13 The y-axis displacement errors after compensation

According to Fig. 8, there was peak value of the radial deviation while the x-axis or y-axis was traveling backward. The primary cause is the influence of the x-axis or y-axis backlash. Comparison of the results of measurement with and without compensation, it is clear that the backlash of x-axis was decreased from 5.0μm to 1.5μm after compensation, and the backlash of y-axis was decreased from 3.4μm to 0.6μm. According to Fig.9-10, Fig.12-13, the x-axis displacement errors were decreased from 12.1μm to 2.5μm, and y-axis displacement errors were decreased from 10.3μm to 1.9μm. Comparison of Table 1 and Table 2, the circular deviation was decreased from 13.8μm to 4.0μm, and squareness error was decreased from 0.3μm/30mm to -0.1μm/30μm. In conclusion, the accuracy of the circular path was improved more than 57%.

5. Conclusions

A non-contact two-dimensional measurement method was presented for measuring the circular path of NC machine tool. The experimental work was conducted to verify the measurement method and error modeling effectively. The experimental results show that the presented method can be set up easily in 20 min and test can be carried out in 4 min with the high feed rate of 2000mm/min for small radius of 15mm. After compensation, the accuracy of circular path of the machine tool is effectively improved by 57%. Therefore, the method can be used to evaluate the accuracy of machine tool rapidly and lay the foundation for error compensation of NC machine tool reliably and availably.

ACKNOWLEDGEMENT

This work is supported by Educational Commission of Zhejiang Province of China (No.Y200909224) and the Science and Technology Project of Zhejiang Province (No. 2009R50008).

REFERENCES

1. Xue-ChengXi, Aun-NeowPoo and Geok-SoonHong, "Improving contouring accuracy by tuning gains for a bi-axial CNC machine," International Journal of Machine Tools & Manufacture, Vol. 49, pp. 395–406, 2009.
2. Weidong Zhun, ZhigangWang and KazuoYamazaki, "Machine tool component error extraction and error compensation by incorporating statistical analysis," International Journal of Machine Tools & Manufacture, Vol. 50, pp. 798–806, 2010.
3. ISO 230-4: Test code for machine tools—Part 4: Circular test for numerically controlled machine tools. 1996.
4. Wen-Yuh Jywe and Yun-Feng Teng, "New nano-contouring measurement techniques for a nano-stage," International Journal of Machine Tools & Manufacture, Vol. 46, pp. 869–876, 2006.
5. J.B. Bryan, "A simple method for testing measuring machines and machine tools," Precision Engineering, Vol. 4, No. 2, pp. 61–69, 1982.
6. J.C. Ziegert and C.D. Mize, "The laser ball bar: a new instrument for machine tool metrology," Precision Engineering, Vol. 16, No. 4, pp. 259–267, 1994.
7. Charles Wang and Bob Griffin, "A noncontact laser technique for circular contouring accuracy measurement," Rev. Sci. Instrum., Vol. 72, No. 2, pp. 1594-1596, 2001.
8. C. Wang, "Vector measurement for coordinate measuring machine," U.S. Patent 6,519,043, 2003.
9. R. Schultschik, "The components of the volumetric accuracy," Annals of the CIRP, Vol. 25, No. 1, pp. 223-227, 1977.
10. G. Zhanga, R. Ouyanga, B., Lua, R., Hockenb, R., Vealeb and A. Donmezb, "A Displacement Method for Machine Geometry Calibration," CIRP Annals, Vol. 37, No. 1, pp. 515-518, 1988.
11. W.Y. Jywe and C.H. Liu, "Application of ball bar system and genetic algorithm for CNC lathe accuracy testing," International Journal of Advance Manufacturing and Technology, Vol. 17, pp. 189-195, 2001.
12. M. Tsutsumi and A. Saito, "Identification and compensation of systematic deviations particular to 5-axis machining centers," International Journal of Machine Tools and Manufacture, Vol. 43, No. 8, pp. 771-780, 2003.
13. Masaomi Tsutsumi,, and Akinori Saitob, "Identification of angular and positional deviations inherent to 5-axis machining centers with a tilting-rotary table by simultaneous four-axis control movements, " International Journal of Machine Tools and Manufacture, Vol. 44, No. 12-13, pp.1333-1342, 2004.
14. Uchiyama N, Nakamura T and Yanagiuchi H, "The effectiveness of contouring control and a design for three-dimensional machining," International Journal of Machine Tools and Manufacture, Vol. 49, pp. 876–84, 2009.
15. Z.Y. He, J.Z. Fu, and X.H. Yao, "Volumetric error modeling and analysis for CNC machine tool based on multi-body system," Key Engineering Materials, Vols. 426-427, pp. 441-446, 2010.