Volumetric Error Identification for CNC Machine Tool Based on Multi-body System and Vector Diagonal Measurement

Zhenya He, Jianzhong Fu*, Xinhua Yao
Zhejiang Province Key Laboratory of Advanced Manufacturing Technology,
Zhejiang University, Hangzhou, 310027, China
hezhenya@163.com, fjz@zju.edu.cn, yaoxinhuazju@gmail.com

Abstract

To reduce the influence of the geometric error on machining precision of CNC machine, a new method based on multi-body system theory and the laser sequential step diagonal vector measurement method to distinguish the geometric errors of CNC machine tool was presented. Firstly geometric errors modelling of CNC machine tool based on multi-body system theory was established. Then laser sequential step diagonal vector measurement method was introduced. Finally comparison experiments of the directly traditional method and the laser vector diagonal measurement method were done, besides, error compensation experiment of CNC machine tool was done. The results show that the new method combined multi-body system theory and laser sequential step diagonal vector measurement method is feasible to distinguish the geometric errors and after compensation machine accuracy is improved by 63%.

Keywords

CNC machine tool, Multi-body system, Vector diagonal measurement, Geometric error.

1 Introduction

With the rapid development of modern manufacturing technology, more and more people concerned about the CNC precision machining and ultra-precision machining technology. To improve the machining accuracy of CNC machine tools, there are two basic methods: Error Prevention and Error Compensation.

In recent years, the error modelling method based on the multi-body system theory was developed [1]. The error modelling using the unique lower array to describe complex systems is more concise and convenient, and stylized, standardized, universal, very suitable for computer to model machine tool [2].

So far, Laser measurement technology has been applied widely in the measurement, calibration and compensation for machine tools. At present, Optodyne Inc. has presented a new measurement method, namely laser sequential step diagonal vector measurement method [3-4], which is suggested by the standards ASME B5.54 [5] and ISO 230-6 [6].

This paper verity the effect of the new method combined the geometric error modelling based on Multi-body system and laser sequential step diagonal vector measurement.

2 Modelling of volumetric errors

2.1 Volumetric positioning errors of 3-axis machine

For a 3-axis machine, there are 21 errors [7], namely 3 linear positioning errors, 6 straightness errors, 9 angular errors and 3 squareness errors. These 21 errors can be expressed as the following [8-9].

Linear displacement errors: δ_{xx} , δ_{yy} and δ_{zz}

Vertical straightness errors: δ_{yx} , δ_{zy} and δ_{xz}

Horizontal straightness errors: δ_{zx} , δ_{xy} and δ_{yz}

Roll angular errors: ε_{xx} , ε_{yy} and ε_{zz}

Pitch angular errors: ε_{yx} , ε_{zy} and ε_{xz}

Yaw angular errors: ε_{zx} , ε_{xy} and ε_{yz}

Squareness errors: s_{xy} , s_{yz} and s_{xz}

Where, δ is the linear error, its first subscript is the error direction and the second is position coordinate. ε is the angular error, its first subscript is the axis of rotation and the second is position coordinate.

2.2 Modelling of volumetric errors based on multi-body system

Multi-body system is a complex mechanical system, which connects by several multi-rigid bodies or flexible connections. The Lower Body Array based on the Multi-body system was presented by Houston in late 70s, which describes the topological structure of multi-body system simply and conveniently. Furthermore, it is suitable for computer description to model volumetric errors.

The matrix of Lower Body Array is gained through marking and calculating multi-body system, *n*-order Lower Body of typical adjacent body B_j is B_i , which is expressed as:

$$L^n(j) = i \tag{1}$$

Where, L is the Operator of Lower Body Supplementary definition:

$$L^0(j) = j \tag{2}$$

$$L^n(0) = 0 \tag{3}$$

Take three axis vertical XYFZ type machine as an example, its volumetric mathematical model is analyzed (Fig.3-4), Table 1 is its Lower Body Array.

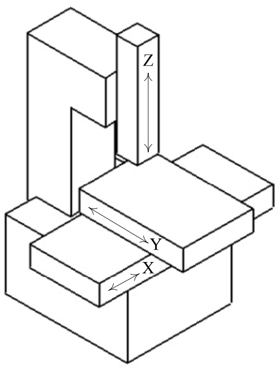
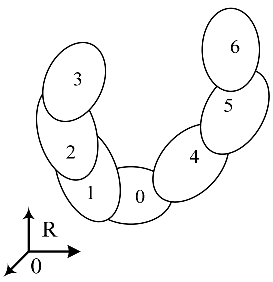


Fig.3: *Structure schematic diagram of three axis vertical XYFZ type machine*



0 bed   1 longitudinal slide   2 horizontal slide
3 workpiece   4 spindle box   5 spindle   6 tool

Fig. 4: *Topological structure of three axes vertical XYFZ type machine*

Table 1: Lower Body Array of XYFZ type machine

j	1	2	3	4	5	6
$L^0(j)$	1	2	3	4	5	6
$L^1(j)$	0	1	2	0	4	5
$L^2(j)$	0	0	1	0	0	4
$L^3(j)$	0	0	0	0	0	0

According to geometric characteristic of typical adjacent bodies B_j and B_i , the error transformation matrixes of geometric errors are given as follows:

$$^{0}T_1 = \begin{bmatrix} 1 & -\varepsilon_{zx} & \varepsilon_{yx} & \delta_{xx} \\ \varepsilon_{zx} & 1 & -\varepsilon_{xx} & \delta_{yx} \\ -\varepsilon_{yx} & \varepsilon_{xx} & 1 & \delta_{zx} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

$$^{1}T_2 = \begin{bmatrix} 1 & -\varepsilon_{zy} & \varepsilon_{yy} & \delta_{xy} - S_{xy}y \\ \varepsilon_{zy} & 1 & -\varepsilon_{xy} & \delta_{yy} \\ -\varepsilon_{yy} & \varepsilon_{xy} & 1 & \delta_{zy} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

$$^{2}T_3 = \begin{bmatrix} 1 & -\varepsilon_{zz} & \varepsilon_{yz} & \delta_{xz} - S_{xy}z \\ \varepsilon_{zz} & 1 & -\varepsilon_{xz} & \delta_{yz} - S_{yz}z \\ -\varepsilon_{yz} & \varepsilon_{xz} & 1 & \delta_{zz} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$

2.3 Vector step diagonal measurement method

The advantage of laser vector measurement method is that the measuring direction or the direction of the laser beam is not necessarily parallel with the positioning errors. Therefore it could reduce the number of building experimental platform, improve efficiency and lessen cost.

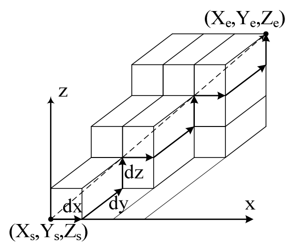


Fig. 5: *Principle of vector step diagonal measurement*

The principle of vector step diagonal measurement is shown in Fig. 5. Each axis is moved separately and the positioning error is collected after each single movement of the X-axis, of the Y-axis and then of the Z-axis.

3 Experiments

The tests were to verify the effect of the volumetric errors modelling based on multi-body system theory when being used for disposing and analyzing data of the laser vector sequential step diagonal measurement method.

Fig.6: *Laser vector step diagonal measurement*

The directly traditional measurement was done to give a reference of the displacement errors of the machine in order to demonstrate the conclusions of the measurement results. All measurements were done bi-directionally with at least three times, namely forward and backward. The work volume of machine is 600mm×360mm×480mm. The whole experimental process can be divided into four steps as follow:

In the first step, the linear positioning errors of the X-, Y- and Z-axis were respectively measured in the directly traditional method by a laser Doppler displacement measurement (LDDM). The measurement results can be found in Fig. 7-9.

In the second step, measurement in the laser vector sequential step diagonal method by LDDM was performed to measure four body diagonals. After being disposed and analyzed data, it can be gained the axis linear positioning errors, vertical straightness errors and horizontal straightness errors. These errors for each axis were shown in Fig. 10-12, the four diagonal displacement errors were shown in Fig. 13 and Table 3 was shown the squareness errors without compensation.

Then new compensation tables were generated based on the above results and activated in the CNC control system.

Eventually, after compensation another measurement by the laser vector sequential step diagonal method was done in order to check the effect of the compensation. Fig. 14-16 and Table 4 were shown these results.

4 Experimental results and discussions

4.1 Linear positioning errors of the axes measured by directly traditional method

Linear positioning errors of the machine were stated as follow. The X-axis had a bigger negative error of a magnitude of 23.1 μm. The positioning errors range of Y-axis was from 2.6 μm to -16.1 μm in the whole stroke. And the positioning errors range of Z-axis was 5.2 μm to -14.6 μm.

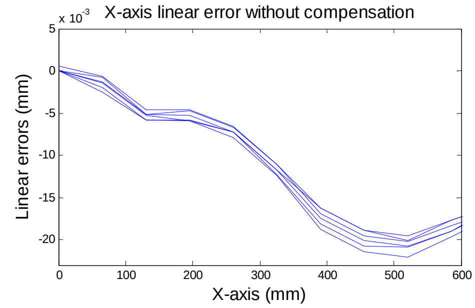


Fig. 7: *X-axis linear positioning errors*

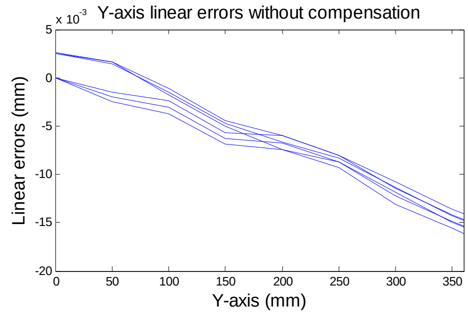


Fig. 8: *Y-axis linear positioning errors*

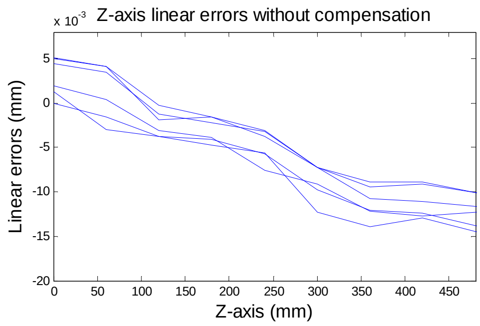


Fig. 9: *Z-axis linear positioning errors*

4.2 Result of measurement by the laser vector step diagonal method without compensation.

Based on the disposed results of the laser vector sequential step diagonal measurement, it can be evaluated with the following results (Fig. 11-14). The X-axis had a

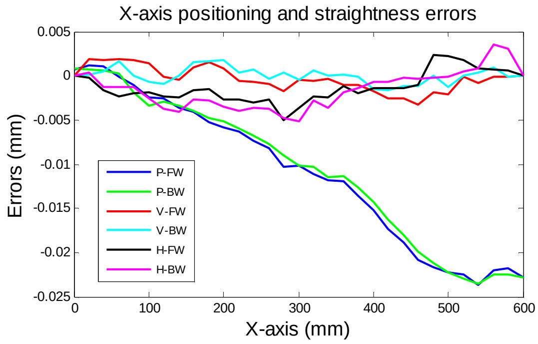


Fig. 10: *X-axis errors without compensation*

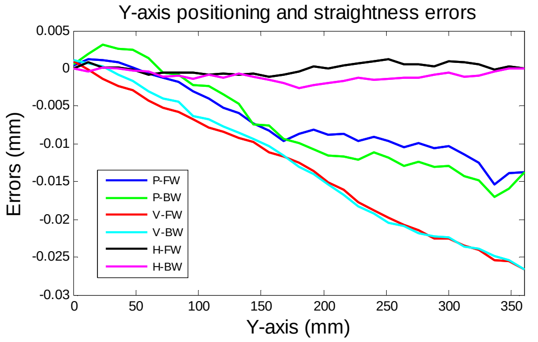


Fig. 11: *Y-axis errors without compensation*

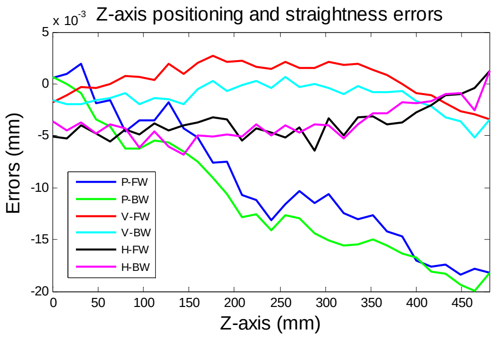


Fig. 12: *Z-axis errors without compensation*

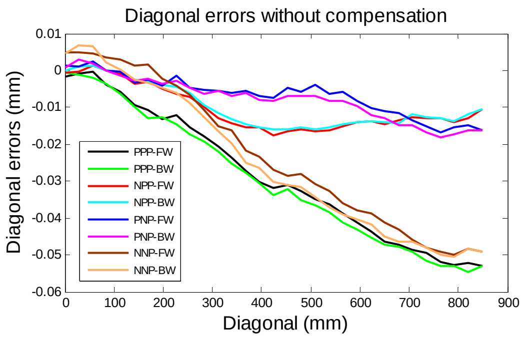


Fig. 13: *Diagonal error without compensation*

Table 2: Squareness errors without compensation

XY(μrad)	YZ(μrad)	ZX(μrad)
-65	-45	51

relatively small vertical straightness errors and horizontal straightness errors of a range from -5.1 μm to 3.3 μm. However the positioning error is the most significant error, which reaches 23.4 μm. The Y-axis positioning error and vertical straightness error is respective 19.8 μm and 27.1 μm, and horizontal straightness is relatively small. In the Z-axis, the maximal positioning error is 19.8 μm, the vertical straightness errors and horizontal straightness error are below 8 μm. Table 2 is shown the squareness errors of the machine without compensation. The range of the diagonal displacement errors is 62.9 μm.

4.3 Comparison of results obtained from the directly traditional measurement and the laser vector step diagonal method without compensation.

According to Table 3, it is clear that the results of linear positioning errors by the laser vector sequential step diagonal method are close to these by the directly traditional measurement in magnitude and sign. Just the most significant deviation is 4.8 μm in the Z-axis, however the range of the Z-axis by two method is 19.8 μm and 22.1 μm, so it is little difference between them. It can be verified that the volumetric errors modelling based on multi-body system theory being used for disposing and analyzing data of the laser sequential step diagonal vector measurement is effective.

Table 3: Comparison of results without compensation

Positioning errors	X(μm)	Y(μm)	Z(μm)
Traditional method	-23.1~0.6	-16.1~2.6	-14.6~5.2
Vector method	-23.4~0.8	-17.0~2.8	-19.8~2.3

4.4 Result of measurement by the laser vector step diagonal method with compensation.

The activated compensation table works as expected, another laser vector measurement performed. The results are shown as following (Fig. 14-17). In the X-axis, the linear positioning errors and both straightness errors are mostly below 8 μm. The Y-axis geometric errors are even smaller, below 6 μm. Z-axis linear positioning errors and horizontal straightness errors are within the range of 8 μm, and the vertical straightness errors are smaller. The squareness errors of the machine without compensation are given in Table 4. The range of the diagonal displacement errors is 22.0 μm.

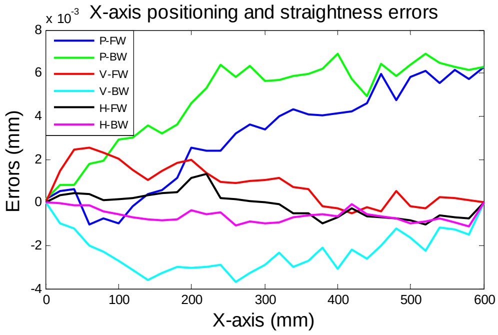


Fig. 14: *X-axis errors with compensation*

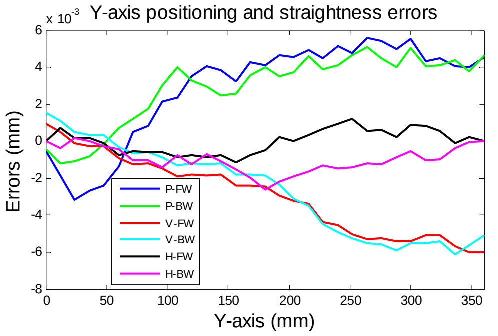


Fig. 15: *Y-axis errors with compensation*

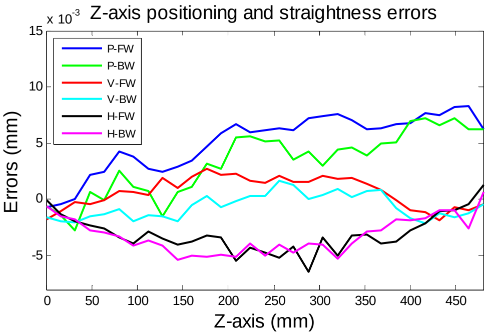


Fig. 16: *Z-axis errors with compensation*

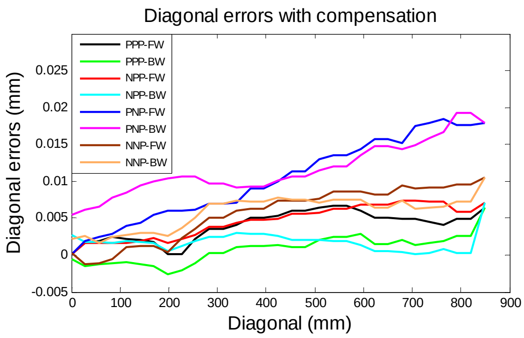


Fig. 17: *Diagonal errors with compensation*

Table 4 Squareness errors with compensation.

XY(μrad)	YZ(μrad)	ZX(μrad)
-11	5	-7

4.5 Comparison of results obtained from the laser vector sequential step diagonal method with and without compensation.

According to the Section 4.2 and 4.4, it is clear that 9 geometric displacement errors are decreased by 63%, 3 squaremess errors are reduced from 65 μrad to 11 μrad. And the volumetric diagonal errors reduced from 55.1 μm to 18.8 μm, it is improved more than 65%. After compensation, machine accuracy is improved significantly.

5 Conclusion

In this paper, volumetric geometric errors modelling of CNC machine tool based on multi-body system theory was established. The result of the experiment shows that error modelling is effective to dispose and analyze data of the laser sequential step diagonal vector measurement, and separate the geometric errors. Besides it can provide compensation table and improve the machine accuracy by 63%.

Acknowledgment

This work is supported by National Natural Science Foundation of China (50675199).

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