韓國精密工學會 '95年度 秋季學術大會論文集 pp.260~265

The enhancement of 3-dimensional positioning accuracy by measuring error factors for CNC machine tools (공작기계의 오차요소 측정을 통한 3차원 위치정밀도 향상)

J.W. SHON[+], S.H. SUH[+], S.Y. JUNG[+], E.S. LEE[++], H.G. WI[++]
(손진욱[+], 서석환[+], 정세용[+], 이응석[++], 위현곤[++])

[+]Computer Automated Manufacturing Lab.
Department of Industrial Engineering, POSTECH
([+]포항공대, 산업공학과)
[++]Automation Division, RIST
([++]산업기술연구소, 자동화부문)

Abstract

Efforts have been devoted to developing rapid and accurate methods for measuring the errors of machine tools. The method of measurement and calibration of machine tool errors should be general and efficient. The objective of this study is to show in detail the full sequence from the measurement of error factors to the verification of the positioning accuracy after compensation for the volumetric error. In this paper, we described the steps in measuring the volumetric error parameters, a general error model composed of error parameters, temperature, and the desired position. The validity of the error calibration methods proposed in this paper was tested using a vertical 3-axis CNC machine with a laser interferometer and a ball bar.

Keywords : Volumetric error, Error model, Compensation of positioning error, Laser interferometer

1. Introduction

It is obvious that the accuracy of machined parts depends on the accuracy of the machine tool. Machine tool accuracy depends on a number of error sources including the geometric error of the body structure, backlash, the distortion due to temperature changes, humidity, servo-control error, and eccentricity of the spindle rotation. In addition, many numerically controlled machine tools do not work within the prescribed accuracy and fall short of the manufacture's claimed accuracy. The reason for this is machine tool accuracy widely varies depending on setup, environment, and operating history. The operating history includes static loads, machining loads and heat productivity in preceding machining. Therefore, CNC machine tools which are required for high precision machining should be regularly calibrated for their volumetric error, 3-dimensional positioning error.

The geometric error of a machined part is not only due to the volumetric error of the machine tool but also to in-process errors and environmental errors. Environmental errors, which can be mainly represented by the thermal distortion and expansion due to temperature changes and heat flux, don't affect the accuracy of a machined part independently. This means that environmental errors always emerge in combination with the volumetric errors and in-process errors in real machining. In other words, the environmental errors largely affect the geometric error of the machine tool structure, the forming of chips and tool deflection. So, temperature change is a very important factor in modelling and compensating for volumetric error. Finally, volumetric error includes all error parameters that result from the geometric deformation of the structure body, for example the distortion and expansion of temperature changes and servo-control mismatch.

For the last several decades, a number of works have focused on the development of geometric error models in multi-axis machine tools. Ferreita and Liu used a quadratic form in connection with rigid-body kinematics.[3-5] However, there does not exist a generalized volumetric error model describing the effects of each error component for each axis on the volumetric accuracy at the final cutting point. This is due to difficulties in describing the interaction between multiple error components. Cho studied the method of volumetric error analysis of a multi-axis machine tool in machining a sculptured surface workpiece with given error data on each component.[2] Fan reported on the relationship between the geometric error of a machine tool and the temperature changes, and suggested a method of measurement and compensation for thermal error.[6] Shin suggested seven tests for the characterization of CNC machining centers.[1]

The objective of this study is to show in detail the full sequence from the measurement of error components to the verification of the positioning accuracy after compensation for volumetric error. Also, we will suggest a generalized kinematic model describing the volumetric error in multi-axis machine tools. In this paper, the kinematic model is composed of 21 error components. To show the effects of thermal distortion and operation history on the error components, we described the measuring of error components several times.

2. Definition of error components and attention in measurement

2.1. Definition of error components

There are 21 component errors to be measured for the complete accuracy analysis of a three-axis machine, consisting of six error components along each axis and three squareness errors. This measurement can be performed using a laser interferometer except on roll angular errors. Roll angular errors moving along the x, y axis can be measured using an electronic level.

The six error components along each axis consist of 3 translational errors and 3 rotational errors. The translational errors for each axis are the sum of one displacement error and two straightness errors. Displacement error is the error between two points, a target and a starting position in the axis of travel. To determine repeatability, measurements must be repeated in two directions until a statistically significant amount of data is obtained. The difference between the measurements in two opposite directions is due to the backlash. The straightness error is the translational error along the other two axes while the tool or table is moving along a designated axis. The rotational errors for each axis are composed of pitch, yaw, and roll. Figure 1 shows the coordinate transformation owing to the translational errors and rotational errors.

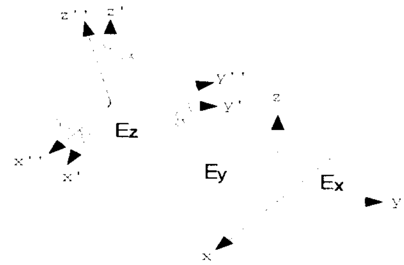

Figure 1, Error components due to linear movement.

Squareness error is defined as the difference with a right angle for two given orthogonal axes. The squareness errors in a 3-axis machine can be represented by 4 parameters shown in figure 2 provided that one axis, the z axis is a reference axis.

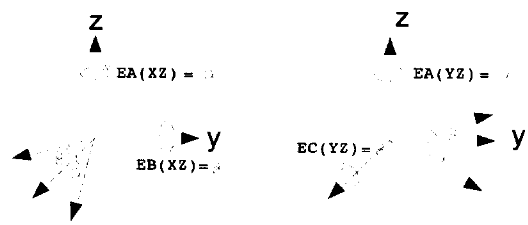

Figure 2, 4-parameters for representing squareness errors.

The data measured by optics for the straightness measurement must be recalculated to separate straightness errors and squareness error. Figure 3 shows the relationship between straightness error and squareness error. Generally the least mean squares line is used as a reference line. The 21 error components can be used as characteristic for machine tool and input as the parameters of the volumetric error model referred to in section 3.

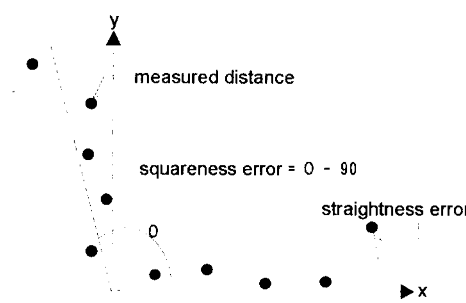

Figure 3, The relationship between straightness error and squareness error.

2.2 Preparing for the measurement

Before measuring error components, we have to prepare by recording accurate data in steps and by paying attention to the measurement as follows ;

- Check workspace on the machine tool and decide on the measuring dimensions.
- Divide the measuring space with points more than 10
- Decide traveling pattern - linear cycle, quasi-pilgrim cycle, etc.
- Decide the number of repetitions.
- Have sufficient warm-up time for the machine tool. Let the spindle revolve at a normal speed and let the table and tool move in the full measuring space for several hours.
- Check the temperature of critical parts of the machine tool with thermocouples. It is necessary to check the temperature of the spindle, the motors of each axis, leadscrews for the x, y table, and hydraulic oil.

The values of error components for any given point can be calculated by linearly interpolating the values of the error components of the neighboring two points, which have already been measured. Error components of a machine tool may be largely affected by the temperature changes. Therefore, we have to identify the trend of the variation of error components according to the temperature change.

3. Volumetric error model

For a typical linear carriage, three translational and three rotational errors can be represented using a 4x4 transformation matrix as follows ;

$$T_i = \begin{vmatrix} 1 & -\alpha(i) & \beta(i) & D_x + \varepsilon_x(i) \\ \alpha(i) & 1 & \gamma(i) & \varepsilon_y(i) \\ -\beta(i) & \gamma(i) & 1 & \varepsilon_z(i) \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

T_i : *transformation matrix* for *linear movement along* $x-$ *direction*

D_x : *the desgignated distance* for $x-$ *direction*

$\varepsilon_x(i), \varepsilon_y(i), \varepsilon_z(i)$: *translational errors* for x, y, z *direction*

α, β, γ : *yaw, pitch, roll* for $x-$ *directional movement*

Similarly, squareness error can be represented by using a 4x4 transformation matrix as shown below. The parameters used in the formula below are explained in figure 2.

$$T_{iz} = \begin{vmatrix} 1 & -EA(XZ) & EB(XZ) & 0 \\ EA(XZ) & 1 & 0 & 0 \\ -EB(XZ) & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

T_{iz}: *transformation matrix* for *squareness error between* $x-$ *axis* and $z-$ *axis*

$EA(XZ)$: *yaw*

$EB(XZ)$: *pitch*

The three dimensional positioning error due to x-directional table movement is the sum of the positioning error by linear movement and the positioning error by squareness error. The positioning error resulting from squareness error can be represented as follows ;

$$L_x = \begin{vmatrix} 1 & 0 & 0 & D_x \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

L_x : *transformation matrix* for *pure movement along* $x-$ *direction*

As a result, the positioning error due to the carriage movement along the x-direction can be represented as the 4x4 transformation matrix shown below. The positioning error due to carriage movement along y-direction can be similarly defined. In modelling the positioning error due to tool movement along the z-axis, it is not necessary to consider the squareness error, as z-axis is a reference axis.

$$T_x = T_{iz} + T_i$$

T_x : *position transformation matrix* for $x-$ *directional movement*

T_{iz} : *position transformation matrix* for *squareness error between* $z-$ *axis* and $x-$ *axis*

T_i : *position transformatin matrix* for *translational* and *rotational errors*

The three dimensional positioning error considering all error factors due to the movements along the x, y, z axis can be defined as follows ;

$$V_{xy} = T_x * T_y * I - O_{xy}$$

$$V_z = T_z * I - O_z$$

$$V_t = V_{xy} + V_z$$

x, y, z : *designated point*

V_{xy} : *positioning error due to table movement*

I : *zero vector.* $[0, 0, 0, 1]^T$

O_{xy} : *the table location after pure movement without errors* $[x, y, 0, 1]$

V_z : *positioning error due to tool movement*

O_z : *the tool location after pure movement without errors* $[0, 0, z, 1]$

V_t : *volumetric error vector*

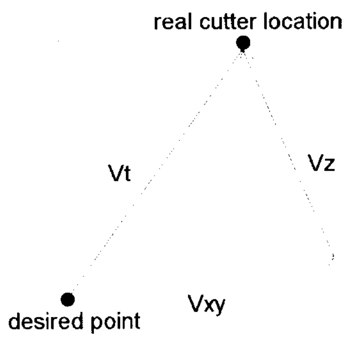

Figure 4, The relations between error vectors shown at a cutter tip.

4. Compensated point

As shown in the previous section, now we can find the 3-dimensional positioning error for any given point using the volumetric error model. Besides, we will suggest an algorithm for finding a compensated point using the volumetric error model. For any given point, the algorithm for finding the compensated point is shown as follows ;

Tp : Target Point

TpE : Error vector for Tp can be calculated using the volumetric error model.

CCpi : ith point of compensated candidates

CCpiE : Error vector for CCpi

ε : distance tolerance between tool position and Tp

Algorithm 1 : To find a compensated point

```
Step 1.  Calculate TpE
Step 2.  CCpi0 = Tp - TpE
Step 3.  for(i = 0; ; i++) {
           d = | CCpi + CCpiE - Tp |
           if( d < ε ) {
             Compensated Point = CCpi
             return    exit_success;
           }
           else
             CCp(i + 1) = CCpi + (CCpi
                         + CCpiE) - Tp
             if( d > dpre)      return   exit_fail;
             dpre = d;
         }
```

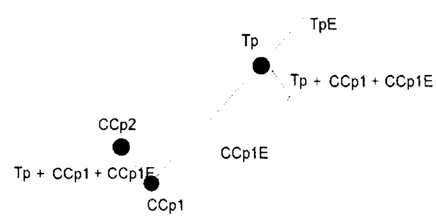

Figure 5, A method to find a compensated point.

5. Experiment and verification

This section presents an experimental study to demonstrate the effectiveness of the proposed strategy. All tests are performed in the vertical 3-axis milling machine.

5.1 Measurement of error components

A laser interferometer is used in measuring 19 error components except rolls, which are measured with an electronic level. The measurement was carried out three times for all 21 error components at different room temperatures. In our experiment, it was found that the effects of temperature change on error components can be negligible. Figure 6 shows the bi-directional positioning error for x-axis, which is the most critical factor in the 21 error components. Figure 7 shows the bi-directional positioning error for the y-axis which has backlash in 10 μm. The error components data given at the third experiment are shown in table 1.

Table 1. The table of the 21 error components.

x axis	0	55	110	165	220	275	330	385	440	495	550
positioning error	-0.5	5	11.5	17.5	24	30.5	39.5	45	57	63	70
straight- for y dir-	2.6	2.6	2.4	0.2	-1.5	-1.7	-2.2	-1.1	1.2	3	3.5
straight- for z dir-	2.7	2.7	0.3	-1.0	-1.3	-1.7	-1.4	-0.7	-0.1	0.6	1.3
pitch	-2.5	3.5	8	12.5	15	19	21	25	30	32.5	37
yaw	0.5	1.5	2.5	4	5	6.5	8	7	7.5	8	7.5
roll	0.7	1.1	2.1	3.5	4.5	5.9	6.6	7	7	7.4	7.7
y axis	0	28	56	84	112	140	168	196	224	252	280
positioning error	-3.5	-6.8	-6.8	-6.8	-8.5	-7	-5.3	-1	2.75	5.3	5.3
straight- for x dir-	0	0	-0.1	0.4	-0.2	-0.2	0.3	-0.2	0.8	0.2	-0.3
straight- for z dir-	-0.6	0.1	0.8	1.8	1.2	0	-0.6	0.1	0.6	1.0	2.8
pitch	-0.5	0	1	2	3	3.5	4.5	6	7	7	7
yaw	1.5	4.5	6.5	7.5	9	10	10	10	8.5	8.5	8.5
roll	0	1.3	2.9	4.4	5.8	6.8	8.5	9.8	11.2	12.4	13.6
z axis	0	-11	-22	-33	-44	-55	-66	-77	-88	-99	-110
positioning error	-4	-2.5	-6	-0.5	2	-1.5	-0.5	-3.5	1.5	2.5	-3.5
straight- for x dir-	-2.7	-0.7	0.7	1.6	1.0	0.4	1.3	1.2	0.1	-0.9	-2.0
straight- for y dir-	1.9	-10.8	1.7	4.0	3.3	1.8	1.9	-0.1	0.4	-1.0	-3.3
pitch	0.5	1.5	1.5	3	4	3	4	3	4	4	5
yaw	-1.5	-2	-2.5	-2.5	-2.5	-1.5	-1.5	-1.5	-0.5	0.5	1
roll	0	0	0	0	0	0	0	0	0	0	0
squareness error	betwn x, y	272		betwn y, z		65.38			betwn z, x		-29.5

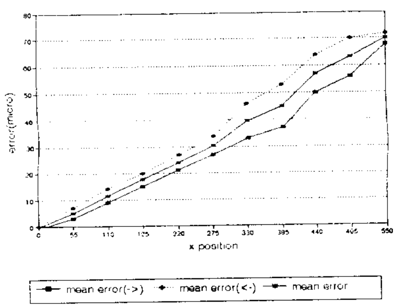

Figure 6, x-directional positioning error.

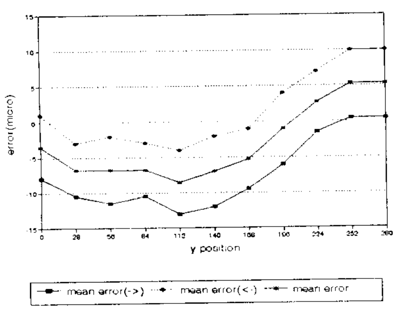

Figure 7, y-directional positioning error.

5.2 Verification of positioning accuracy after compensation

With a laser interferometer, the positioning accuracy after compensation was tested on the x-y plane. The distance errors between measurements without and with compensation is compared in figure 8.

With compensation, the positioning accuracy is about ± 10 μm. The 7 measured points are (20, 20, -50), (100, 60, -50), (180, 100, -50), ... , (520, 260, -50)

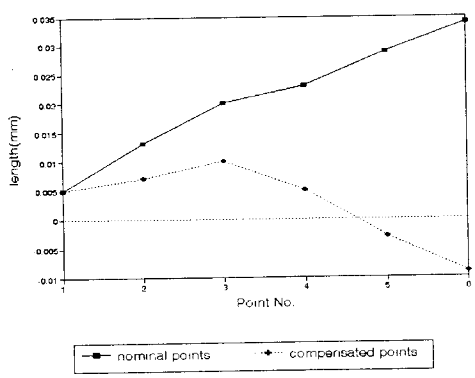

Figure 8. Comparison of distance error without and with compensation

6. Conclusions and future study

In this study, a general method for improving the positioning accuracy of CNC machine tool has been developed. The 21 error components of the machine tool were measured with a laser interferometer and an electronic level under various environmental conditions. A generalized volumetric error model composed of 21 error components was suggested and the algorithm was established for finding a compensated point using the suggested volumetric error model. The results also show that the positional accuracy after compensation is less than $\pm 10\mu m$, while positioning accuracy of without compensation is over $\pm 40\mu m$, with a CNC machine of 5 μm positional resolution.

We plan to measure the positional accuracy after compensation and verify it with a ball bar, which is a device to measure the contouring accuracy in the 3-dimensional space. We will also proceed to study the thermal effects due to temperature changes on volumetric errors.

References

[1] Yung, C. Shin, Henry Chin., Michael J. Brink., "Characterization of CNC Machining Centers", Journal of manufacturing systems, Vol 10, No.5 1995. pp407-421.

[2] J. H. CHO., M. W. CHO.,"Volumetric error analysis of a multi-axis machine tool machining a sculptured surface workpiece", INT. J. PROD. RES., 1994, VOL 32, No. 2, pp345-363

[3] J. Mou, C.Richard Liu., "A Method for enhancing the Accuracy of CNC Machine Tools for On-Machine Inspection", Journal of manufacturing systems, Vol 11, No.4 1995. pp229-237

[4] V. B. Kreng, C. R. Liu., C. N. Chu., "A Kinematic Model for Machine Tool Accuracy Characterization", Int J AdvManuf Technol, 1994, Vol 9, pp79-86

[5] M.A. Donmez, d.S. Blomquist, R.J. Hocken, C.R. Liu and M. M. Barash, "A General Method for Machine Tool Accuracy Enhancement by Error Compensation, " Precision Engineering, October 1986, Vol 8, No4, pp187-195

[6] K.C.FAN, J.F. LIN, S.S LU, "Measurement and compensation of thermal error on a machining center", Department of Mechanical Engineering, National Taiwan University. ROC pp261 - 268