Assessment of Positional Error CNC Machine Tools using Laser Interferometer

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Keywords: Positional Error, Measurement Standard, Accuracy, Repeatability, Error Compensation.

Abstract: The geometric error of machine tools significantly contributes to the machined workpiece's dimensional and geometric error. This study aims to show a method for assessment of the positional error of the machine axes movement. It is worthwhile since its information outcome could be a reference for obtaining error compensation parameters of machine tools and G-code program correction nowadays. Data collection of positional error was conducted by measuring method using a laser interferometer based on ISO 230-2 as a measurement standard of positioning accuracy and repeatability. The positional error parameters are analysed for getting mean deviation, systematic position deviation, repeatability, and accuracy. Then, machine tools' assessment status is obtained by comparing measurement results with ISO 10791-4 tolerance standard. The machine object tested of this study are CNC machine tools with a measurement distance travelled of X, Y and Z-axis are about 500 mm, 200 mm and 350 mm. Finally, the linear positional errors on each machine tools axis could be identified. The X-axis and Z-axis of machine tool exceed the tolerance range of the standard systematic position deviation, because the systematic position deviation value occurred on X, Y and Z axes are approximately 31.8 µm, 12.9 µm and 33.3 µm. The X and Z machine axes are out of tolerance in accuracy standard because the accuracy value in X, Y and Z axes are 34.2 µm, 14.4 µm, and 35.8 µm. And the X, Y and Z axes are still within tolerance in repeatability standards because the X, Y and Z axes repeatability values are 4.2 µm, 33.3 µm and 6.3 µm. The compensation error values of the X and Z axes have been generated based on their linear position errors. It will be further utilized as the main data for setting back error compensation parameters on CNC controller and developing G-Code correction modelling.

1 INTRODUCTION

More than 50% of total machining errors are caused by error sources of machine tools, such as geometric errors, servo errors, and thermal errors (Bryan, 1990) (Weck et al., 1995) (Chen et al., 1997). Geometric error is the greatest effect on machine tools' accuracy and precision (Chen et al., 1997) (Schwenke et al., 2008) (Tian et al., 2014). Hence, the machine tools' geometric errors significantly contribute to the dimensional and geometric errors of machined workpieces.

The geometric error of machine tools could be reduced in two ways, (i) design and manufacture precision machine tools, and (ii)set the compensation error parameters (Tian et al., 2014). The first way necessitated highly cost exponentially, but the second one was highly cost-effective to improve the geometric error of machine tools (Yang et al., 2004). The second one is performed by assessment and setting the error compensation parameters of machine tools.

Figure 1 shows that there are 6 components of geometric error in a single axis. Those are positional error $\delta_x(X)$, two straightness error motions, which are called horizontal straightness error motion $\delta_z(X)$ and vertical straightness error motion $\varepsilon_y(X)$, and three angular error motions that consist of roll error motion and two tilt error motions. Two tilt error motions are yaw and pitch error motion (Okafor and Ertekin, 2000).

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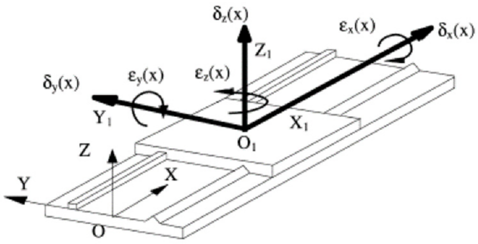

Figure 1: Component geometric error in single axis (Okafor and Ertekin, 2000).

The geometric error in three-axis machine tools has 21 geometric error components, which are three linear positional errors, six straightness error motions, nine angular error motions, and squareness error. Twenty-one geometric error types in three-axis machine tools are shown in Table 1. There are (i) linear straightness horizontal and vertical error of each axis, (ii) linear positional error of each axis, (iii) pitch angular error of each axis, (iv)yaw angular error of each axis, (v)roll angular error of each axis, (vi) and squareness error between XY axis, XZ axis and YZ axis.

Table 1: Components of geometric error in three-axis machine tools (Okafor and Ertekin, 2000).

Geometric error component	Linear position error	Angular error (roll, pitch, yaw)
X-axis	$\delta_x(X)$, $\delta_y(X)$, $\delta_z(X)$	$\varepsilon_x(X)$, $\varepsilon_x(X)$, $\varepsilon_x(X)$
Y-axis	$\delta_x(Y)$, $\delta_y(Y)$, $\delta_z(Y)$	$\varepsilon_x(Y)$, $\varepsilon_x(Y)$, $\varepsilon_x(Y)$
Z-axis	$\delta_x(Z)$, $\delta_y(Z)$, $\delta_z(Z)$	$\varepsilon_x(Z)$, $\varepsilon_x(Z)$, $\varepsilon_x(Z)$
Squareness error	φ_{xy}, φ_{xz}, φ_{zy},	

This paper focuses on the assessment of the linear positional error of three-axis CNC machine tools. Measurement and analyzing data were performed based on ISO standards. Measuring on machine object tested was conducted using a calibrated laser interferometer.

The research has the aim to show an assessment method for measuring the linear position error of machine tools axes. Its outcome could be used for determining the compensation error value of the machine parameter.

2 MATERIAL AND METHOD

2.1 Material

The machine object tested of this study is CNC machine tools with measurement travel of X, Y and Z-axis are about 500 mm, 200 mm and 350 mm.

There are differences between axis travel and measurement travel. Axis travel on the machine axis is maximum travel in a linear movement where the moving parts can be move under controller, but the measured travel is part of the selected axis travel and is used to capture data. Hence the first and the last target positions can be approached in both directions.

2.2 Method

There are several stages for assessment of positional error of machine tools: measuring the geometric error data, Analyzing measuring data results, evaluating the assessment status of tested machine tools by comparing the information value of positional error parameters with ISO standard tolerance of geometric error and calculating compensation error value.

Data collection of positional error was conducted by measuring methods based on ISO 230-2 as a measurement standard of positioning accuracy and repeatability. Its measurement uses a laser interferometer (International Organization for Standardization, 2006). Environment condition and machine tools thermal are two factors that should be considered in its measurement operation. Environmental condition factors are like air temperature, air pressure, and relative humidity (Wang et al., 2002). Hence laser interferometer system should be equipped by the environmental compensation unit. Its unit has three functions: (i)measuring environmental conditions, (ii)compensates the wavelength of the laser beam, which is influenced by these distraction variations, and (iii)virtually eliminating any measurement errors.

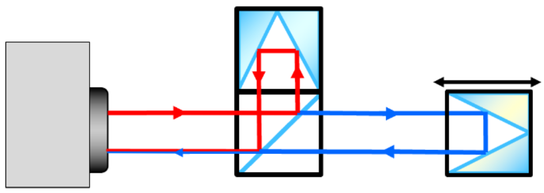

Figure 2: Configuration of positional error measurement using laser interferometer (Renishaw, 2008).

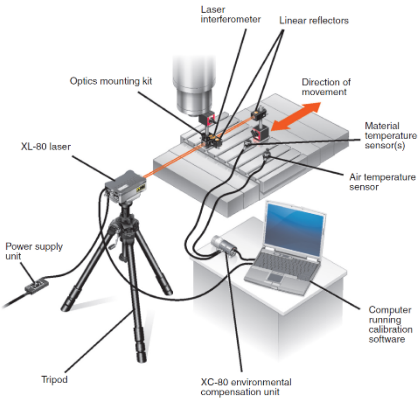

Figure 3: Set up the laser interferometer equipment for linear positional error measurement (Renishaw, 2008).

The configuration of linear positional error measurement was shown in Figure 2. Figure 3 shows the set up for linear positional error measurement using laser interferometer equipment. Linear positional error value was obtained by comparing a target position data and actual position data. A target position is displayed on the axis read-out of machine tools, and the laser measures the factual position as an actual position. A retroreflector is mounted to a beam splitter in linear measurement. It is to form a fixed-length reference arm of an interferometer. Another retroreflector is moved relative to the beam splitter to form a variable-length measurement arm. Then, the laser is used to track any changes in separation between the measurement arm retroreflector and a beam splitter (Renishaw, 2008).

The stages of testing or measuring the linear positional error, and calculation stages for obtaining the positioning accuracy value of CNC machine tools axes and also its reliability value has been explained clearly on ISO 230-2. Measurement operation directly measures to each axis on the machine tools. ISO 230-2 explains detailly about (i)definition and symbols which is used in measurements such as axis travel, measurement travel, positional deviation, mean positional deviation, systemic positional deviation, repeatability, and accuracy, (ii)testing condition for the environment and tested machine tools, (iii)testing program guidance that focuses describe target measurement, measurement setup, (iv)evaluation of measurement result and result presentation. ISO 230-2 states information about the minimum requirement of total position target and complete capture data of each target position. The axis travel up to 2000 mm, the minimum total position target should be selected and measured five target positions per meter. Each target position in positive and negative directions should be fully measured five times (International Organization for Standardization, 2006).

Measurement can be made unidirectional or bi-directional. Unidirectional measurement is series measuring of target positions that are always done in the same direction along the axis. The symbol ↑ signifies a parameter of measurement direction in a positive direction and ↓ one in the negative direction. e.g., $X_{ij}\uparrow$ or $X_{ij}\downarrow$. Bidirectional measurement is a series of measurements that approach the target position, taken in either direction along the axis.

Measurement results are analyzed to estimate linear positional error parameters value such as positional deviation, mean deviation, systematic position deviation, repeatability, and accuracy.

Positional deviation $[X_{ij}]$ is calculated result from subtracting actual position value $[P_{ij}]$ by target position value $[P_i]$.

$$X_{ij} = P_{ij} - P_i \tag{1}$$

Target position $[P_i]$ is the coordinate of the programmed position and must be reached, where i= 1 to m. Actual position $[P_{ij}]$ with i= 1 to m and j= 1 to *n*. It is the measured position reached by the moving part on the *j*th approach to the *i*th target position.

The calculation can be continued for obtaining mean unidirectional ($\bar{X}_i\uparrow$ and $\bar{X}_i\downarrow$) or mean bidirectional $\bar{X}_i$.

$$\bar{x}_i \uparrow = \frac{1}{n}\sum_{j=1}^{n} Xij \uparrow \tag{2}$$

$$\bar{x}_i \downarrow = \frac{1}{n}\sum_{j=1}^{n} Xij \downarrow \tag{3}$$

Mean unidirectional positional deviation on a position xi↑ (positive direction) or xi↓ (negative direction) is an arithmetic mean of the positional deviations obtained by a series of n approaches the position Pi in one direction.

$$\bar{x}_i = \frac{\bar{x}_i \uparrow + \bar{x}_i \downarrow}{2} \tag{4}$$

Mean bidirectional positional deviation on a position is an arithmetic mean of the mean unidirectional positional deviations xi↑ (positive direction) and xi↓ (negative direction). It is obtained from position Pi in the two measurement directions.

Systematic positional deviation of an axis (E, E ↑ , E ↓) is the difference between the algebraic maximum and minimum of the mean unidirectional positional deviations in an approach direction (positive xi ↑ or negative xi ↓ direction) at any position Pi along the axis.

$$E\uparrow = \max.\,[\bar{x}_i\uparrow] - \min.\,[\bar{x}_i\uparrow] \tag{5}$$

$$E\downarrow = \max.\,[\bar{x}_i\uparrow] - \min.\,[\bar{x}_i\uparrow] \tag{6}$$

$$E = \max.\,[\bar{x}_i\uparrow;\bar{x}_i\downarrow] - \min.\,[\bar{x}_i\uparrow;\bar{x}_i\downarrow] \tag{7}$$

The symbols E ↑ and E ↓ are used in unidirectional measurement, and the E one is used in the bidirectional measurement.

The mean bidirectional position deviation of an axis (M) is the difference between the algebraic maximum and minimum of the average bidirectional positional deviations x_i at any position P_i along the axis.

$$M = \max.\,[\bar{x}_i] - \min.\,[\bar{x}_i] \tag{8}$$

Reversal value at a position (Bi) is the difference between the average unidirectional positional deviations obtained from the two approach directions at a position Pi.

$$Bi = \bar{x}_i\uparrow - \bar{x}_i\downarrow \tag{9}$$

The reversal value of an axis (B) is the maximum of the absolute reversal values |Bi| at all target positions along the axis.

$$B = max.\,[|Bi|] \tag{10}$$

The mean reversal value of an axis ($\bar{B}$) is arithmetic average of the reversal values Bi at all target positions along the axis.

$$\bar{B} = \frac{1}{m}\sum_{i=1}^{m} Bi \tag{11}$$

si↑ or si↓ is the repeatability estimator of unidirectional axis positioning at a specific position. It is an estimator of the standard uncertainty of the positional deviations obtained by a series of n unidirectional methods on a position Pi.

$$Si\uparrow = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(Xij\uparrow - \bar{x}_i\uparrow)^2} \tag{12}$$

$$Si\uparrow = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(Xij\uparrow - \bar{x}_i\uparrow)^2} \tag{13}$$

$$Si\downarrow = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(Xij\downarrow - \bar{x}_i\downarrow)^2} \tag{14}$$

Unidirectional positioning repeatability of the Ri↑ or Ri↓ position is a range of the unidirectional axis positioning repeatability on the position Pi obtained from the estimator using a coverage factor 2.

$$Ri\uparrow = 4Si\uparrow \tag{15}$$

$$Ri\downarrow = 4Si\downarrow \tag{16}$$

$$Ri\max.\,[2Si\uparrow + 2Si\downarrow + |Bi|;\, Ri\uparrow;\, Ri\downarrow \tag{17}$$

$$Ri\uparrow = \max.\,[Ri\uparrow] \tag{18}$$

$$Ri\downarrow = \max.\,[Ri\downarrow] \tag{19}$$

$$Ri = \max.\,[Ri] \tag{20}$$

Ri ↑ or Ri ↓ is the unidirectional positioning repeatability of a specific position. Ri is the bidirectional positioning repeatability of a particular position.

A ↑ or A ↓ is unidirectional positioning accuracy of an axis. It is range derived from the combination of unidirectional system deviation and the bidirectional positioning axis repeatability estimator using a coverage factor of 2.

$$A\uparrow = \max.\,[Xi\uparrow + 2Si\uparrow] - min.\,[Xi\uparrow - 2Si\uparrow] \tag{21}$$

$$A\downarrow = \max.\,[Xi\downarrow + 2Si\downarrow] - min.\,[Xi\downarrow - 2Si\downarrow] \tag{22}$$

A is bidirectional positioning accuracy of an axis. It is range derived from the combination of the bidirectional system deviation and the bidirectional positioning axis repeatability estimator using a coverage factor of 2.

$$A = \max.\,[Xi\uparrow + 2Si\uparrow; Xi\downarrow + 2Si\downarrow] - min.\,[Xi\uparrow - 2Si\uparrow; Xi\downarrow - 2Si\downarrow] \tag{23}$$

3 DISCUSSION AND RESULT

Figure 4 shows the measurement data of positional error on the X-axis. The highest mean deviation value of position error occurred in X-axis with a negative value of 29.7 µm in the measurement position of 475 mm or the absolute machine coordinate of 106 mm.

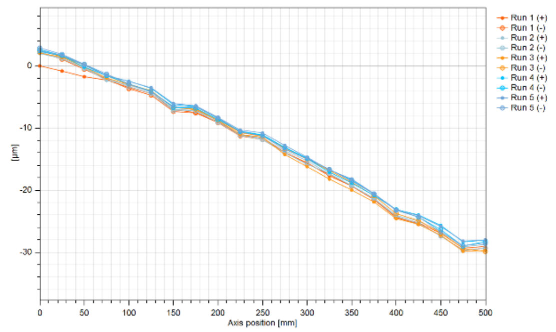

Figure 4: Measurement data of positional error on X-axis in 500 mm.

The measurement data of the positional error on Y-axis is shown in Figure 5. The highest mean deviation value of position error occurred in Y-axis with a negative value of 13.6 µm in the measurement position of 200 mm or the absolute machine coordinate of 70 mm.

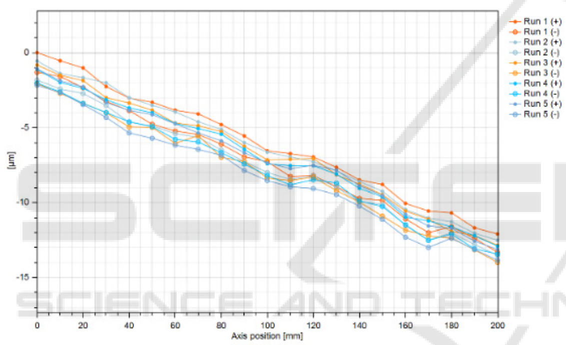

Figure 5: Measurement data of positional error on Y-axis in 200 mm.

Figure 6 shows the measurement data of positional error on the Z-axis. The highest mean deviation value of position error is negative 29.4 µm in the measurement position of 325 mm or the absolute machine coordinate of 70 mm.

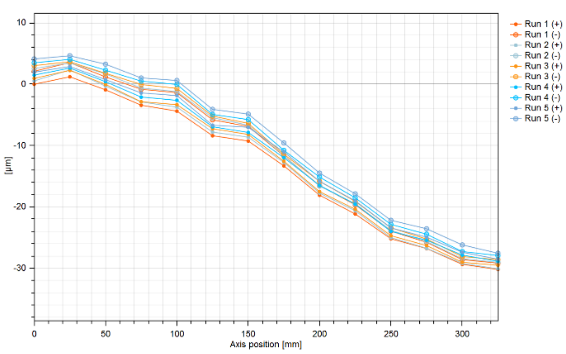

Figure 6: Measurement data of positional error on Z-axis in 300 mm.

There are several positional error values on each axis. Those are systematic position deviation, mean reversal, unidirectional repeatability forward and reverse, bidirectional repeatability, unidirectional accuracy in forward and reverse, and bidirectional accuracy. Equation (1) until number (23) are used to calculate its positional error values. Table 2 shows the information about positional error measurement.

Table 2: The information of positioning measurement.

No	Item	X-axis	Y-axis	Z-axis
	Measurement travel	500 mm	200 mm	350 mm
1	Bidirectional Systemic position deviation	31.8 µm	12.9 µm	33.3 µm
2	Unidirectional repeatability			
	forward	4.2 µm	2.3 µm	3.9 µm
	reverse	2.6 µm	2.2 µm	4.0 µm
3	Bidirectional repeatability	4.2 µm	3.3 µm	6.3 µm
4	Unidirectional accuracy			
	forward	34.1 µm	13.7 µm	34.5 µm
	reverse	33.4 µm	13.0 µm	34.7 µm
5	Bidirectional accurracy	34.2 µm	14.4 µm	35.8 µm

The assessment status of tested machine tools was identified by comparing the information value of positional error parameters with ISO 10791-4 (International Organization for Standardization, 1998).

The systematic position deviation value that occurred in X is about 31.8 µm, and its value is out of tolerance in standard systematic position deviation. The accuracy value in the X machine axis is 34.2 µm. The X machine axis is out of tolerance in accuracy standard. The repeatability value in X-axis is 4.2 µm. The repeatability of X-axis is still in tolerance in repeatability standard.

The systematic position deviation value that occurred in Y is about 12.9 µm, and its value is still in tolerance in standard systematic position deviation. The accuracy value in the Y machine axis is 14.4 µm. The Y machine axis is still in tolerance in accuracy standard. The repeatability value in Y-axis is 3.3 µm. It is still in tolerance in repeatability standard.

The systematic position deviation value that occurred in Z is about 12.9 µm, and its value is still in tolerance in standard systematic position deviation. The Z machine axis's accuracy value is 33.3 µm, and its value is out of tolerance in accuracy standard. The repeatability value in the Z-axis is 6.3 µm. The repeatability of the Z-axis is still in tolerance in repeatability standard.

The machine tools case study's assessment status is found by comparing positional error values with ISO 10791-4 tolerance standard. The X and Z machine axis is out of tolerance in standard systematic position deviation and accuracy standard. The repeatability of the X, Y and Z-axis are still in tolerance in repeatability standard. The X and Z machine axis's positional error should be improved by setting the error compensation parameters of machine tools on CNC controller.

Table 3: Compensation error of X-axis.

Index	Position (mm)	Forward direction (scale:1)	Reverse direction (scale:1)
1	0	0	-0.716
2	25	0.751	1.014
3	50	1.488	1.512
4	75	1.467	1.668
5	100	0.962	1.44
6	125	1.056	1.132
7	150	2.622	2.605
8	175	0.352	0.133
9	200	1.726	1.75
10	225	2.162	2.112
11	250	0.514	0.621
12	275	2.227	2.058
13	300	1.786	1.723
14	325	2.099	1.718
15	350	1.688	1.848
16	375	2.104	2.137
17	400	2.634	2.787
18	425	0.904	1.085
19	450	1.715	2.087
20	475	2.486	2.394
21	500	-0.245	-0.251

Table 3 and Figure 7 show the compensation error value with an interval coordinate position interval in 25 mm along the X-axis.

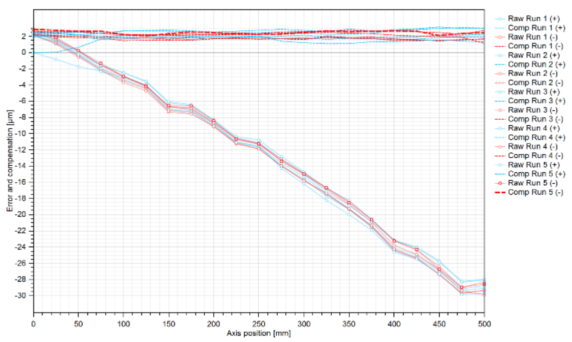

Figure 7: Compensation error value of X machine axis.

The compensation error value with interval coordinate position interval in 25 mm along the Z-axis is shown in Table 4 and Figure 8.

Table 4: Compensation error of X-axis.

Index	Position (mm)	Forward direction (scale:1)	Reverse direction (scale:1)
1	0	0	-2.079
2	25	-1.281	-0.801
3	50	2.286	1.827
4	75	2.52	2.029
5	100	0.642	0.547
6	125	4.234	4.558
7	150	0.781	1.02
8	175	4.135	4.912
9	200	4.808	4.693
10	225	3.009	3.214
11	250	4.32	4.313
12	275	1.578	1.698
13	300	2.525	2.784
14	325	0.878	0.737

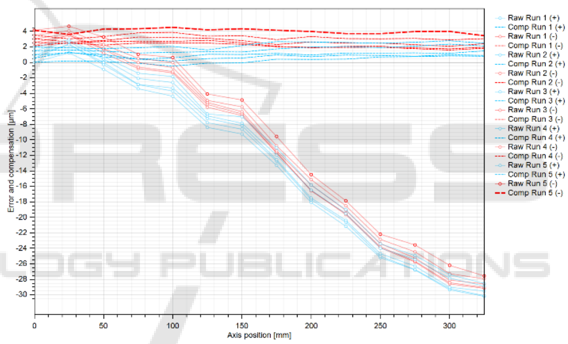

Figure 8: Compensation error value of Z machine axis.

Their compensation error values could be a reference to set back error compensation parameters on the machine controller to improve the linear positional geometric error of the machine tool X and Z axis.

4 CONCLUSIONS

Their linear positional error of the machine axes movement could be identified using the measuring method. Measuring was conducted based on ISO measurement standards and the calibrated laser interferometer. It resulted in the information about the highest positional deviation, systematic position value, accuracy, and repeatability of each machine axis.

The X-axis and Z-axis of machine tool exceed the tolerance range of the standard systematic position deviation, because the systematic position deviation value occurred on X, Y and Z axes are approximately 31.8 µm, 12.9 µm and 33.3µm. The X and Z machine axes are out of tolerance in accuracy standard because the accuracy value in X, Y and Z axes are 34.2 µm, 14.4 µm, and 35.8 µm. And the X, Y and Z axes are still within tolerance in repeatability standards because the X, Y and Z axes repeatability values are 4.2 µm, 33.3 µm and 6.3 µm.

The compensation error values of the X and Z axes have been generated based on their linear positional errors. It will be further utilized as the primary data for setting back error compensation parameters on CNC controller and developing G-Code correction modelling.

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