Jurnal Polimesin
Department of Mechanical Engineering
State Polytechnic of Lhokseumawe
http://e-jurnal.pnl.ac.id/polimesin

e-ISSN	: 2549-1999	No.	: 4	Month	: August
p-ISSN	: 1693-5462	Volume	: 21	Year	: 2023

Article Processing Dates: Received on 2023-05-31, Reviewed on 2023-06-04, Revised on 2023-08-02, Accepted on 2023-08-09 and Available online on 2023-08-25

Experimental study of geometric error of CNC turning machine tools based on ISO 13041-6

Herman Budi Harja*, Elan Suherlan, Nandang Rusmana, Dhion Khairul Nugraha

Teknik Manufaktur, Politeknik Manufaktur Bandung, Bandung, 40135, Indonesia

*Corresponding author: herman@polman-bandung.ac.id

Abstract

The product quality of machining results is greatly influenced by the accuracy and precision of CNC lathe machine tools. Regular inspection of the geometric inaccuracy of the machine tool is necessary to verify its operational viability. This research contribution focuses on conducting experimental studies to evaluate machine tool geometric error. The aim is to explore cost-effective measurement methods as alternatives to direct measurements, which often involve laser interferometers and ball bar tests. The objective of this study is to investigate the geometric inaccuracy of a CNC turning machine by conducting experimental cutting tests in accordance with ISO 13041-6:2009. The testing will utilize conventional workpiece forms and requirements, including circularity features, flatness, circular features, and maybe combination features. Several geometric errors that can be acquired with this method include circularity errors, linear positional errors, and squareness errors. The cutting test for each workpiece feature of the given shape and specification requires the use of five specimens. Consequently, the mean value of the geometric error may be computed. The geometric error value is derived by the analysis of measurement data collected from a Coordinate Measuring Machine (CMM) applied to a specimen of the machined workpiece. Moreover, the evaluation of the geometric error condition of machine tools is ascertained through the comparison of the average data for each category of geometric error against the permissible standard values given in ISO 10791-2, ISO 10791-4, and ISO 13041-4. The findings of the study indicate that the implementation of the object machine study is not viable for the production of machined workpieces of satisfactory quality. This is primarily due to the presence of geometric errors in CNC turning that exceed the acceptable tolerance levels. Specifically, these errors manifest as linear positional deviations along multiple coordinates along the X-axis and Z-axis, as well as squareness deviations between the X-axis and Z-axis. The maximum value of the linear positional error along the X-axis is 55.2 µm, while the maximum value of the linear positional error along the Z-axis is 25.6 µm. Additionally, the greatest observed squareness error is 37.3 µm. The X and Z machine axes exhibit deviations beyond acceptable limits in terms of unidirectional accuracy and unidirectional repeatability, as per the established norm.

Keywords:
Turning CNC machine tools, geometric error, experimental study, ISO 13401-6.

1 Introduction

The performance of machine tools, particularly CNC machine tools, has a considerable impact on the quality of the products they generate during machining activities. The performance of a machine tool is contingent upon its capacity to accurately position and manipulate the cutting tool in relation to the workpiece. The concept is characterized by its adherence to correctness and precision. Accuracy refers to the minimum distance that can be achieved by a machine's tool movement when it is precisely controlled and measured. The machine controller must effectively regulate the cutting tool's movement to ensure precision, which is defined as the minimum distance traveled accurately. The precision of a machine tool refers to its capacity to consistently position and maneuver the cutting tool along a predetermined path during repetitive operations. The accurate positioning and motion of the cutting tool trajectory on the workpiece are crucial factors in determining the precise dimensions and shape of the machined workpiece. The accurate positioning and trajectory of the cutting tool path relative to the workpiece are crucial factors in determining the precise dimensions and shape of the machined workpiece. Hence, the degree of accuracy and precision will be contingent upon the machine's capacity to accurately position and manipulate the cutting tool in relation to the workpiece.

In the machining process, the cutting-edge position, also referred to as the functional point, undergoes a displacement from its intended location. Consequently, this displacement leads to the occurrence of imperfections in the final machined product. The extent of inaccuracies or deviations in machine tool performance is contingent upon factors such as the precision of the machine tool's geometry, the deflection caused by static and dynamic loads, and the occurrence of thermal drift [1]. Machine tool geometric errors are sourced from manufacturing problems for each machine component and the machine tool assembly process [2]. Geometric errors are caused by imperfections and misalignment of the moving elements. All machine tools degrade during operations and their geometric error slowly increases during operation, thus machine tools should be diagnosed and monitored for the growth of geometric error conditions [3]. The geometric error of the machine tool on a single axis consists of six, namely 1) linear positional error, 2) linear vertical straightness error, 3) linear horizontal straightness error, 4) pitching angular error, 5) yawing angular error, and 6) rolling angular error [4].

A total of six geometric mistakes may occur on each axis, along with an additional geometric defect that manifests as a straightness error between the X and Z axes. Hence, a total of thirteen geometric mistakes are present. Fig. 1 depicts an illustration of the various types of geometric errors that might occur on turning machine tools.

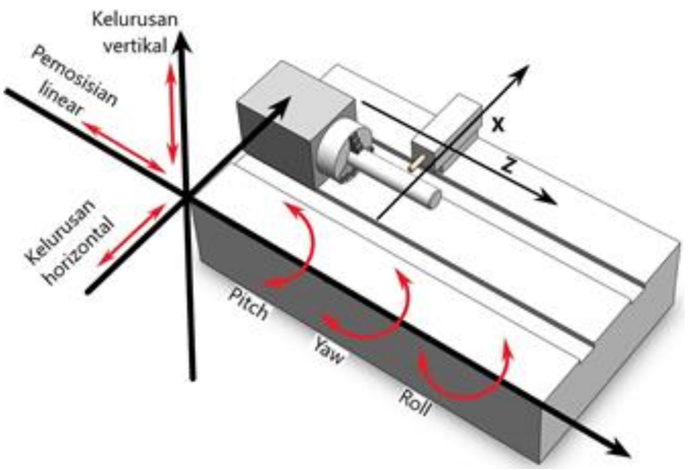

Fig. 1. Ilustration of geometric error type on turning machine tools.

Table 1 shows 13 types of geometric errors on turning machine tools, namely linear positional errors on the X axis (δx (x)) and Z axis (δz (z)), vertical straightness errors on the X axis (δz (x)) and Z axis (δy (z)), horizontal straightness error on the X axis (δy (x)) and Z (δx (z)), rolling angular error on the X axis (εx (x)) and Z axis (εz (z)), pitching angular error on the X axis (εz (x)) and Z axis (εz (z)), and yawing angular error on the X axis (εy (x)), and Z axis (εy (z)), as well as squareness error Φx (z) between the X and Z axes.

Table 1. The types of geometric errors on turning machine tools

Geometric error type	Notation
Linear positional error	δx (x), δz (z)
Vertical straighness error	δz (x), δy (z)
Horizontal straighness error	δy (x), δx (z)
Rolling angular error	εx (x), εz (z)
Yawing angular error	εy (x), εy (z)
Pitching angular error	εz (x), εx (z)
Squareness error	Φx (z)

Numerous investigations have been conducted pertaining to the evaluation of machine tool performance, encompassing areas such as power consumption efficiency, geometric error analysis, and assessment of machining product quality. In their study, Harja (2021) conducted an evaluation of lathe efficiency by employing the Specific Energy Consumption (SEC) value indicator method. The evaluation was carried out during machining, considering two distinct situations of the machine tool pulley-belt transmission system: aligned and misaligned. The consideration of mechanical losses, specifically in relation to the misaligned condition of the pulley-belt transmission system, is imperative due to its direct impact on the energy consumption efficiency of machine tools, resulting in a loss above 5% [5]. Assessment of the accuracy and precision of machine tool geometric errors under no-load conditions has been carried out by several researchers, including Sabahudin (2015) and Holub (2018) using the QC Ballbar to monitor the development of machine tool geometric errors through routine measurements [6][7]. The ball bar is also used for the assessment of geometric error for 5-axis CNC milling machines [8]. Data population from Ballbar measurement results were statistically analyzed to obtain geometric error values for machine tools [9]. Then Winarno (2021) verified the geometric error of educational machine tools using the fringe counting method, which processes and calculates the test data using Python software to calculate the number of H-Ne fingers and the number of motor drive pulses [10]. Harja (2023) used a Laser Interferometer for measuring machine tools' geometric error based on ISO 230-2 to conduct a study of evaluating geometric error for the types of linear-positional error and straightness error on CNC milling machines, and recommend setting back the error compensation value in the machine controller parameters, hence that geometric errors are within the ISO 10791-2 and ISO 10791-4 tolerance standards [11][12]. Furthermore, the evaluation of the geometric error of the Mini-Custom turning machine was conducted by examining machined workpieces under two cutting conditions, namely dimension and length. The specimens used for this assessment had two sets of dimensions: 1) diameter of 15 mm and 17 mm, and 2) length of 20 mm and 30 mm. The measuring instrument employed for this purpose was a micrometer with a precision level of 0.001 mm [13].

The majority of studies examining the geometric errors of machine tools focus on conditions where there is no load or during the non-cutting phase of machine operation. These studies typically involve direct measurement using instruments such as laser interferometers or ball bar tests. The evaluation of geometrical errors in machine tools using measuring instruments necessitates a substantial financial commitment or increased funding, whether it be for the procurement of measuring instruments or the utilization of calibration services. The medium machining manufacturing business, particularly the machining workshops of Micro, Small, and Medium Enterprises (UMKM), face a significant hindrance. Hence, the purpose of this study was to assess the geometric error of a Computer Numerical Control (CNC) turning machine when subjected to cutting loads. The determination of the machine tool's geometric error is derived indirectly through the analysis of the measured geometric error of the machined workpieces. The cutting test specified by ISO 13041-6 is used to evaluate the product features of machined workpieces [14].

2 Research Methodology

The precision of a machined workpiece on a CNC machine is heavily influenced by the geometric inaccuracy inherent in the CNC machine itself. The chosen approach involves assessing the geometric error of the machine tool indirectly, as it is derived from the observed geometric error on the workpiece that has been machined during cutting experiments. The study was carried out in multiple phases, including 1) identification of the test machine subject, 2) selection of the test object based on the product characteristics specified in ISO 13041-6 and its machining process, 3) utilization of a Coordinate Measuring Machine (CMM) to measure the machined test object, and 4) evaluation of the geometric error condition in accordance with ISO 10791-2, ISO 10791-4, and ISO 13041-4. Coordinate Measuring Machines (CMMs) are precision machine tools specifically engineered to do accurate measurements on three-dimensional workpieces [15].

CNC turning machine CTX 310 was made in 2008 and has been used at POLMAN Bandung since 2010. Fig. 2 displays CNC turning machine CTX 310 Eco. The last machine usage history shows machine workpieces' geometric errors are frequently out of standard tolerance. Hence this machine is a research object to identify the geometric error status of its machine. This machine uses a Siemens 810D controller and has X and Z axis travel of 160 mm and 450 mm. Based on the literacy of the machine manual book and direct observation of the machine, the working area for cutting that allows utilization is 170 mm on the X-axis and 252 mm on the Z-axis. The visualization of the cutting work area for the CNC turning machine is shown in Fig. 3.

Fig. 2. CNC turning machine CTX 310 Eco.

The machined workpiece standard for test results refers to ISO 13041-6 which describes standards and specifications for the shape and dimensions of the test piece for cutting on a CNC turning machine. Some other information contained in this cutting test standard includes 1) the material and dimensions of the cutting tool, 2) the material and dimensions of the test object, cutting speed, depth of cut, the axis used for machining, and other parameters.

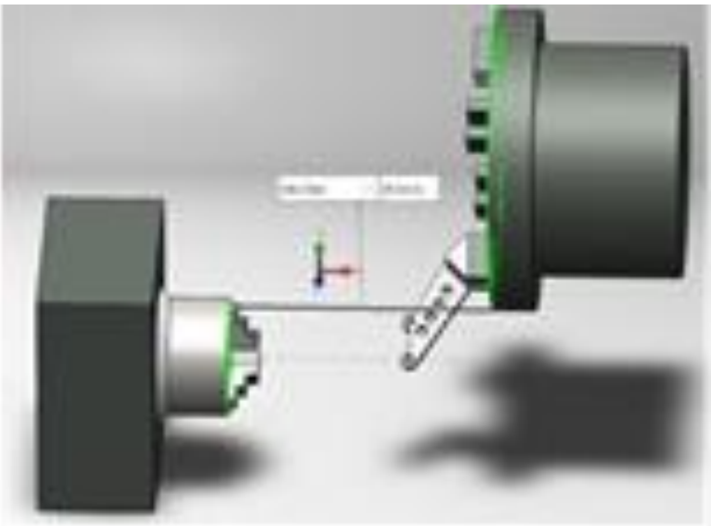

Fig. 3. Visualization of the cutting work area for CNC CTX 310 Eco.

According to ISO 13041-6, the categorization of test objects for machines equipped with horizontal holder spindles is based on their dimensions, which are divided into three distinct groups as presented in Table 2. Consequently, the test objects used in the machines fall under Category 1. ISO 13041-6 encompasses three primary product features, namely cylindrical workpiece features, flatness feature workpieces, and round feature workpieces [14] .

Table 2. Dimension range of test pieces for machines with a horizontal working spindle [14]

Criteria	Category 1	Category 2	Category 3
Swing diameter over bed	D≤ 250	250 < D ≤ 500	500 < D ≤ 1000
Nominal bar diameter	d'≤ 25	25 < d' ≤ 63	63 < d'
Nominal diameter of chuck	d≤ 125	125 < d ≤ 250	250 < d

Standard cylindrical features of the workpiece are shown in Fig. 4, accompanied by the notation of geometric features A, B, C, D, E, F, G, and H. An explanation of the measurement features for each notation is shown in Table 3. Engineering drawings of cylindrical feature test objects complete with the inclusion of their dimensions are shown in Fig. 5.

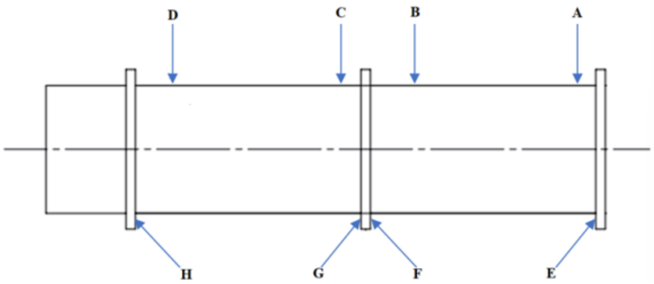

Fig. 4. Standard cylindrical features of the workpiece.

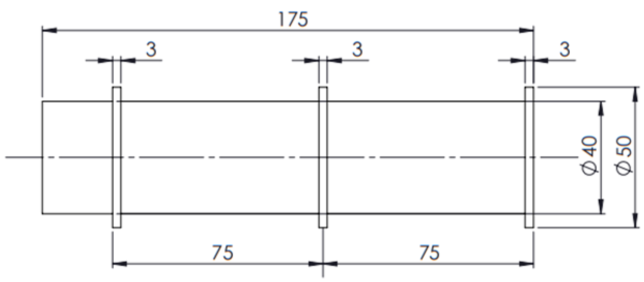

Fig. 5. Engineering drawing of the cylindrical feature test object.

The workpiece specimen test involving a standard cylindrical feature consists of 17 measurement positions. These positions provide valuable information regarding the geometric errors of the features being measured. The information obtained includes the circularity measurements at points A, B, C, and D, the consistency of diameters, the linear positional error along the Z axis at measurement positions E, F, G, H, and the linear positional error along the X axis at measurement positions A, B, C, D. Additionally, the test also assesses the squareness error between planes A and E, B and F, C and G, and G and H. The determination of coordinate data from point A to point H has been conducted, utilizing the Machine Coordinate System (MCS) as the coordinate reference for the testing machine object. The zero point of the MCS serves as the reference point for the coordinate system and is a stationary location on the machine tool. This position is established by the manufacturer of the machine tool. The reference point serves as a basis for other coordinate systems, including the Workpiece Coordinate System (WCS). The coordinates for each point of the cylindrical feature workpiece, specifically the X and Z MCS coordinates, are presented in Table 3. The coordinates of the object are utilized in both the G-code program for machining and the measuring program on the Coordinate Measuring Machine (CMM).

Table 3. The X and Z MCS coordinates for each point of the cylindrical feature workpiece

Measurement feature	MCS coordinate	
	X	Z
Circularity (point A)	147.281	297.189
Circularity (point B)	147.281	234.189
Circularity (point C)	147.281	224.189
Circularity (point D)	147.281	159.189
Consistency of diameters (mean value of point A, B, C, and D		
Linear position Z axis (point E)	144.281	301.189
Linear position Z axis (point F)	144.281	230.689
Linear position Z axis (point G)	144.281	227.689
Linear position Z axis (point H)	144.281	157.189
Linear position X axis (point A)	147.281	297.189
Linear position X axis (point B)	147.281	234.189
Linear position X axis (point C)	147.281	224.189
Linear position X axis (point D)	147.281	159.189
Squareness between planes A & E		
Squareness between planes B & F		
Squareness between planes C & G		
Squareness between planes D & H		

The test object depicted in Fig. 6 is a conventional flatness feature, which includes geometric error feature notations labeled as A and B. Table 4 displays the X and Z MCS coordinates corresponding to each point of the flatness feature workpiece. Fig. 7 depicts the engineering drawing of the flatness feature test object, encompassing the dimension values.

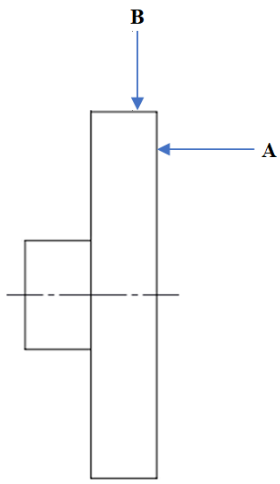

Fig. 6. The standard flatness feature test object.

Table 4. The X and Z MCS coordinates for each point of the flatness feature workpiece

Measurement feature	MCS coordinate	
	X	Z
Flatness (point A)	142.281	194.189
Linear positional Z axis (point A)	142.281	194.189
Linear positional X axis (diameter B)	133.281	174.189
Squareness planes A and B		

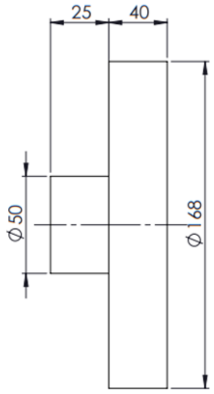

Fig. 7. The Engineering drawing of the flatness feature test object complete with dimension values.

The coordinates for each point of the cylindrical feature workpiece, specifically the X and Z MCS coordinates, are presented in Table 4. The coordinates of the given location are utilized in the G-code program for the purpose of cutting workpiece specimens, as well as in the measuring program implemented on the CMM machine. The standard for testing the flatness feature of a workpiece specimen specifies four positions that need to be measured. These positions correspond to different geometric error measurement features, namely: 1) flatness at point A, 2) linear positional error on the Z axis for the measurement position at point A, 3) linear positional error on the X axis for the measurement position at point B (diameter), and 4) squareness error between plane A and plane B.

Fig. 8 shows the standard circular feature test object. The notation indicates a circular feature on plane A. Engineering drawing of a circular feature test object completed with its dimensions values is shown in Fig. 9. Circular feature with angular interpolation cuts of a radius of about 50 mm.

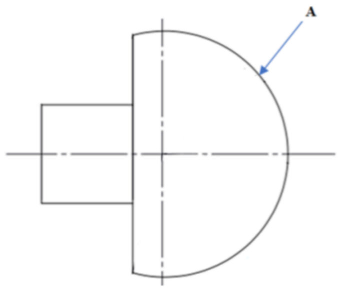

Fig. 8. The standard circular feature test object.

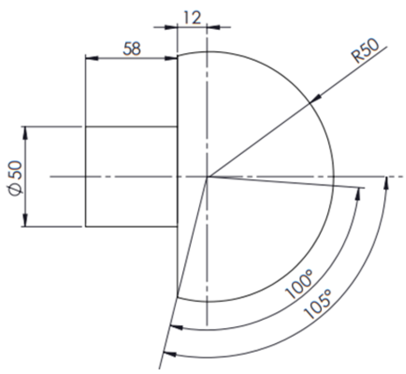

Fig. 9. Engineering drawing of a circular feature test object.

Fig. 10 shows the test object with a combination of 3 standard features. Table 5 shows the measurement features for each notation and the X and Z MCS coordinates for the 7 points. The engineering drawing of the test objects complete with dimension values is shown in Fig. 11. The workpiece specimen provides 12 positions that should be measured. It informs the measurement features of geometric error as 1) circular interpolation of radius A, 2) linear positional error on the Z axis for measuring positions at points B, C, and D, then linear positional error on the X axis for measurement positions at points E, F and G, and 3) squareness error between E & B plane, B & F plane, F & C plane, C & G plane, and G & D plane. Data coordinate from point A to point G has been determined with the reference from the MCS coordinates of the testing machine object.

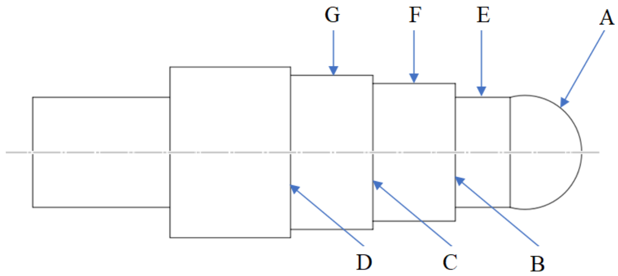

Fig. 10. The test object with a combination of 3 standard features

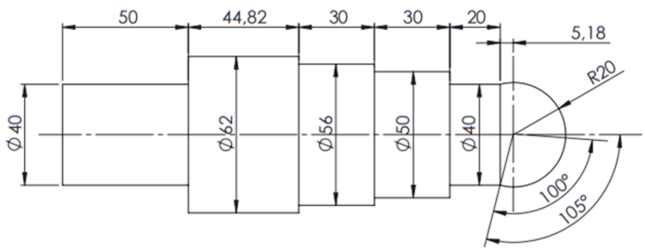

Fig. 11. The engineering drawing of combination of 3 standard features.

Table 5. The X and Z MCS coordinates for each point of the combination feature workpiece

Measurement feature	MCS coordinat	
	X	Z
Circular (radius A)	142.281	194.189
Linear positional Z axis (point B)	142.281	194.189
Linear positional Z axis (point C)	133.281	174.189
Linear positional Z axis (point D)	137.481	199.009
Linear positional X axis (point E)	147.281	269.009
Linear positional X axis (point F)	142.281	244.009
Linear positional X axis (point G)	139.281	214.009
Squareness between planes E & B		
Squareness between planes B & F		
Squareness between planes F & C		
Squareness between planes C & G		
Squareness between planes G & D		

Each test workpiece was made using aluminum material and cut by a carbide cutting tool material. The machining parameter values such as cutting velocity, workpiece rotation, and cutting motion speed are calculated according to the material properties of the workpiece and cutting tool [16]. The machining parameter values such as cutting velocity, workpiece rotation, and cutting motion speed are calculated according to the material properties of the workpiece and cutting tool. The stages of machining the workpiece was conducted through the roughing stages and finishing stages for obtaining good quality cutting results. Fig. 12 shows specimens of the cutting test result.

The Mitutoyo Coordinate Measuring Machine (CMM) was utilized to measure the machined workpiece specimens for each group of standard characteristics. The CMM has an accuracy level of 1 µm. Fig. 13 depicts the procedure employed for measuring the workpiece specimen utilizing the Coordinate Measuring Machine (CMM). The MCS coordinates of the functional point of cutting the workpiece serve as the measurement coordinates for each position of the specimen. Consequently, the sort of geometric error observed on the machined workpiece signifies the deviation in geometry of the testing machine tool.


Fig. 12. Specimens of the cutting test result.


Fig. 13. The measuring process of the workpiece specimen using the CMM.

The measuring results of each geometric error of the cylindrical feature test object are shown in Table 6. The mean value for each geometric error is obtained from the calculation of the mean geometric error of 5 test object specimens. The highest mean value of circularity error is about 55.2 µm which is at measurement point B. The highest mean value of squareness error is about 19.5 µm which is between the E and F plane.

Table 6. The measuring results of each geometric error of the cylindrical feature test object

Feature	Mean (µm)
Circularity (point A)	94
Circularity (point B)	55.2
Circularity (point C)	8
Circularity (point D)	37.4
Consistency of diameter (mean value of point A, B, C dan D)	27.5
Linear positional Z axis (point E)	5.6
Linear positional Z axis (point F)	6.2
Linear positional Z axis (point G)	7.2
Linear positional Z axis (point H)	3.8
Linear positional X axis (point A)	9.4
Linear positional X axis (point B)	55.2
Linear positional X axis (point C)	8
Linear positional X axis (point D)	37.4
Squareness between A & E plane	15.1
Squareness between B & F plane	19.5
Squareness between C & G plane	15.5
Squareness between D & H plane	18.6

The calculating results of the mean value of geometric error from 5 flatness feature specimens are shown in Table 7. The mean value of flatness errors is 25.7 µm, the linear positional errors of the X and Z axes are known about 18.3 µm and 25.7 µm, and the squareness error between planes A to B is 17.3 µm.

Table 7. The calculating results of the mean value of geometric error from 5 flatness feature specimens

Feature	Mean (µm)
Flatness (point A)	25.7
Linear positional X axis (diameter B)	18.3
Linear positional Z axis (point A)	25.7
Squareness error between plans A & B	37.3

The calculating results of the mean value of geometric error from 5 specimens of circular feature test objects are shown in Table 8. The mean value of circular geometric error is 37.7 µm.

Table 8. The calculating results of the mean value of geometric error

Feature	Mean (µm)
Nominal radius (circular error)	37.7

The calculation results of the mean value of geometric error from 5 specimens of the combined feature test specimens are shown in Table 9. Based on the calculation results in Table 9, it is known that the highest Z-axis mean linear positional error is 23.4 µm at point D and X-axis is 19.4 µm at point G, and the highest squareness error between the C & G plane is 30.6 µm.

Table 9. The calculation results of the mean value of geometric error from 5 specimens of the combined feature test specimens

Feature	Mean (µm)
Circularity (radius A)	8.6
Linear positional Z axis (point B)	10.3
Linear positional Z axis (point C)	13
Linear positional Z axis (point D)	23.4
Linear positional X axis (diameter E)	9.1
Linear positional X axis (diameter F)	18
Linear positional X axis (diameter G)	19.4
Squareness between planes E & B	17.6
Squareness between planes B & F	12.5
Squareness between planes F & C	27.6
Squareness between planes C & G	30.6
Squareness between planes G & D	27.4

CMM measurement results data are also analyzed for obtaining information on geometrics error parameters, such as repeatability estimator, accuracy, and repeatability. Eq. 1, Eq. 2, and Eq. 3 are used for calculating the repeatability estimator of unidirectional ($Si\uparrow$), unidirectional repeatability ($Ri\uparrow$), and unidirectional accuracy ($A\uparrow$). Its calculation is unidirectional because the cutting operation of the specimen test object in a single direction. $Xij\uparrow$ is deviation or each geometric error of the speciment test object. $xi\uparrow$ is the mean geometric error as shown in Tables 6, 7, 8, and 9 [17, 11, 12]. Its unidirectional repeatability and unidirectional accuracy obtained is the machine's ability to produce quality workpiece dimensions accurately and repeatably.

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

$$\mathrm{Ri}\uparrow = 4Si\uparrow \quad (2)$$

$$A\uparrow = \max.[Xi\uparrow + 2\mathrm{Si}\uparrow] - min.[Xi\uparrow - 2\mathrm{Si}\uparrow] \quad (3)$$

3 Results and Discussion

Assessment of geometric error status is obtained by comparing each item of workpiece geometry error measurement results to the standard tolerance values refer to ISO 10791-2, ISO 10791-4, and ISO 13041-4 [18][19][20]. Table 10, Table 11, Table 12, and Table 13 show the geometric error status from the workpieces cutting test results with cylindrical, flatness, circular features, and standard feature combinations. Table 10 shows the status of the geometry error of the cylindrical feature cutting test. There is an out of tolerance of linear positional error X axis on points B and D. Those are at MCS coordinate X147.281 is 55.2 µm, and X147.281 is 37.4 µm. And measurement positions on A, C, E, F, G, and H for linear positional errors on the X/Z axes and squareness errors between the X and Z axes of machine tools are indicated still in standard tolerance.

Table 10. The geometric error status of the cylindrical feature cutting test

Position	Feature	Error (µm)	Tolerance (µm)	Status
E	Linear positional error Z axis	5.6	10	Ok
A	Linear positional error X axis	9.4	10	Ok
A-E	Squareness	5.14	20	Ok
F	Linear positional error Z axis	6.28	10	Ok
B	Linear positional error X axis	55.2	10	Out of tolerance
B-F	Squareness	19.5	20	Ok
G	Linear positional error Z axis	7.2	10	Ok
C	Linear positional error X axis	8.0	10	Ok
C-G	Squareness	15.5	20	Ok
H	Linear positional error Z axis	3.8	10	Ok
D	Linear positional error X axis	37.4	10	Out of tolerance
D-H	Squareness	18.6	20	Ok

Table 11 shows the geometric error status from the results of the flatness feature specimen cutting test. Position measurements were made at the MCS coordinates position A(X142.281; Z194.281) and B (X133.281; Z174.189). Based on the comparing results between the mean value of geometric error and the standard tolerance value of ISO 13041-4, it is obtained an out-of-tolerance status of geometric error for 1) linear positional error on the X and Z axes, and 2) the squareness between planes the X and Z axes.

Tabel 11. The geometric error status from the results of the flatness feature specimen cutting test

Position	Feature	Error (µm)	Tolerance (µm)	Status
A	Linear positional error Z axis	25.6	10	Out of tolerance
B	Linear positional error X axis	18.3	10	Out of tolerance
A-B	Squareness	37.3	20	Out of tolerance

The geometric error status of the circular feature cutting test results is shown in Table 12. It is known that the circular interpolation geometry error value of 37.7 µm has exceeded the ISO 13041-4 tolerance range of 22 µm, therefore the circular interpolation deviation status is out of tolerance.

Tabel 12. The geometric error status of the circular feature cutting test

Position	Feature	Error (µm)	Tolerance (µm)	Status
A	Circular	37.7	22	Ok

Table 13 presents the geometric error status observed during the combined feature cutting test. The geometric error values of the measurement findings at positions A, B, C, D, E, F, and G were compared with reference to the ISO1304 tolerance standard. The existence of an out-of-tolerance geometric error state has been shown for both linear positional error and squareness error. An excessive deviation in linear positional inaccuracy along the X axis is observed at locations F and G, whereas a similar deviation is observed along the Z axis at places C and D. Additionally, the determination of the out-of-tolerance condition is also derived from the assessment of the squareness error between planes C and F, as well as planes D and G.

Tabel 13. The geometric error status from the combination feature cutting test

Position	Feature	Error (µm)	Tolerance (µm)	Status
A	Circular	8.62	22	Ok
B	Linear positional error Z axis	10.34	10	Out of tolerance
E	Linear positional X axis	9.08	10	Ok
B-E	Squareness	17.64	20	Ok
C	Linear positional Z axis	13.00	10	Out of tolerance
F	Linear positional X axis	18.04	10	Out of tolerance
C-F	Squareness	27.62	20	Out of tolerance
D	Linear positional Z axis	23.4	10	Out of tolerance
G	Linear positional X axis	19.38	10	Out of tolerance
D-G	Squareness	27.38	20	Out of tolerance

Based on the results of the geometry error assessment that were shown in Tables 6, 7, 8, 9,10, 11, 12, and 13. It can be concluded that out-of-tolerance geometric errors have been identified in linear positional error in several coordinates along the X and Z axes, and squareness error between planes on the X and Z axes. Fig. 14 shows the linear positional error data of the X-axis for five specimens of each feature product. The mean highest value of the X-axis linear positional error which is out of tolerance is 55.2 µm. Fig. 15 shows the linear positional error data of the Z-axis for five specimens of each feature product. The mean highest value of the Z-axis linear positional error which is out of tolerance is 25.6 µm.

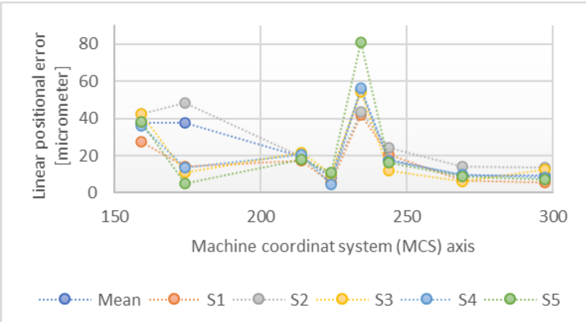

Fig. 14. The linear positional error data of X-axis for five specimens of each feature product.

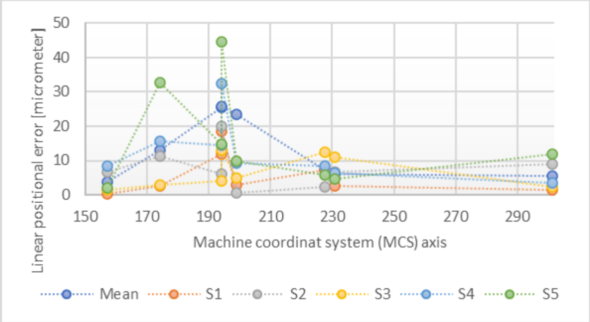

Fig. 15. The linear positional error data of Z-axis for five specimens of each feature product.

Analyzing CMM measurement results from data of specimen's test objects are estimated using Eq. 1, Eq. 2, and Eq. 3 for obtaining the information of geometric error on the X and Z axes. Table 14 shows the unidirectional repeatability (Ri↑), and unidirectional accuracy (A↑) of linear positional error of X and Z axes. The unidirectional repeatability of linear positional errors is 68.7 µm and 50.5 µm of the X and Z axes, 102 µm and 62.3 µm of the X and Z axes unidirectional accuracy.

Tabel 14. The shows the unidirectional repeatability and accuracy of linier positional error of X and Z axes

Parameter	X axis	Z axis
Unidirectional repeatability (Ri↑) [µm]	68.7	50.6
Unidirectional accuracy (A↑) [µm]	102	62.3

The CNC turning machine object is not feasible to use until its machine geometric errors are repaired. The machine geometric error should be improved by setting back the compensation error on machine controller parameters or replacing the axis mechanical component with a new one [21]. Hence the quality of the machining workpiece does not always exceed the standard tolerance.

4 Conclusion

The evaluation of geometric error on the CNC turning machine, with the testing object being the subject of analysis, has been successfully concluded. The study methodology involves conducting an evaluation under cutting load conditions. The assessment is performed indirectly, as the geometric error is derived from the geometric error observed on the machined workpiece during the cutting test. The assessment method employed involves conducting experimental cutting tests in accordance with ISO 13041-6:2009. These tests utilize standard workpiece shapes and specifications, including circularity features, flatness, circular features, and optionally, combination features.

According to the findings of this study, it is not advisable to utilize the CNC turning machine CTX310 ECO until the necessary repairs have been made to address its machine geometry flaws. The machine's identification as being in an out of tolerance state for geometric errors is based on the standards ISO 10791-2, ISO 10791-4, and ISO 13041-4. The geometric faults of the system manifest as linear positional mistakes in many coordinates along the X and Z axes, as well as squareness errors across the X and Z axes planes. The X-axis linear positional error exhibits a maximum value of 55.2 µm, while the Z-axis linear positional error has a maximum value of 25.6 µm. Additionally, the squareness error attains its peak value at 37.3 µm. The X and Z machine axes exhibit deviations from the specified tolerance levels in terms of unidirectional accuracy and unidirectional repeatability. This is evident from the recorded values of 102 µm and 62.3 µm for unidirectional accuracy in the X and Z axes, respectively, as well as the values of 68.7 µm and 50.6 µm for unidirectional repeatability in the X and Z axes, respectively.

In order to rectify the machine geometric error, it is vital to either adjust the compensation error within the machine controller parameters or substitute the axis mechanical component with a new one. This course of action is necessary to ensure that the quality of the machined workpiece consistently adheres to the prescribed tolerance standards.

References

[1] Z. Jiang, *Precision Machines*, 1st ed. Singapore: Springer Singapore, 2020.

[2] W. Tian, W. Gao, D. Zhang, and T. Huang, "A general approach for error modeling of machine tools," *Int. J. Mach. Tools Manuf.*, vol. 79, pp. 17–23, 2014, doi: 10.1016/j.ijmachtools.2014.01.003.

[3] G. W. Vogl, M. Calamari, S. Ye, and M. A. Donmez, "A Sensor-based Method for Diagnostics of Geometric Performance of Machine Tool Linear Axes," *Procedia Manuf.*, vol. 5, pp. 621–633, 2016, doi: 10.1016/j.promfg.2016.08.051.

[4] A. C. Okafor and Y. M. Ertekin, "Vertical machining center accuracy characterization using laser interferometer Part 1. Linear positional errors," *J. Mater. Process. Technol.*, vol. 105, no. 3, pp. 394–406, 2000, doi: 10.1016/S0924-0136(00)00661-0.

[5] H. B. Harja, F. Mohammad, and A. Fathan, "Evaluasi Kinerja Efisiensi Energi Mesin Bubut Melalui Penilaian Indikasi Specific Energy Consumption," *J. Tek. Energi Elektr. Tek. Telekomun. Tek. Elektron.*, vol. 9, no. 2, pp. 389–403, 2021, doi: http://dx.doi.org/10.26760/elkomika.v9i2.389 |.

[6] S. Ekinovic, E. Begovi, and E. Hekic, "Ballbar QC10 Measuring Device – Fast Experimental Check of Machine Tools Accuracy," *J. Trends Dev. Mach. Assoc. Technol.*, vol. 19, no. 1, pp. 29–32, 2015.

[7] M. Holub, F. Bradac, Z. Pokorny, and A. Jelinek, "Application of a ballbar fordiagnostics of CNC machine tools," *MM Sci. J.*, no. December, pp. 2601–2605, 2018, doi: 10.17973/MMSJ.2018_12_2018032.

[8] J. X. Chen, S. W. Lin, X. L. Zhou, and T. Q. Gu, "A ballbar test for measurement and identification the comprehensive error of tilt table," *Int. J. Mach. Tools Manuf.*, vol. 103, pp. 1–12, 2016, doi: 10.1016/j.ijmachtools.2015.12.002.

[9] W. Monika and M. Paweł, "Reproducibility of machine tools' circularity test according to ISO 230-4 with respect to testing position," *Arch. Mech. Technol. Mater.*, vol. 37, no. 1, pp. 22–26, 2017, doi: 10.1515/amtm-2017-0003.

[10] A. Winarno, S. Lasiyah, B. Tulung Prayoga, I. Aris Hendaryanto, and F. X. Sukidjo, "Development of Accuracy Evaluation Method for Open Loop Educational CNC Milling Machine," *J. Rekayasa Mesin*, vol. 12, no. 1, pp. 217–225, 2021, doi: 10.21776/ub.jrm.2021.012.01.23.

[11] H. B. Harja and A. Candra, "Assessment of Positional Error CNC Machine Tools using Laser Interferometer," in *Proceedings of the 4th International Conference on Applied Science and Technology on Engineering Science (iCAST-ES 2021)*, 2023, pp. 1352–1358, doi: 10.5220/0010965300003260.

[12] H. B. Harja, A. Nurbaniah, N. S. B. Muhadi, and A. Noviandi, "Straightness Geometric Error Assessment for CNC Milling Machine," *Key Eng. Mater.*, vol. 939, pp. 39–46, 2023, doi: 10.4028/p-a8n75m.

[13] E. Kurniawan, Syaifurrahman, and B. Jekky, "Pengujian Tingkat Akurasi dan Error Dimensi Hasil Produk Mesin CNC Lathe Mini Custom," *J. Rekayasa Mesin*, vol. 12, no. 3, pp. 747–756, 2021, doi: 10.7202/1082036ar.

[14] I. O. for Standardiz, *ISO 13041-6 : Test conditions for numerically controlled turning machines and turning centres*

– *Part 6 : Accuracy of a finished test piece.* Switzerland: International Organization for Standardization., 2009.

[15] R. J. Hocken and P. H. Pereira, *Coordinat Measuring Machines and Systems (Manufacturing Engineering and Materials Processing)*, 2nd ed. CRC Press LLC, 2017.

[16] M. Groover, *Fundamentals of Modern Manufacturing*, 5th ed. New Jersey: New Jersey: John Wiley & Sons, Inc, 2016.

[17] International Organization for Standardization, *ISO 230-2 Test code for machine tools- Part 2: Determination of accuracy and repeatability of positioning numerically controlled axes*, Third. Switzerland, 2006.

[18] International Organization for Standardization, *ISO 10791-2 : Test Coditions for Machining Centres - Part 2 : Geometric Tests for Machines with Vertical Spindle or Universal Heads with Vertical Rotary Axis (Vertical Z-Axis)*. Switzerland: International Organization for Standardization, 2001.

[19] International Organization for Standardization, *ISO 10791-4: Test Conditions for Machining Centres-Accuracy and Repeatability of Positioning of Linear and Rotary Axes*. Switzerland: International Organization for Standardization, 1998.

[20] *ISO 13041-4 : Test conditions for numerically controlled turning machines and turning centres – Part 4 : Accuracy and repeatability of positioning of linear and rotary axes.* Switzerland: International Organization for Standardization, 2004.

[21] R. Ramesh, M. A. Mannan, and A. N. Poo, "Error compensation in machine tools- a review. Part II: Thermal errors," *Int. J. Mach. Tools Manuf.*, vol. 40, no. 9, pp. 1257–1284, 2000, doi: 10.1016/S0890-6955(00)00010-9.