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Three axis deviation analysis of CNC milling machine

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Abstract

The manufacturing technology has developed rapidly, especially those intended to improve the precision. Consequently, increasing precision requires greater technical capabilities in the field of measurement. A prototype of a 3-axis CNC milling machine has been designed and developed in the Research Centre for Electrical Power and Mechatronics, Indonesian Institute of Sciences (RCEPM-LIPI). The CNC milling machine is driven by a 0.4 kW servo motor with a spindle rotation of 12,000 rpm. This study aims to measure the precision of the CNC milling machine by carrying out the measurement process. It is expected that the CNC milling machine will be able to perform in an optimum precision during the manufacturing process. Accuracy level testing is done by measuring the deviations on the three axes namely X-axis, Y-axis, and Z-axis, as well as the flatness using a dial indicator and parallel plates. The measurement results show the deviation on the X-axis by 0.033 mm, the Y-axis by 0.102 mm, the Z-axis by 0.063 mm, and the flatness of the table by 0.096 mm, respectively. It is confirmed that the deviation value is within the tolerance standard limits set by ISO 2768 standard. However, the calibration is required for this CNC milling machine to achieve more accurate precision. Furthermore, the design improvement of CNC milling machine and the application of information technology in accordance with Industry 4.0 concept will enhance the precision and reliability.

Keywords: precision measurement; orthogonal axes; manufacturing machine; automation industry.

I. Introduction

Since the beginning of the industrial revolution, there has been a dramatic increase in manufacturing quality and quantity by the application of industrial mechanization, from steam powered machines to modern days automation [1]. Today, there is greater demand for higher quality and quantity products and services which consequently requires manufacturing complexity and better quality of machining which makes industrial equipment construction more complicated [2]. In developed countries, the slowing down of population growth and ageing population cause shortage in manpower for the industry. Other common problems nowadays are the depleting natural resources and shortening product life cycle [3]. All those problems are tried to be overcome by implementing the state of the art technologies in the form of Internet of Things (IoT) and Cyber-Physical System (CPS) [1][4]. Germany is the country which introduced the concept of Industry 4.0, a concept as an embodiment of those new technologies [1]. Together with Japan, Germany has been the leading country in developing manufacturing equipment such as computer numerical control (CNC) machine [5]. The concept will make the future industry more agile and flexible to meet a quickly and constantly changing market demands [6]. From the first introduction in 2011, the concept of Industry 4.0 has been gradually studied, developed and implemented not only in Europe but worldwide. The Indonesian Ministry of Industry introduced a concept of Making Indonesia 4.0 in 2019 [7]. One emphasize of Making Indonesia 4.0 is greater automation in manufacturing technology to increase competitiveness.

Recently, the development and application of manufacturing industry technology in Indonesia have been rapidly increasing, as evidenced by the increasingly modern equipment used to work on a product, such as a CNC machine which is a machine that has been equipped with a computer to facilitate the operation of the machine [8][9]. In a few examples, computer technology has been applied to machine

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tools including lathes, milling machines, scrap machines, and drilling machines [9][10]. The operation of the CNC machine uses a program that is controlled directly by a computer [10]. Hence, the operation of CNC machine tools works by synchronizing the computer and its mechanics [9].

Nowadays many industries have begun to abandon conventional machine tools and switch to using CNC machine tools. Quality and productivity aspects are the basic reasons computer-based production machines are widely adopted in the manufacturing industry [11]. Several attributes expected from modern CNC machine include better product quality produced in higher quantity with high speed and precision [12]. The process of synchronizing movements on the axis of motion requires an interpolator system that specifically divides the movements of each axis based on global movement commands which are manifested in the form of motion command signals to the drive system [13][14]. As technology develops, the CNC milling machine conditions must be measured to have reliable performance [14][15]. Afkhamifar *et al.* conducted research on the analysis of variations for the CNC milling process with results were compared with ISO 2768, a guidelines for general geometrical tolerances and technical drawings [16]. The study underlined that the precision of the machine can be improved either by better machine design or software development.

The quality of the results of machining processes is quantified by machining performance index which includes milling accuracy and surface quality [12]. The index is affected by the integrated operations of various factors namely CAD/CAM, CNC controller, servo control, feed drive system, and mechanical bodies [12]. Another possible effector which often neglected is probe hysteresis [17] and the subsequent deformation [18]. Improving machining precision has been a widely known challenge in industry as the CNC machine is composed of various moving and rotating shafts that makes machining motion complicated [19]. With regard to milling accuracy, the vibration of the mechanical bodies, sliding motion of stick, and axial motion affect precision [12]. To solve the vibration problem, a real-time resonance signal analysis coupled with online surface quality monitoring has been proposed [20]. Another study suggested kinematic modelling as a method to improve the precision of a multi axis CNC machine [19]. Analyzing the complex CNC machine motion has been one of the most important subjects in industrial machining study [19]. Thus, when the researchers at the Research Centre for Electrical Power and Mechatronics, Indonesian Institute of Sciences (RCEPM-LIPI) developed a CNC milling machine, it is important to analyze the machine motion to measure its precision.

In a previous study, Zaynawi and Bisono calibrated the X, Y, and Z-axis of the wood CNC router machine using a dial indicator and block gauge [8]. In another study, Wijaya performed calibration of the Y-axis to the accuracy of the workpiece on a 3-Axis CNC Router Machine [21]. With regard to the Z-axis, Nayorama, and Sedyono conducted a Z-axis analysis on the calibration process and the movement of the CNC router machine [22]. Fauzi *et al.* suggested that it is necessary to carry out measurements and analysis of data in every laboratory activity to make a conclusion [23]. Therefore the analysis of measurement uncertainty becomes very important [22][24].

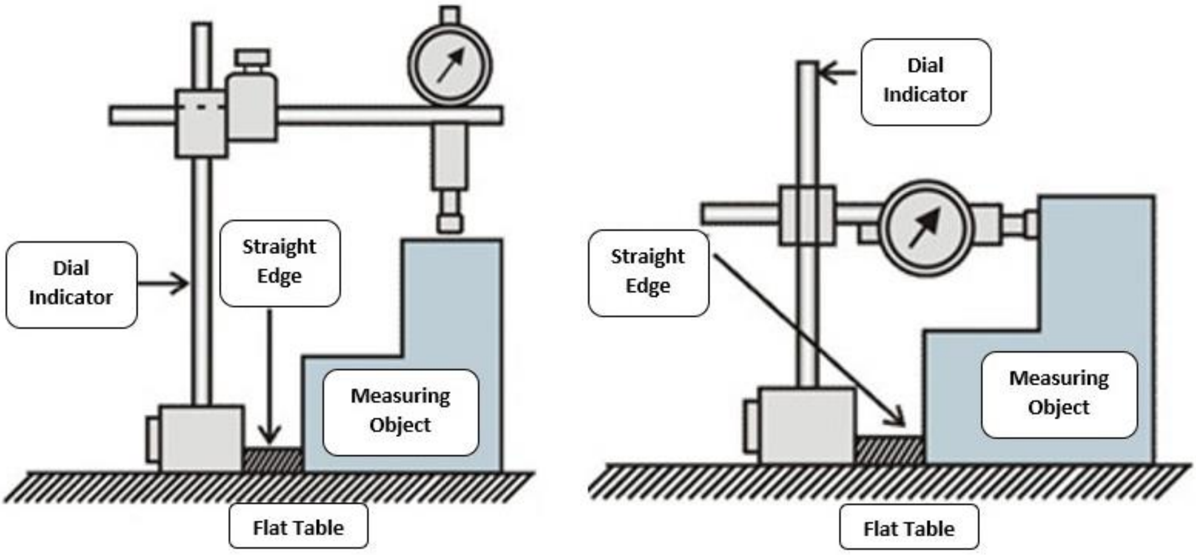
From the above-mentioned previous studies, we found out that the respective researchers calibrated the machine that has been calibrated by the manufacturer, whereas in this study, the measurement was performed on a self-designed CNC milling machine developed at RCEPM-LIPI. The objective of this study was to investigate the precision of the CNC milling machine developed at RCEPM-LIPI by measuring how much the deviation of the machine measurement on the X, Y, and Z-axes. The measurement of machining deviation is important in analyzing machine accuracy [25]. The results of this study will serve as the basis for the next process which is calibration, and it is expected that the CNC machine will be able to operate in optimum precision during the manufacturing process.

II. Materials and Methods

A. Straightness checking

Several predictive methods for CNC milling machine maintenance to improve reliability and prevent faults and unnecessary loss have been introduced [26]. The methods include reliability statistics method, physical model-based method, and data-driven method. Reliability statistics method is the simplest method without any mathematical model or detailed information as the method depends on historical deviation data. The physical model-based method uses a mathematical model to predict the internal working mechanism through degradation prediction. The data-driven method is the most complicated method which can be performed online. The method is very suitable for complex and expensive equipment manufacturing such as in the aircraft industry. The CNC milling machine developed in RCEPM-LIPI is a simple machine intended for an inexpensive and easy operation in small and medium enterprises. Therefore the reliability statistics method was considered the most appropriate to assess its precision.

The workpiece surface is said to be flat or straight if the results of the measurement of the plane on the surface are straight lines in three-dimensional space as measured by the tangential contact between the tool and the workpiece surface [27]. This means that there are no deviations both horizontally and vertically on the measurement results for a certain distance. Straightness of the component surface is very important in machining such as lathes, scrap machines, milling machines, and grinding machines due to the work system requires a very precise level of straightness [28]. The skills to make the surface of the workpiece completely straight are also necessary, including how to check the straightness itself [24]. In order to measure the straightness/flatness, a straightness check of the X, Y, and Z-axis, as well as



(a) (b)

Figure 1. Straightness checking in (a) the horizontal deviation direction and (b) the vertical deviation direction

levelling checks of the machine table is performed by using a dial indicator, parallel plates, and a flat table [29].

The straightness/flatness check on the machine with a dial indicator was performed to understand the magnitude of the deviation. Any changes in the distance experienced by the dial indicator sensor will be designated by the pointer. In order to achieve accurate results, the measurements must be conducted on a flat working table [29]. It is necessary to insert a parallel plate/straight edge between the measuring plane and the dial indicator base to stabilize the dial indicator movement so that a change in the position of the sensor pressure on the measuring plane can be avoided. When placing the sensor on the measuring plane, the pointer should be set to zero. If the measuring plane is relatively long, it should be divided into several sections with the magnitude of the distance of each part being determined in advance. Between one part with another is marked by a dot or short line/strip. At each of these points, it can be described the magnitude of the deviation from the alignment of the measuring plane. Thus it can be known which parts of the measuring plane are not straight. The examples of straightness checks are shown in Figure 1. The direction of the horizontal deviation is shown in Figure 1 (a) and the direction of the vertical deviation is shown in Figure 1 (b). Figure 2 describes the deviation in the orthogonal axes, namely X-axis (X), Y-axis (Y), and Z-axis (Z). The deviation is defined as the distance between the nominal point (Pn) to the measurement point (Pm).

Measurement results and magnitude of deviations are usually illustrated in graphical form with a sign (+) for positive deviations or (-) for negative deviations. Deviations marked positive or negative are based on allowed threshold values. If the inspection result turns out to exceed the allowed threshold values, it can be said that the level of straightness of the measuring object is not good or low, regardless of whether the deviation is positive or

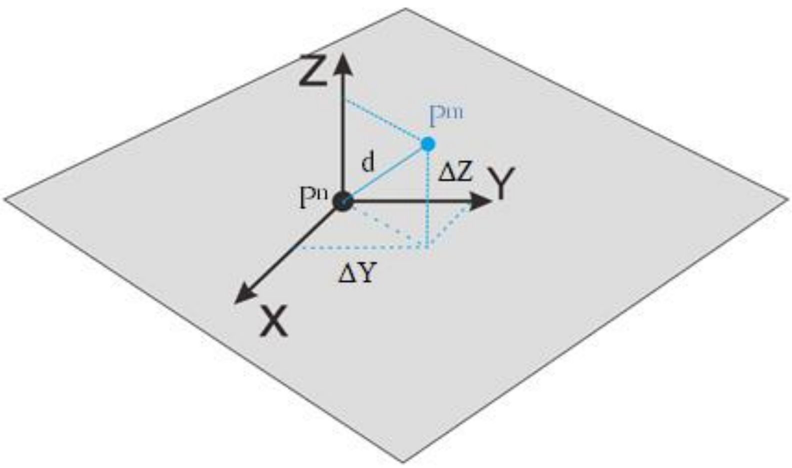


Figure 2. CNC milling machine deviation in the three axis (adapted from Werner, 2018 [25])

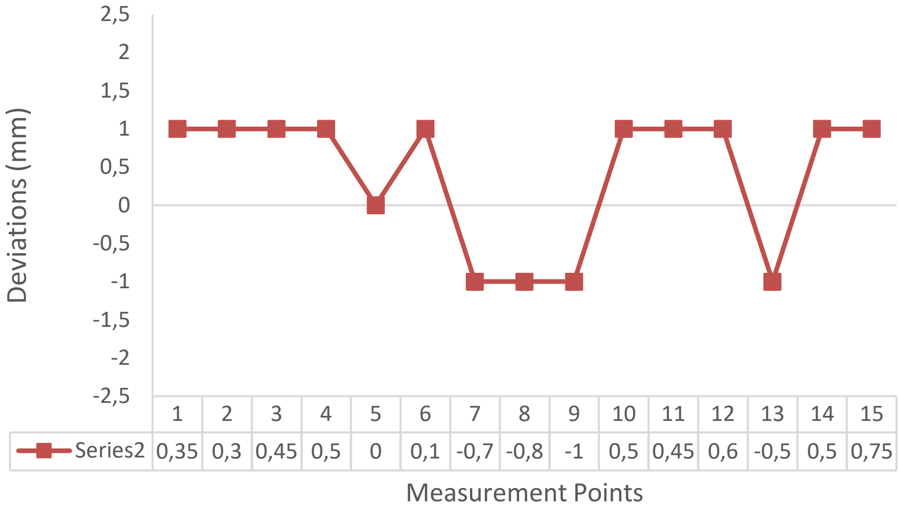


Figure 3. The results of the surface straightness check of the measurement object using the dial indicator

negative. An example of the results of the straightness checks in the form of a line graph is illustrated in Figure 3.

The above method is suitable for examining the relatively narrow side of the measuring plane and its longitudinal direction (the thick side of the measurement object). If the measuring plane is wide enough in the extended direction then the straightness check can be carried out several times in different positions according to more favourable considerations in the measurement process. Therefore, the examination is not only on one line but can be more than one line [23].

B. Object specifications, instruments, and measurement methods

The measurement object is a prototype 3-axis CNC milling machine developed by RCEPM-LIPI (Figure 4). This CNC milling machine has the following specifications:

- Maximum spindle speed = 12,000 rpm.
- Stroke of the X-axis = 180 mm, Y-axis = 160 mm and Z-axis = 200 mm.
- Servo motor power used for X, Y, and Z axes = 400 W.
- The maximum diameter of the chisel can be used on a spindle = 6 mm.
- Maximum workpiece material = aluminium.

While the equipment used in this measurement process is as follows:

- Parallel Plates or flat part of the machine on the horizontal and vertical sides.
- Clamping.
- Dial Indicator with a level of accuracy of 0.05 mm.

Dial indicator or dial gauge is used to measure bending, run out, slackness, end play, backlash, and flatness. Inside the dial indicator, there is a mechanism that can magnify the small movements. When the spindle moves along the measured surface, the movement is enlarged by a magnifying mechanism and indicated by the pointer. The procedure for using the dial indicator is as follows:

- The spindle dial indicator position must be perpendicular to the measured surface.
- The line of imagination from the measuring eye to the pointer must be perpendicular to the dial indicator surface while reading the measurement results.
- The dial indicator must be installed carefully mounted on the supporting rod, meaning that the dial indicator must not shake.
- Turn the outer ring and set it to zero. Move the spindle up and down, then check that the pointer always returns to zero after the spindle is released.
- Observe and record the changes that occur in the indicator dial pointer for each measurement point, which is every 15 mm.

Figure 4. The prototype of 3-axis CNC milling machine developed at RCEPM-LIPI

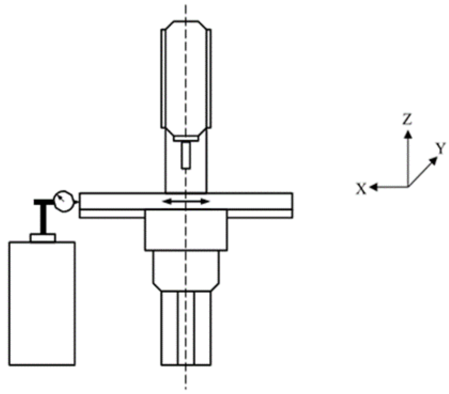


Figure 5. The deviation measurement scheme on the X-axis [10]

If the measurement has been completed up to 13 times or the last point, then return the dial indicator position to its original position by moving in the direction of the X-axis, Y-axis, or Z-axis being measured.

III. Results and Discussions

A. X-axis measurements

The measurement process on the CNC milling machine designed and developed at RCEPM-LIPI was carried out on its three axes, namely the X, Y, and Z axes. The data collection scheme on the X-axis is shown in Figure 5. X-axis measurement was carried out 3 times where each process was performed by measuring 12 measurement points. The X-axis measurement results are displayed in tabular and graphical form as shown in Table 1 and Figure 6. Table 1 and Figure 6 show that the maximum deviation on the X axis is -0.183 mm at the second test point. The smallest deviation is at the testing points 1 and 9 that are -0,017 mm. The average deviation is -0,033 mm. The minus sign means the measured area is away from the indicator needle while the positive sign means the measured field is close to the indicator needle.

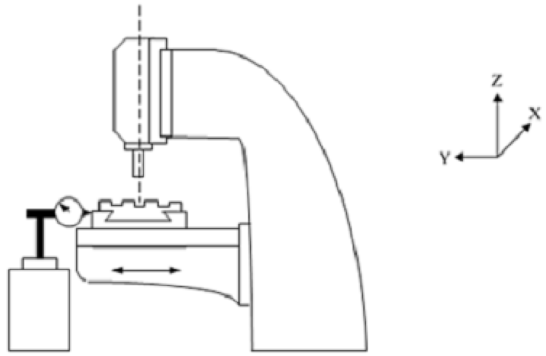


Figure 7. The deviation measurement scheme on the Y-axis [10]

Compared with previous studies, the results in this study were lower than a study by Afkhamifar *et al.* whose X-axis position error was 0.134 mm at average value [16] and within the range of acceptable deviation which a reference suggested between -0.030 mm to +0.045 mm [25]. However compared to the higher precision of CNC machine with laser measurement system, the average deviation is higher [24].

B. Y-axis measurements

The process of measuring a CNC milling machine using the indicator dial on the Y-axis is illustrated in Figure 7. Y-axis measurement was carried out 3 times where each measurement was performed on 10 points. Y-axis measurement results are shown in Table 2 and Figure 8. As described in Table 2 and Figure 8, the maximum deviation on the Y axis is -0,300 mm at the fourth test point. The smallest deviation is at the second test point of -0,033 mm. The average deviation is -0,102 mm. The minus sign means the measured area is away from the indicator needle, while the positive sign means the measured field is close to the indicator needle. The deviation in Y-axis is greater than the previous studies which reported an average deviation on Y-axis is 0.056 mm [16].

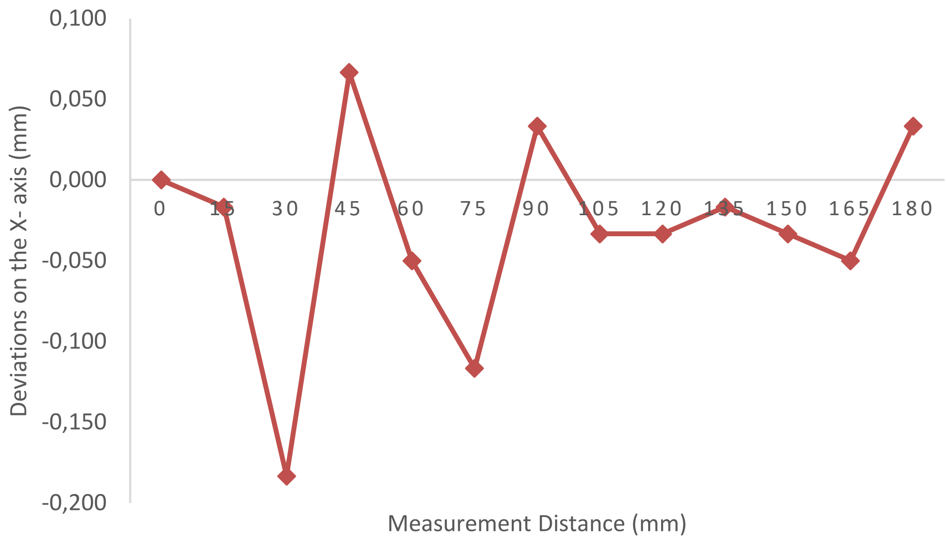


Figure 6. X-axis deviation graph

Table 1.
X-axis measurements results

NO	Measurement Distance (mm)	Deviations (mm) 1	2	3	Average Deviation (mm)
	0	0,00	0,00	0,00	0,000
1	15	-0,15	0,20	-0,10	-0,017
2	30	-0,30	-0,15	-0,10	-0,183
3	45	0,25	0,15	-0,20	0,067
4	60	-0,15	0,10	-0,10	-0,050
5	75	-0,10	-0,15	-0,10	-0,117
6	90	-0,15	0,10	0,15	0,033
7	105	0,10	-0,10	-0,10	-0,033
8	120	-0,10	0,15	-0,15	-0,033
9	135	-0,15	0,20	-0,10	-0,017
10	150	-0,20	0,20	-0,10	-0,033
11	165	-0,15	-0,15	0,15	-0,050
12	180	0,10	0,10	-0,10	0,033
Average					**-0,033**

Table 2.
Y-axis measurements results

NO	Measurement Distance (mm)	Deviations (mm) 1	2	3	Average Deviation (mm)
	0	0,00	0,00	0,00	0,000
1	15	-0,20	0,40	-0,30	-0,033
2	30	-0,20	-0,10	-0,25	-0,183
3	45	0,20	0,15	-0,15	0,067
4	60	-0,25	-0,25	-0,40	-0,300
5	75	-0,15	-0,25	-0,25	-0,217
6	90	-0,35	0,25	0,25	0,050
7	105	0,20	-0,25	-0,15	-0,067
8	120	-0,15	0,15	-0,35	-0,117
9	135	-0,35	0,20	-0,25	-0,133
10	150	-0,25	0,20	-0,20	-0,083
Average					**-0,102**

C. Z-axis measurements

The measurement scheme of the CNC milling machine on the Z-axis is illustrated in Figure 9. The measurements on the Z-axis were carried out 3 times wherein each process measurements were made of 10 points. The Z-axis measurement results are shown in Table 3 and Figure 10.

Table 3 and Figure 10 present the measurement results of the deviation on the Z-axis. The maximum deviation on the Z-axis is -0.233 mm at the sixth point test. The smallest deviation is at the ninth test point which is equal to 0 mm. The average deviation is -0,063 mm. A minus sign means the measured area is away from the indicator needle, while the positive sign means the measured field is close to the indicator needle. The average deviation of the Z-axis is larger than the previous study which resulted in a deviation on the Z-axis of -0.021 mm [16], and much larger than the previous study using laser measuring system whose largest deviation on the Z-axis is only 0.004 mm [24].

D. Flatness of the machine base table

In addition to measuring the straightness of the three working axes of the CNC milling machine designed at RCEPM-LIPI, a measurement process was also carried out on the flat table base of the machine. The scheme that shows data collection from the measurement of the flatness of the machine table is depicted in Figure 11. The measurement of the machine table flatness was also carried out 3 times with each process measuring 10 points. The CNC milling machine table measurement results are shown in Table 4 and Figure 12.

Table 4 and Figure 12 show that the maximum deviation on the X axis is -0.217 mm at the eleventh point test of 165 mm measurement distance. The smallest deviation is at the third test point at a measurement distance of 45 mm which is equal to 0.033 mm. The average deviation is -0.096 mm. A minus sign means the measured area is away from the indicator needle, while the positive sign means the measured field is close to the indicator needle.

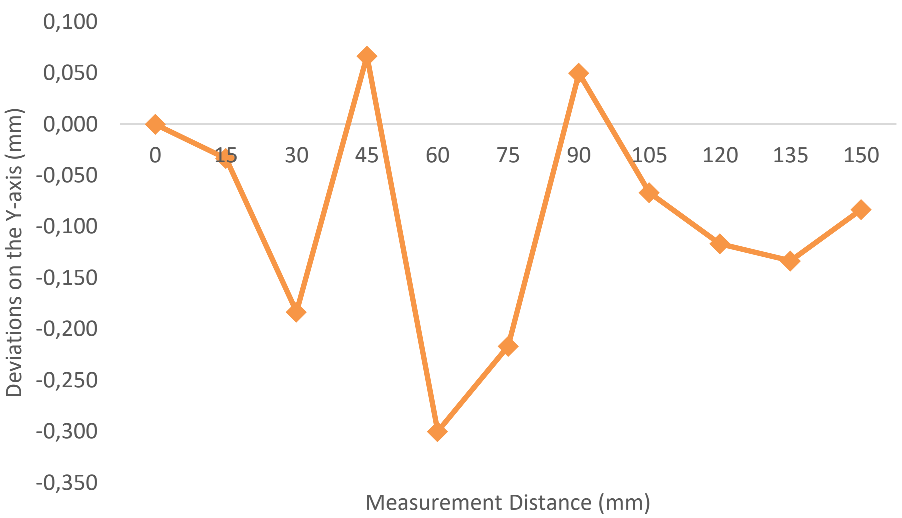


Figure 8. Y-axis deviation graph

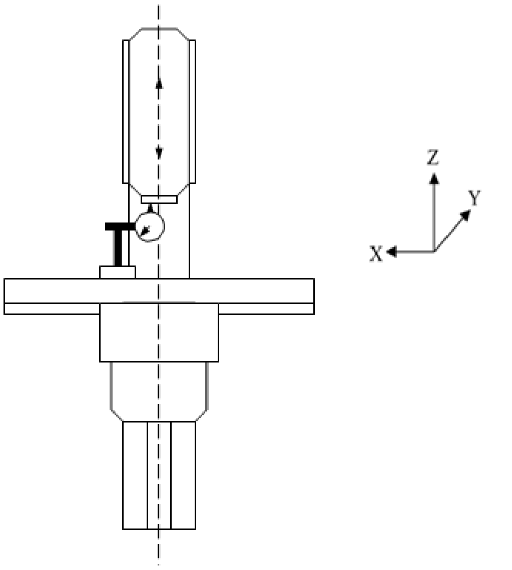


Figure 9. The deviation measurement scheme on the Z-axis [10]

Figure 11. Test scheme on the machine table

From the X, Y, Z, and flatness measurements, it is known that the deviation values: the average X axis deviation is -0.033 mm, Y -0.102 mm axis, Z -0,063 mm, and -0.096 mm flatness, respectively. The value of the deviation is still within the limits of the tolerance standard set at ISO 2768. These results are almost the same compared to previous studies conducted by Afkhamifar *et al.* where in his research it was found that the results of the X, Y, and Z axis deviations were 0.134 mm, 0.056 mm, and -0.021 mm, respectively [16].

While the results are acceptable based on ISO 2768 standard, the deviation at Y-axis and Z-axis are relatively greater than the comparable previous study which indicates an improvement for the developed CNC milling machine is necessary. There are several possible causes which resulted in inaccuracies in this study as suggested by the previous study [16]. The first possibility comes from the machine table which plays a role as a base. The second possibility comes from the upper body of the machine. The third possibility comes from the head and the last possibility comes from the interaction between the base and the workpiece. These shortcomings require a better machine design as suggested by the previous study [16]. Other solutions include a better software implementation [16][29], more complex yet reliable mathematical modelling [30], or more precise sensors such as real-time vibration monitoring [20], transducer in a kinematic probe [17], or laser measurement systems [24]. Furthermore, as a technology driven product research, the design and development phase of CNC milling machine often overlook the interdisciplinary approach, especially from industrial and human factors studies [31]. The machine design without consideration of the human factors often leads to human error and operation faults in addition to the limited technical performance of machine technology.

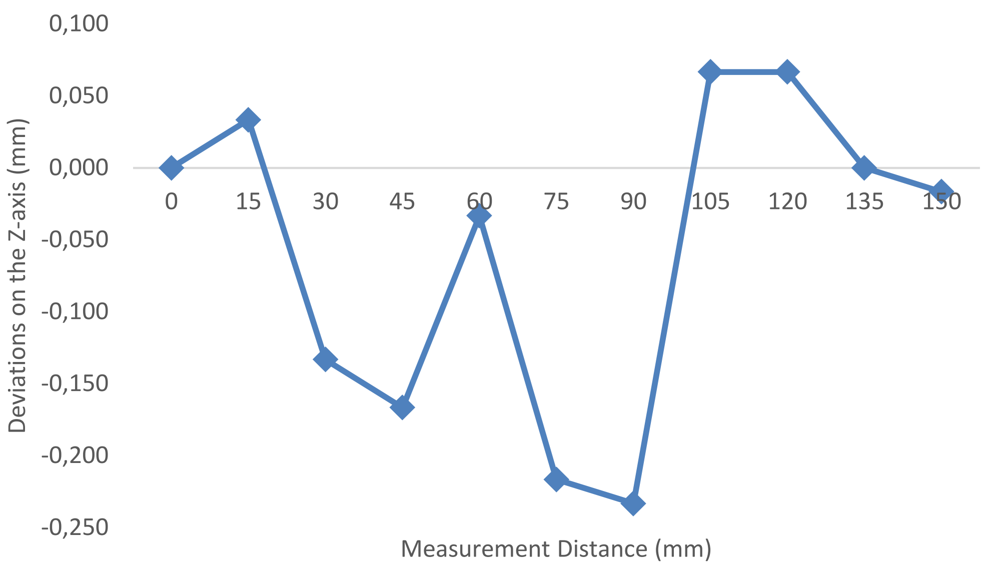


Figure 10. Z-axis deviation graph

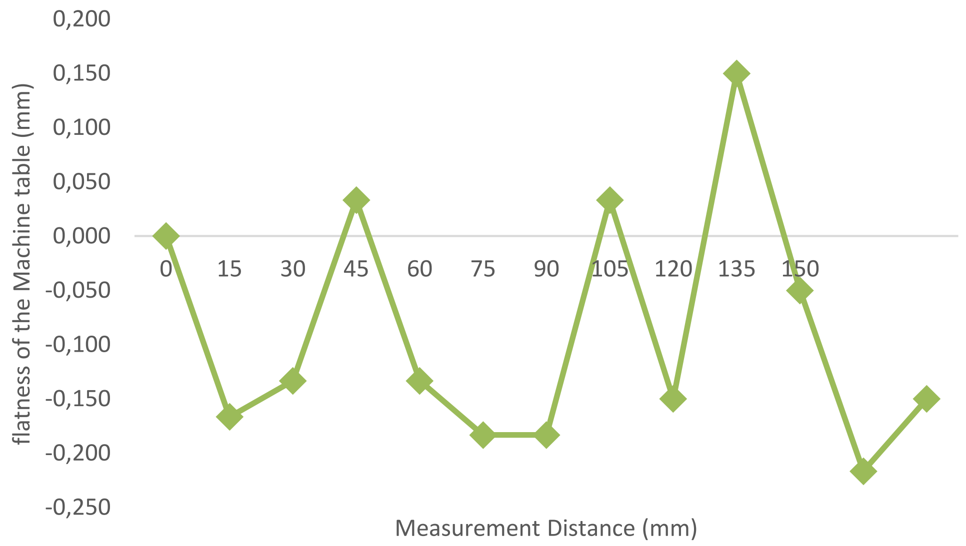


Figure 12. Machine table flatness deviation graph

Table 3.
Z-axis measurements results

NO	Measurement Distance (mm)	Deviations (mm)			Average Deviation (mm)
		1	2	3	
	0	0,00	0,00	0,00	0,000
1	20	0,15	-0,15	0,10	0,033
2	40	-0,10	-0,10	-0,20	-0,133
3	60	-0,15	-0,15	-0,20	-0,167
4	80	0,25	-0,15	-0,20	-0,033
5	100	-0,15	-0,25	-0,25	-0,217
6	120	-0,20	-0,25	-0,25	-0,233
7	140	-0,15	0,15	0,20	0,067
8	160	0,15	-0,15	0,20	0,067
9	180	0,10	0,15	-0,25	0,000
10	200	-0,15	0,25	-0,15	-0,017
Average					**-0,063**

Table 4.
Machine table flatness measurement results

NO	Measurement Distance (mm)	Deviations (mm)			Average Deviation (mm)
		1	2	3	
	0	0,00	0,00	0,00	0,000
1	20	0,15	-0,15	0,10	0,033
2	40	-0,10	-0,10	-0,20	-0,133
3	60	-0,15	-0,15	-0,20	-0,167
4	80	0,25	-0,15	-0,20	-0,033
5	100	-0,15	-0,25	-0,25	-0,217
6	120	-0,20	-0,25	-0,25	-0,233
7	140	-0,15	0,15	0,20	0,067
8	160	0,15	-0,15	0,20	0,067
9	180	0,10	0,15	-0,25	0,000
10	200	-0,15	0,25	-0,15	-0,017
Average					**-0,063**

IV. Conclusion

The measurement results of the CNC Milling machine developed at RCEPM-LIPI in Bandung show that the CNC milling machines have deviations on each axis, including the X-axis of 0.033 mm, the Y-axis of 0.102 mm, the Z-axis of 0.063 mm, and flatness of the table 0.096 mm, respectively. The results are within the acceptable performance limits required by ISO 2768. Based on these measurements, this CNC milling machine can be used for machining work processes that can move together on 3 axes namely X, Y, and Z axes where the machine can be used to make components that have tolerances above 0.1 mm. However, future manufacturing needs may require higher precision and the developed CNC milling machine still has quite high inaccuracy compared to some previous studies. The application of Industry 4.0 concept as well as more sophisticated sensors, mathematical modelling, data processing, and software are necessary for future study.

Declarations

Author contribution

All authors contributed equally as the main contributor of this paper. All authors read and approved the final paper.

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Conflict of interest

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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