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Identification of Machine Tool Defects Using Laser Interferometer

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The geometric accuracy of a machine is primarily determined by the accuracy of assembly, manufacturing, and overall setup. Standardized procedures for assessing geometric accuracy are established and detailed in delivery protocols for various types of machine tools. To effectively monitor and analyze machine tools errors, the most suitable approach is to construct a comprehensive error balance that accounts for the overall performance of the machine. This error balance methodology, a tool within the realm of system analysis, is utilized for predicting and managing systemic errors. The errors observed in machined components are intimately connected to the errors present in the machine tools themselves. These errors are further intertwined with the design and physical properties of individual machine components, as well as their interactions. In the case of multi-axis machines, they collectively determine the overall accuracy of the produced components. The objective of this study is to analyze machine tools errors using the Renishaw XL-80 laser interferometric system. The findings of this study reveal that errors in machine tools can also be the result of the dynamics of the cutting process, which may have a significant impact on accuracy.

Keywords: Diagnostics, Machine tools, Laser Interferometry, Machine tools Errors

1 Introduction

Currently, manufacturing companies face various challenges related to accuracy and production efficiency. These attributes are subjected to rigorous demands and criteria, placing significant emphasis on the regular and efficient maintenance of production equipment and machinery. However, the planning and execution of machine diagnostics can prove to be formidable tasks, particularly in scenarios where continuous operation of machining equipment is required. Modern machines and systems allow for ongoing monitoring of pivotal machine parameters, encompassing speed, vibrations, load, and temperature. To derive maximum utility from the data acquired through diagnostic devices, it becomes imperative to accurately pinpoint and comprehend specific machine defects. Therefore, it is crucial to analyse errors that affect the accuracy of machine tools and explore the possibilities for their identification and elimination [1,2,3,4].

In the realm of metrology, accuracy, as defined by the International Vocabulary of Metrology (VIM), signifies the closeness of agreement between a measured value and a reference value of a measurand. In the context of machine tools, accuracy can be defined as the maximum error in displacement or rotation between any two points within the operational space of the machine. Repeatability, or accuracy, is defined as the proximity of agreement among sequential measurements of the same quantity or the outcomes of a specific operation, such as axis movement, performed under identical conditions. In the context of machine tools, this concept can be understood as the error observed during multiple repeated attempts to position the machine in the same location under identical predefined conditions [5,6,7].

Various measurement instruments, including the laser interferometer, are employed to measure diverse accuracy criteria. Laser interferometry is predominantly tailored for gauging and diagnosing CNC machine tools [8,9,10,11]. The essence of laser interferometry revolves around the evaluation of equipment based on optical interference principles. In practical terms, interferometric measurement devices function based on a fundamental principle: one of the linear mirrors is affixed to the beam splitter, while the other is situated on either a mobile table or the spindle of the machine. The actual measurement process involves detecting differences between the light emanating from these two returning beams [12,13,14,15,16].

Lin et al. employ a novel method involving Legendre polynomials to predict geometric errors in CNC machine tools. Within their study, they used the XL-80 laser interferometer to measure the geometric errors of the machine tools. It is important to note that each measurement is subject to random errors, which are influenced by the accuracy of polynomial fitting. Notably, Legendre polynomials offer greater accuracy and provide a closer approximation to the actual machine tool errors [17]. On the other hand, Zha et al. introduce a measurement and compensation strategy for addressing volumetric errors. Within their study, they investigate the calibration methods utilized by laser tracers and subsequently verify geometric errors using a laser interferometer. The measurement results demonstrate a significant reduction in volumetric errors post-compensation, thereby underscoring the effectiveness and accuracy of the proposed error compensation strategy [18,19,20].

The article focuses on the significance of monitoring machine tools. In this experiment, the XL-80 laser interferometric system is employed to measure positional deviations in compliance with ISO 230-2 standards. The research aims to analyze the manifestation of errors in the output data obtained from this test, evaluate their impact on machine accuracy, and clarify the potential for their correction or elimination.

2 Methodology

The aim of the experiment is to perform a diagnostic evaluation of the positioning accuracy of machine tools and to analyze the associated errors. This diagnostic was performed on a machine tool classified as a three-axis machining centre. The differences between the positioning accuracy evaluations were attributed to differences in the age of the experiments and the characteristic technical parameters. The measurements were carried out using equipment in accordance with ISO 230-2 standards, which specify methods for evaluating the accuracy and repeatability of positioning of numerically controlled axes during direct measurements of individual machine axes.

The tested machine can be defined as an older three-axis machining centre. Diagnostic assessments for this machine were conducted on three occasions, following regular annual intervals, in accordance with the machine operator maintenance schedule. At the time of the initial measurement, the machine had been in operation for 18 years. Throughout the machine diagnostics process, adjustments to its correction map were possible, resulting in three distinct measurement phases. The first measurement, evaluating positioning accuracy, was carried out with the machine in its original state, using the original correction map. Subsequently, the previously recorded compensations in the correction map of the machine were reset, and another measurement was executed. Prior to the final measurement, a new correction map was introduced into the control system of the machine, generated based on data from prior measurements, and its verification was undertaken. Table 1 provides details on the selected parameters of the diagnosed machining centre.

Tab. 1 *Diagnosed center parameters*

Machine Parameters	Parameter Value
Movement in X/Y/Z Axis	762/460/460 mm
Clamping Surface Size	1000 x 460 mm
Max Table Load	700kg
Spindle-to-Table Distance	150 – 610 mm
Rapid Traverse in X/Y/Z	40/40/32 m.min^{-1}
Maximum Working Feed	32 m.min^{-1}
Accuracy	5μ

To determine the linear positional deviation in the individual axes of the machine, we used the Renishaw XL-80 laser interferometric system. The fundamental principle of laser interferometry is based on optical interference. The laser beam, emitted from the laser source (or laser head), is guided into a beam splitter, which bifurcates it into two distinct beams. One of these beams, termed the reference beam, is directed towards the reference optics (mirror) affixed to the beam splitter, while the other, referred to as the measurement beam, traverses the beam splitter and reaches the mobile optics (mirror). Subsequently, both beams are reflected from their respective mirrors to the beam splitter, where they converge and are then redirected into the laser head or detector.

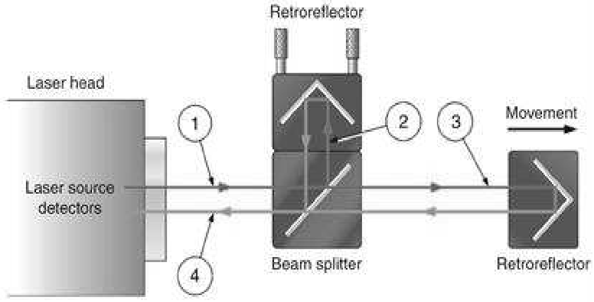

Fig. 1 *Principle of Laser Interferometry [21]*

The measurement process began with the assembly of a stand equipped with an adjustable table, onto which the XL-80 measuring laser head was mounted. This stand facilitated the rough positioning of the working area height. To ensure the laser head was horizontally aligned, a circular level (Fig. 2) was employed, and precise adjustments were made by extending or retracting the telescopic legs of the stand, followed by fine-tuning through the use of the table positioning screws.

Fig. 2 *Alignment of the laser head using a circular level*

A power cable and a communication cable were then connected to the laser head to link it to the computer.. Subsequently, the measuring instrument was powered on, allowed to warm up, and stabilized. Before commencing the measurements, it was imperative to initialize the respective machine and ensure that the machine being measured attained its operational temperature. The subsequent phase entailed the assembly of optical components and their precise positioning within the working environment. In the concurrent experiment, the components depicted in Figure 3 were employed, with the exclusion of targeting optics.

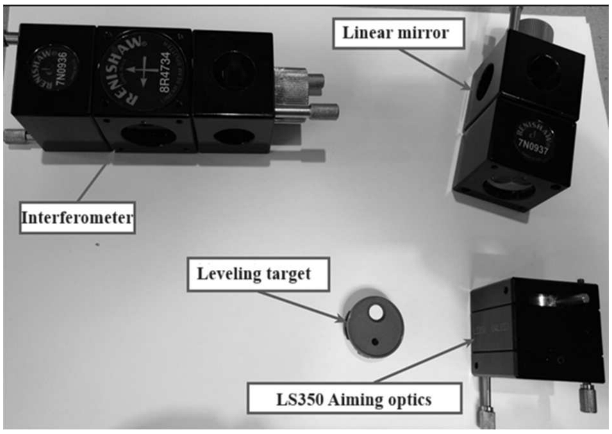

Fig. 3 *Optical setup required for measuring linear positional deviation*

As our initial step in the setup, we positioned the interferometer on the worktable, allowing us to bifurcate the laser beam into two separate beams. During the measurements, it was situated in closer proximity to the laser head. The assembly of the interferometer onto the table was achieved using a magnetic stand. Ensuring that the laser beam emerging from the source was properly directed through the beam splitter, aided by an alignment target, and subsequently inserted into the optics, was a crucial requirement (Fig. 4).

Fig. 4 *Interferometer mounted on the machine table with a target*

Throughout the measurement process, the laser beam needed to enter the optics while traversing the entire measurement range. Precise control of the beam direction was achieved by fine adjustment screws located on the table housing the laser head. This ensured that the laser beam remained accurately aligned with the centre of the target as the table moved across the entire range. Following the successful alignment of the initial laser beam, the alignment target was disengaged from the optical setup and inserted into the second optics of the linear mirror. Subsequently, the same beam alignment procedure was executed as in the preceding optical element (Fig. 5).

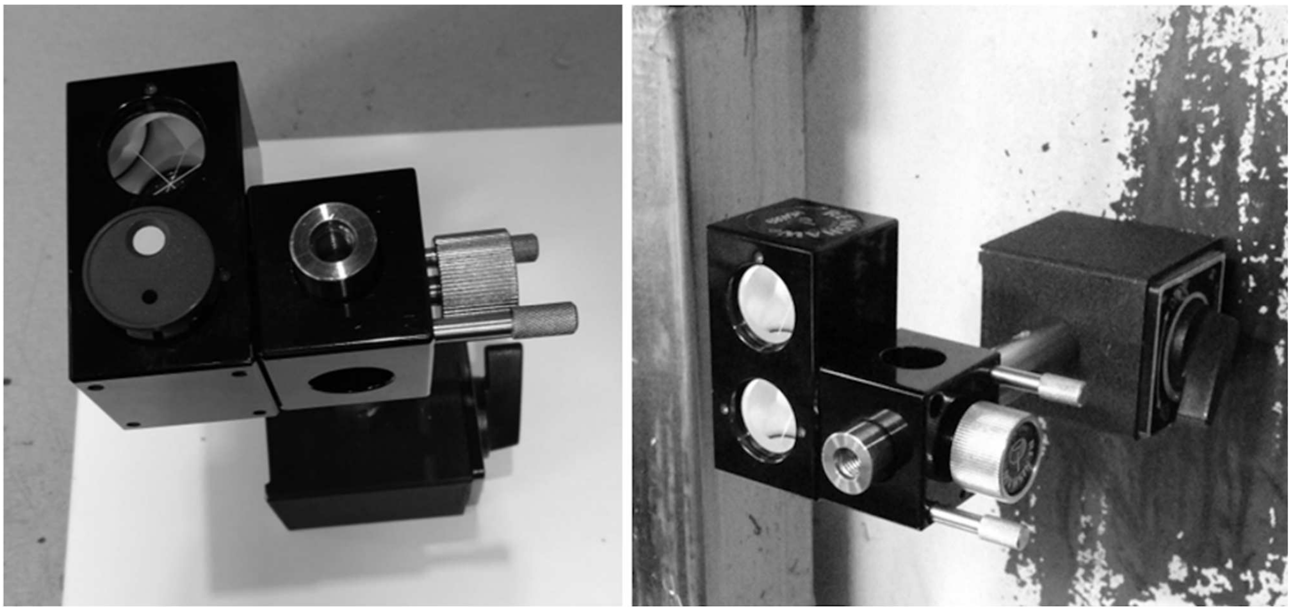

Fig. 5 *Mounted Linear Optics on the Machine with a Target*

Upon the removal of the target, two beams are directed back into the laser head, a phenomenon also visible on the screen situated at the laser head. However, these returning laser beams are non-parallel, leading to less optimal parallel alignment of optical elements in most cases. In such scenarios, the positions of individual optics must be finely adjusted until the convergence of both beams is attained, as illustrated in Figure 6. This adjustment is essential to ensure their parallel alignment.

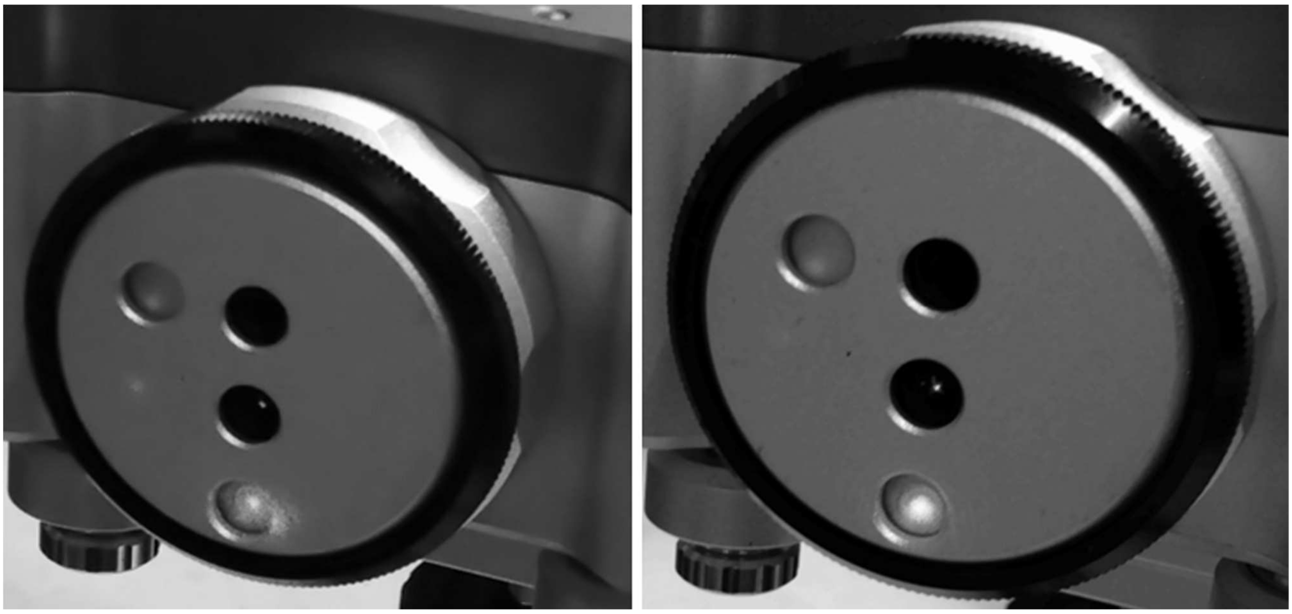

Fig. 6 *Laser beams on the detector of laser head – non-parallel (left), parallel (right)*

The signal strength is conveyed through the green indicator LEDs located on the upper surface of the laser head. As shown in Figure 7, the laser head presents five illuminated green LEDs, denoting the maximum signal strength. It is essential to ensure that the signal intensity remains constant during the movement of the mobile component along the measured axis, a state that is indicated by the flashing of these LEDs.

Fig. 7 *Diodes on the laser head indicating signal strength*

The last phase entailed the setup within the measurement software, LaserXL, developed by Renishaw. This software offers the flexibility to configure various parameters concerning the measurement method and diagnostic data about the instrument. Before inputting specific parameters, it is imperative to create the corresponding NC program, which serves as the basis for instructing the machine to perform the desired movements along the measured axis.

3 Results

As one of the outcomes of the LaserXL software, we generated and analyzed graphs following the initial two measurements on a three-axis machining center, conducted when the machine was 18 years old. These measurements were performed along the X-axis, using both the original and subsequently reset machine correction map. Figure 8 illustrates the graph depicting the average deviation on the X-axis with the original correction map, while Figure 9 displays the graph showing the average deviation on the X-axis without the correction map. Notably, on the average deviation graphs, one can observe a significant divergence in the curves representing measurements in both positive and negative directions of axis movement within the range of positions from 150 to 400 mm.

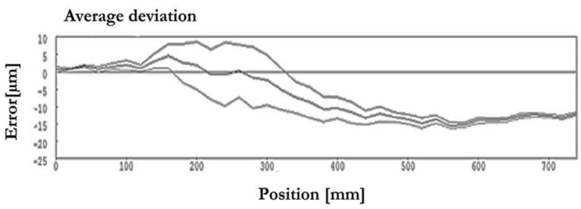

Fig. 8 *Graph of average deviation in the x-axis with the original correction map*

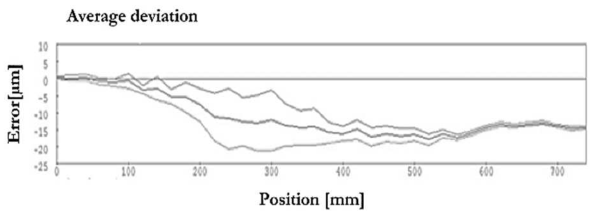

Fig. 9 *Graph of average deviation in the x-axis without a correction map*

In the following graphs (Fig. 10), it becomes evident that this irregularity persisted even after the subsequent measurement, where a new correction map was applied to the machine. Despite the introduction of the new correction map, there was only a marginal improvement in the values of the evaluated parameters. However, the systematic error E consistently remained at a high level, as illustrated in Figure 11.

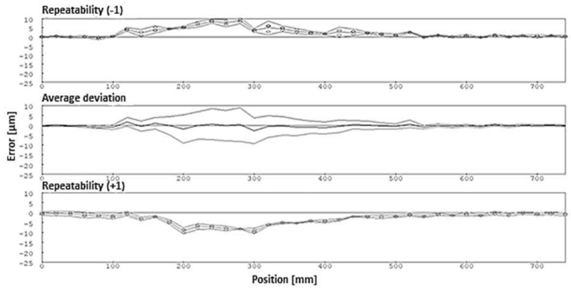

Fig. 10 *Graphs of position deviations after measurement with a new correction map*

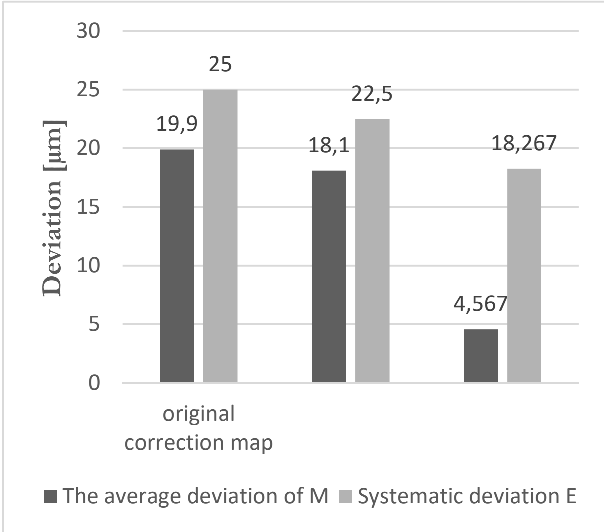

Fig. 11 *Graph comparing parameters after individual measurements*

When the curves in the graphs exhibit unusual distortion, the most common underlying cause is damage to the ball screw or another component responsible for horizontal axis movement. In this specific case, an error in the preloading of the ball screw was pinpointed. The solution to this identified issue entailed tightening the screw (Fig. 12), thereby adjusting its preloading in alignment with the machine manual provided by the manufacturer.

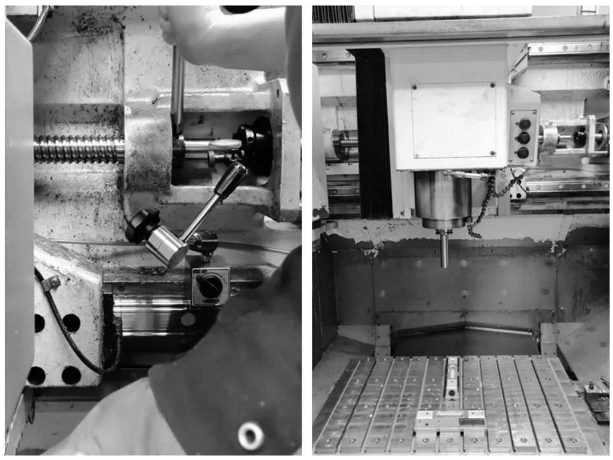

Fig. 12 *Ball screw preload adjustment (right) and machine levelling check with spirit levels (right)*

A year later, another diagnostic evaluation was performed at the same machining centre, which was then 19 years old. Throughout this period, the machining centre had been anchored to the floor using chemical anchors to ensure both its stability and the evenness of its setup. Figure 13 presents a graph depicting the accuracy and repeatability of position adjustments along the X-axis after the initial measurement with the original correction map.

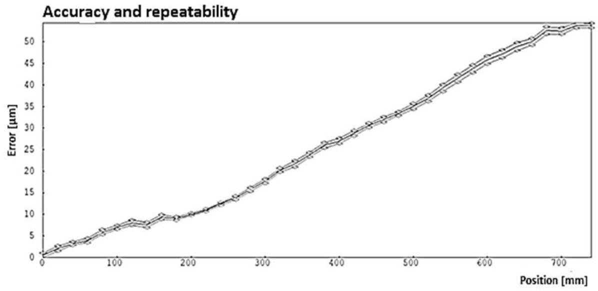

Fig. 13 *Accuracy and repeatability graphs in the x-axis after measurement with the original correction map*

Based on the results from the graph, we can conclude that no irregularities are evident in this particular case. However, a substantial increase in error has been noted. The graph clearly illustrates that the measured value exceeds 50 µm. In accordance with the manufacturer specifications, the machining centre was intended to operate with an accuracy of 5 µm, while the operator mandated an accuracy of 0.01 mm. Consequently, a novel compensation table was devised to rectify the generated error, subsequently integrated into the Renishaw machine. Following a repetition of the measurement process, the resulting graph is displayed in Figure 14.

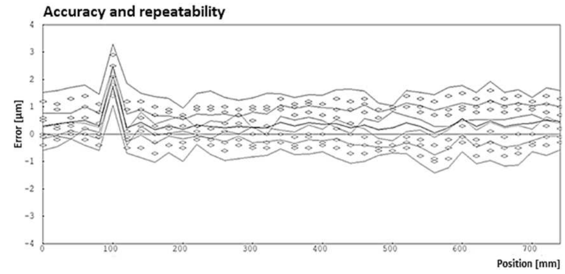

Fig. 14 *Accuracy and repeatability graphs in the x-axis after implementing a new correction map*

Based on the acquired data, it becomes evident that the error experienced a substantial reduction following the implementation of new corrections, ultimately reaching a level of 2 µm. It is reasonable to infer that this improvement was attributed to a poorly designed calibration interval. To guarantee the desired production accuracy, a recommendation has been made to shorten the calibration interval of the machine to either 6 or, even more optimally, 4 months.

Tab. 2 *Comparison of test parameters between the original and new correction maps*

Measurement errors	Original correction map	New correction map
Average Deviation M [µm]	53,300	2,083
Systematic Error E [µm]	54,400	3,267

The most recent measurement was conducted when the machining centre had been in operation for 20 years. The analysis was carried out following the same operational procedure, involving measurements in the X and Y axes, accompanied by the creation of a new correction map. Notably, this analysis was performed without loading the machine, under static conditions. However, in this case, dynamic errors occurring during the machining processes were also considered. To account for machine errors occurring during machining in the corrections, a test sample needed to be manufactured. In our case, this sample was a 200 mm x 200 mm cube, and its geometry was subsequently evaluated using a Coordinate Measuring Machine (CMM). Deviations occurring on the individual X and Y axes were measured on the sample. These measured deviations were then converted for each axis into a single step, based on the correction map of the machine, effectively dividing them by the number of steps entered into the correction map. Finally, the measured values had to be converted into the desired units specified in the correction map (in our case, in mm). Table 3 displays the corrected values for the individual X and Y axes.

Tab. 3 *Example of correction value calculation*

Axis	Deviation not measured in SMS mm [mm]	Deviation converted to one step [mm]	Corrected step value [0.1µm]
X	0.013	0.00031707	3
Y	0.021	0.0005122	5

Subsequently, the calculated correction value had to be subtracted from the original correction value on the corresponding axis for each step (increment). The process of modifying the correction map using the previously computed correction values is depicted in Figure 15.

Machine correction map				
Step Nr.	Original X-axis correction value [μm]	New X-axis correction value [μm]	Original Y-axis correction value [μm]	New Y-axis correction value [μm]
1	40	37	40	35
2	40	37	50	45
3	30	27	50	45
4	30	27	20	15
5	30	27	20	15
6	20	17	20	15
7	10	7	10	5
8	0	-3	0	-5
9	-30	-33	-10	-15
10	-40	-43	-10	-15
11	-40	-43	-10	-15
12	-60	-63	0	-5
13	-60	-63	-10	-15
14	-70	-73	-20	-25
15	-70	-73	-20	-25
16	-60	-63	-30	-35
17	-50	-53	-30	-35
18	-40	-43	-50	-55
19	-20	-23	-60	-65
20	-10	-13	-80	-85
21	0	-3	-80	-85

Machine correction map				
Step Nr.	Original X-axis correction value [μm]	New X-axis correction value [μm]	Original Y-axis correction value [μm]	New Y-axis correction value [μm]
22	10	7	-90	-95
23	30	27	0	-5
24	30	27	0	-5
25	30	27	0	-5
26	50	47	0	-5
27	40	37	0	-5
28	50	47	0	-5
29	50	47	0	-5
30	40	37	0	-5
31	60	57	0	-5
32	60	57	0	-5
33	70	67	0	-5
34	70	67	0	-5
35	50	47	0	-5
36	50	47	0	-5
37	40	37	0	-5
38	40	37	0	-5
39	40	37	0	-5
40	20	17	0	-5
41	20	17	0	-5

Fig. 15 *Example of correction map adjustment*

The updated correction map of the machine takes into consideration the impact of dynamic errors occurring during the machining process. It is important to note that the errors that emerged during machining were effectively transferred to the manufactured component, and the identified deviations in the individual axes were subsequently integrated into the respective compensation values entered into the Renishaw machine.

4 Conclusion

Diagnostics of manufacturing equipment in the mechanical engineering industry currently represents one of the fundamental processes closely linked to ensuring the accuracy of machine tools and the overall quality of production. It has been observed that errors within machine tools can stem from the machines themselves, their components, and incorrect configurations. Furthermore, these errors can also be attributed to the dynamic aspects of the cutting process, where they can exert a significant impact. Among the frequently utilized diagnostic systems, the Renishaw XL-80 laser interferometer takes precedence and was also utilized in the experiments conducted.

As part of our long-term research, we conducted a diagnostic evaluation of the tested machine, a three-axis machining centre integrated into the production facility. These diagnostics were conducted three times at regular annual intervals, following the inspection schedule set by the machine operator. After these repeated diagnostic evaluations, a notable enhancement in the accuracy of CNC machine positioning became evident through the creation and implementation of new correction maps. It is imperative to ensure the correct calibration interval settings, particularly for older machine tools, where positional deviations can fluctuate rapidly and unpredictably. Calibration, which includes error corrections and subsequent adjustments, must be carried out more frequently on older machines.

Upon the identification of a preload ball screw error, it can be concluded that machine component errors can also be discerned based on the shape of the output graphs. The experiment additionally entails the development of advanced corrections using a laser interferometer, which encompasses dynamic error manifestations occurring during the machining process. When investigating the impact of machine operating temperature on measurement results, it was confirmed that the accuracy of machine positioning significantly improved after the machine had been heated.

Considering the presented facts and the conducted experimental measurements, we can confidently assert that laser interferometers can function as efficient tools for identifying and rectifying emerging errors. This, in consequence, guarantees not only the accuracy of the machines but also the quality of the manufactured components, meeting the expectations of end customers.

Acknowledgement

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