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Reproducibility of machine tools' circularity test according to ISO 230-4 with respect to testing position

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ABSTRACT

In this paper circularity of three different machine tools by Virtual Machine was analyzed. To get circularity we make a ball bar test according to ISO 230-4. The test is very common in engineering for a quick diagnostic Computerized Numerical Control (CNC) technical conditions. We implemented earlier calculations of Volumetric Error in our Virtual Machine. Then we simulated testing of circularity of CNC machine tools. The place to take the test was chosen randomly from Uniform Distribution in three different kinds of machine tools. Those machines had different characteristics of kinematic errors and squareness and also different sizes of working space. We observed significant differences in the indicator (circularity) depending on the place where the test was taken. Moreover we showed that there was no reason to take the test in the center of working table.

1. INTRODUCTION

Achieving the best processing accuracy plays an increasingly large role in industry. The products of tooling are more sophisticated with more complex shapes. For this reason engineers develop more reliable, accurate, and more efficient machine tools [1]. Machine tools can be used to manufacture different kind of workpieces, made from different materials. Therefore machines are influent by forces acting on a cutting tool, the temperature, and vibration [2-4], which changes machine tool characteristics such as straightness position errors or rotation errors. This affects the final shape and dimension of the product.

The general tendency is to compensate for any machine errors. To do this it is necessary to know the technical condition of each machine. CNC machine measurements were standardized [5].There are many different machine condition tests corresponding to this norm. They differ in equipment, cost, duration, and type of results. We can mention at least laser track test, ball bar test, R test [1-6]. Laser tracer test is commonly used for generating the whole vector space of Volumetric Error (VE) [7]. Since the test is time consuming, which translates in to higher costs, it is not recommended to use it in standard technical inspector. The ball bar test provides a better practical alternative and gives only a partial information of machine condition. One can list a lot of papers about Ball bar test – beginning with the publications describing the test procedures [8], through those analyzing the results of the test [9], and ending with the attempts to widen the results by positional or trajectory variations [10,11]. In engineering practice the test is always conducted

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in a place within workspace, which is commonly the center of the table.

The current trend is to build a Virtual Machine (VM) corresponding to real one. It helps to predict machining operation impact on the dynamics of the machine tool [12-15]. Using VM avoids high costs of examination or tools wear and allows to design new engineering solutions.

This study addresses an analysis on reproducibility of machine tools' circularity test with respect to testing position using Virtual Machine. It also shows that taking the test in the most common place– in the center of the working table – is not purposeful.

2. VOLUMETRIC ERROR OF MACHINE TOOLS

At first, using laser tracer, we examined three different kinds of machine tools. Selection of machines was not random, those three machine tools have different size of work space and, what is more important, different sources of dominant error. First machine tool was a machine from Polish producer distinguished by the very high accuracy. Its cyclic pitch error was 3 µm. The second machine was also from a Polish producer, equipped with linear scales but without compensation of positions of the axis. The last machine was an old laser cutter having large kinematic errors. The machine tools characteristics are listed below in Table 1, where in first row the ranges related to G53 code – machine coordinate system – was presented.

Table 1. Machine Tools characteristic

		Machine 1	Machine 2	Machine 3
Machine volume [X] [Y] [Z] mm		[0 : 600] [-20 : 380] [-10 : 540]	[-270 : 270] [-250 : 260] [270 : 720]	[150 : 1110] [-280 : 280] [-400 : 0]
EXX	µm	12	57	899
EYY		4	74	175
EZZ		8	75	692
C0Y	µrad	0.1	-11	-1100
B0Z		-2.3	67	-931
A0Z		-81	-183	-3800

As mentioned before, in ITM of ZUT in Szczecin we examined real machine tools by laser tracer. Then we built a mathematical model of Volumetric Error using multi-lateration algorithm. The VE includes position errors, straightness errors, rotation errors and squareness of axis. The characteristic of errors, both of position and of straightness, of one of the examined machine were presented in Figure 2.

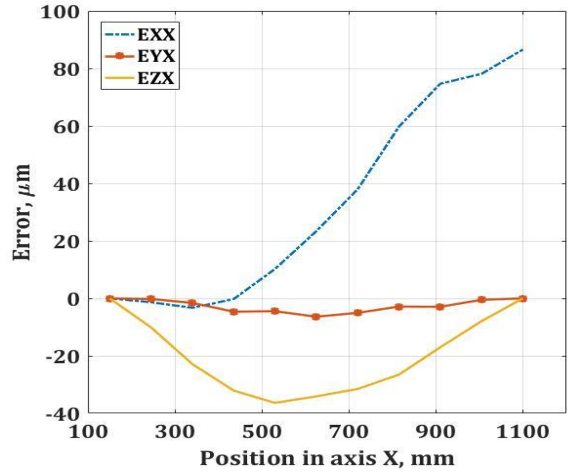

Fig. 1. Characteristic of straightness and position

3. STANDARD PROCEDURES

Machine tool test procedures were developed according to international standards. The standards ISO 230-4 – 2005 propose test procedures during circular interpolation. The procedure requires fixed assigned feed rate and diameters. The test gives performance index called circularity deviation G. It is defined as a difference between maximum and minimum distance of points of actual path from the center of the least squares circle.

The main advantage of the ball bar test is its simplicity, short duration and the ability to uniquely identify sources of errors of dynamic positioning actuators of tested machine. Evaluation of test results' quality is positive if the machine tool has dominant typical error source in circularity. Such cases are encountered in industrial practice, usually after machine's first run (by the manufacturer). Interpretation of such results may uniquely improve the positioning accuracy of the machine by simply selecting the appropriate parameters (the so-called machine variables) in the CNCs control system. Generally, after this short compensation, we will obtain diagrams, with interpretation not that obvious as the results of the next circular tests. Commonly such diagrams show circularity impacted by various types of errors. The example is shown in Figure 2.

Generally, circularity is interpreted as an indicator strictly related with the accuracy of the projection of programmed tool motion relative to the workpiece. In other words it seems to be a strong relationship between circularity and the ability of the machine for precise shaping of workpieces. Furthermore, it seems that the circularity indicator could be useful to compare different kinds of machine tools, in view of projections programmed trajectory of motion.

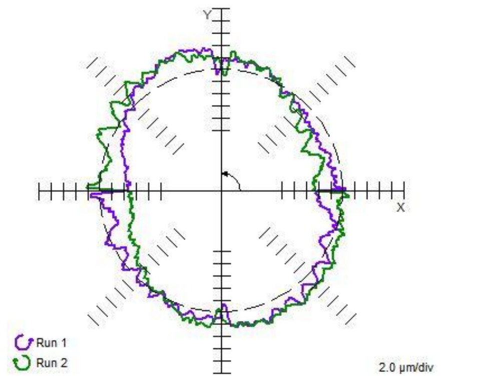

Fig. 2 Example of circularity test results CNC machine tool with visible impacts in a variety of machine errors

Later we analyzed characteristics of errors of different kinds of machine tools. It will be shown that even for machine tools with dominant component of the error (i.e. squareness) there will be serious problems with the results interpretation with respect to the position of the center and the plane where the test was taken.

To obtain results of Ball Bar test, the Virtual Machine was created for each of three examined machine tools. The centers of testing circles were determined in a random way using uniform distribution. In each point we encircled three circles: in XY plane, YZ plane and in XZ plane. Only in the first plane it was a whole circle, in the other planes we used an arc of 220 degrees angle, all circles and arcs had 100 mm radius. As a result of this procedure we obtained a dome, shown in Figure 3.

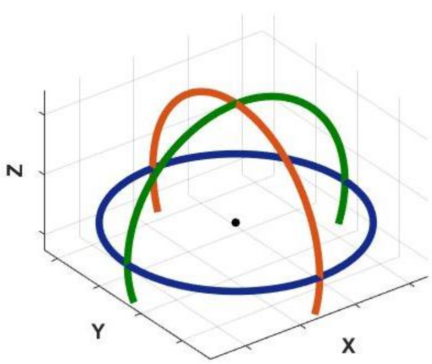

Fig. 3 Result trajectory of ball bar test in three planes with one circle center.

The 400 centers were chosen for analysis, therefore it gave 1200 results for each machine tool – three circularities for each center. The circularity deviation was filtered from errors without direct impact on accuracy of manufactured workpiece in interpolated moments. Such errors as: reversal spikes, backlash and servo mismatch were eliminated. The deviation of circularity with respect to testing location was used as reproducibility measurement. To better understand the result in each plane, in Figure 4 the trajectory of the test in each plane was shown.

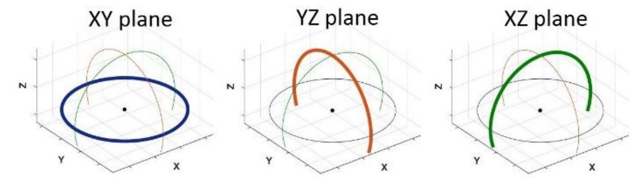

Fig. 4 Trajectory of the circularity test for each plane

4. RESULTS

To illustrate dispersion of circularity in each plane we drew histograms. Red column is the one corresponding to circularity of the center of table.

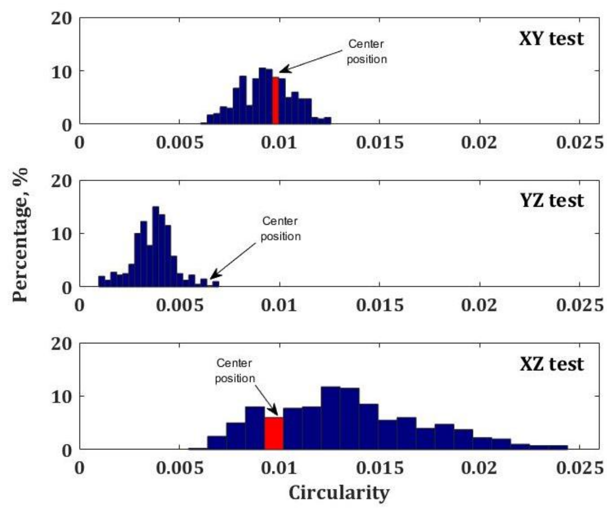

Fig. 5. Histogram of simulated circularity in three planes for Machine 1

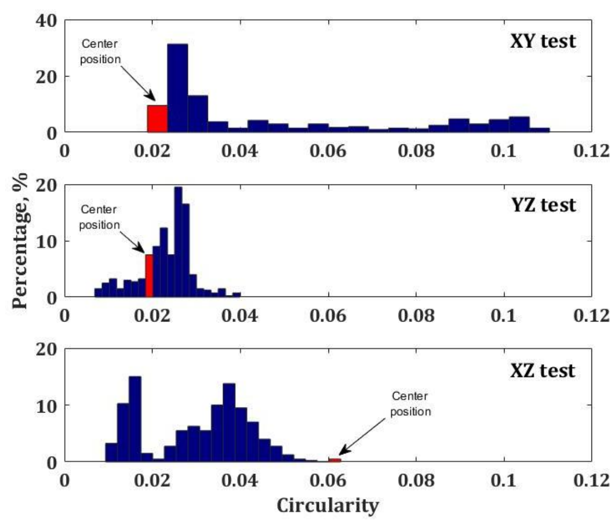

Fig. 6. Histogram of simulated circularity in three planes for Machine 2

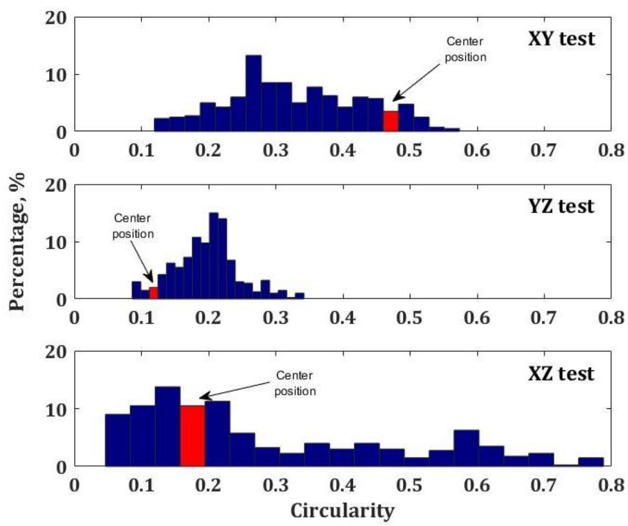

Fig. 7.Histogram of simulated circularity in three planes for Machine 3

Normality of circularity in each plane (XY, XZ, and YZ) for each machine tool was tested by Kolmogorov-Smirnov test. The null hypothesis (H_0)for each machine and plane was the same – the distribution of the circularity is Gaussian. In each test the significance level was set as $\alpha = 0.05$. This test shows that only in the first machine tool all three distributions of circularity are Gaussian. In other cases the result of the test was negative, so $H_0$was rejected – the distributions are not normal. The first machine tool is the most accurate, so as it might be expected, the circularity is normally distributed, but even then the circularity of the middle of the table is not the representative value of this indicator as can be seen on Fig. 5.

The next fact we can observe, is that the circularity of the center of table is not only not the most common value of this test, furthermore, in some cases, it is the least common value. This situation takes place in all three kinds of machine tools, and in all planes.

The other conclusion is the circularity is not a right indicator to compare machines condition, especially when assuming only one ball bar test run. For example, in the first machine there exists a place where the circularity in XZ plane is greater than 0.02 μm, and the same test at the same plane in machine 2 gives a smaller value. It might suggest that machine 2 is more accurate than the first one, and it would not be a correct conclusion.

To present differentiation of obtained circularity results we marked randomly selected centers of circles in the color corresponding to the value of circularity (see Figures 8, 9,10). We present the variability of circularity only for the first machine, for clarity of the results, because the other machines had similar randomness level of results.

It can be seen, from Figures 8, 9, 10 that the circularity depends of the testing position. There is no dominant value of this indicator (multi modal distribution). Moreover, in each plane the distribution of the circularity is different. In the first machine in YZ plane the largest circularity is at the top of the workspace, and in the same machine but in XZ plane the situation is exactly the opposite – the largest circularity is near the table. What is interesting, in machine 3 in XY plane we can observe concentric areas from the right-up corner.

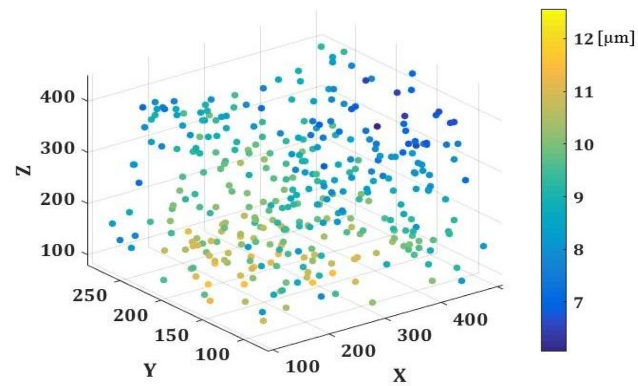

Fig. 8. Simulated circularity in each random center of circle in Machine 1, XY - plane

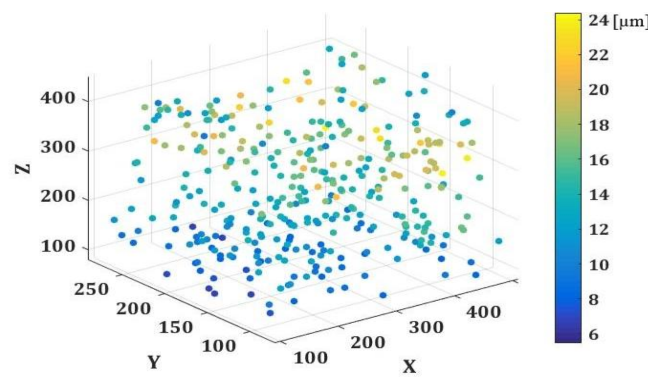

Fig. 9. Simulated circularity in each random center of circle in Machine 1, XZ - plane

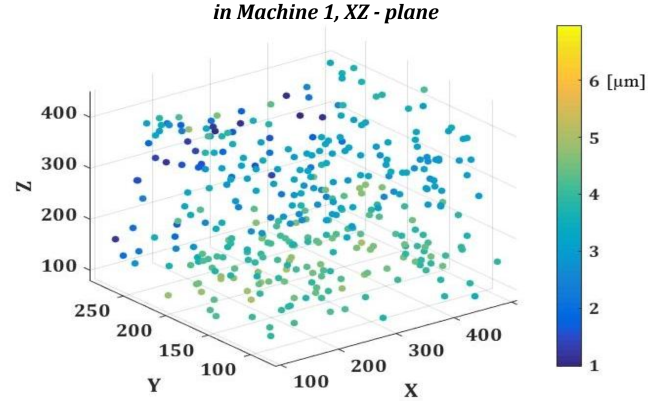

Fig. 10. Simulated circularity in each random center of circle in Machine 1, YZ - plane

All the above shows how unpredictable is the value of circularity, when treated alone as a main indicator of machines' accuracy.

5. CONCLUSION

The ball bar test based on ISO 230-4 is commonly used in engineering for quick diagnosis. It helps increase accuracy of machines without long downtime of the work. The test is uncomplicated to use and the interpretation of results is simple, especially when machine has dominant source of error. Although our analysis proves that it is not a universal test. We showed that there is no reason to compare machine tools based on their circularity alone. Reproducibility of the test results with respect to testing position is thus impossible because of such a large deviation of values of this indicator within one machine tool. Thus comparing circularity on different machines seems to be unjustified and can lead to incorrect conclusions.

It was demonstrated that the most common place to take the test – the very center of machines' table – is not the best place. Moreover, there does not exist such a place, the variability of circularity in the workspace is too large to point out the best position of the test.

Summarizing, the ball bar test is good for a quick diagnosis of one machine, but not to compare machines' conditions. Taking the test one should remember that the center of the table is not always the best position.

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