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EVALUATION OF CONTOUR ERRORS IN CNC 3-AXIS MACHINING CENTER USING THE TELESCOPING BALLBAR SYSTEM

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Abstract. *The quality in the production of manufactured products has been a prominent factor and strongly demanded by the industries and clients. In the manufacturing industry, machining centers play a crucial role in obtaining parts with good accuracy and repeatability: dimensional, geometric and profile tolerances close to those specified in the design. This paper seeks to highlight and evaluate how contour errors affect the geometric quality of machined parts by means of a circular interpolation process and thus propose compensation actions. To measure the errors, a measurement system, known as the Ballbar System, was used in a 3-axis CNC machining center. The main errors of this center were evaluated, as well as deviations verified according to ISO 230: 4. The results show the urgent need for corrective maintenance of the machining center.*

Keywords: *Contour Errors, Telescoping Ballbar System, Machining Center, ISO 230:4*

1. INTRODUCTION

This paper aims to answer the following questions: i. Which contour errors most affect the performance of the machining center chosen as the object of study? ii. Why is it important to identify these errors? iii. What are the possible mitigation actions?

Improving the accuracy of products and processes enables significant benefits in the industrial scope for mass production with higher quality and better reliability. The development of ultra-precision machine tools has only become possible due to the studies of industrial and scientific metrology under qualitative and quantitative aspects. (Mekid, 2009).

These studies have led to excellent ranges of nanometric quantities. The Table (1) shows a difference between conventional machining parameters and ultra-precision machining.

CNC Machining Centers are being increasingly demanded by the technicians in the area because the demand for high accuracy components and quality consistency is increasing, so it's necessary to study the errors present in these machining centers, so that be possible to minimize them - either by compensation models or by components of high accuracy - and, consequently, to maximize quality.

Table 1 - Comparison between machining with conventional cutting tool and diamond (Mekid, 2009).

Parameter	Conventional	Diamond
Depth of Cut	0,1 - 10 mm	1 - 20 μm
Forces of cut	> 100 N	< 1 - 5 N
Roughness	0,2 - 5 μm	2 - 20 nm
Form Deviation	> 10 μm	0,1 - 1 μm

The work developed by Polli, 2005, classifies the errors of a machine tool into two categories. Differently, Silva, 2017 divide them into four categories, and in this work, we will investigate some errors that are, according to Silva, categorized in Error type III - Contour Errors.

The contour error is used to designate the component of orthogonal error to the desired path, i.e., it's the deviation of the tool from the programmed contour. One of the main indicators related to the final quality of the workpiece, although axial errors are a very important specification of CNC machines.

2. EXPERIMENTAL PROCEDURE

The measuring instrument used in this research is the Telescoping Ballbar System (TBS) QC-20W, Renishaw, together with its software, Tab. (2). By means of them, it's possible to measure geometric errors existing in CNC machine tools and to detect inaccuracies induced by the command and control system of the servos. Errors are measured by means of circular motions or arcs executed by the machine tool.

Table 2 – Specifications of the TBS.

Sample rate	1000 Hz (maximum)
Nominal length	100 mm (between centers of balls)
Stroke	-1,25 to +1,75mm
Resolution	0,1 µm
Range	±1 mm

Ballbar Setup consists of two essential steps. The first in the system preparation methodology in the CNC machine tool to be evaluated. The second step consists of the parameterization of the program; After performing these two steps, the TBS is ready to perform the data capture and analysis.

The test was carried out at the 3-axis vertical machining center, ROMI-D600, located at the mechanical workshop of the Federal Institute of Education, Science and Technology of Paraíba, Campus João Pessoa. The test aimed to characterize, diagnose and predict actions to be taken for machine errors of this machining center only for the XY-workplane (G-Code: G17).

The methodology of system preparation for any machine tool consists of the systematic step-by-step organized in Tab. (3):

Table 3. Preparation Method for Ballbar Test

Step	Description
I	Secure the magnetic housing to the tool holder.
II	Position the table and the magnetic stand with the fixing bracket unlocked.
III	Allocate the magnetic housing approximately 80 mm above the table.
IV	Place the adjustment ball on the magnetic holder.
V	Align the magnetic holder and the magnetic housing.
VI	Lower the spindle approximately 2 mm.
VII	Check the socket of the ball in the magnetic housing.
VIII	Locking mechanism.
IX	Set the position as the work source (G54).
X	Check that the tool offset is active and, if it is positive, ensure that it is active until the end of the analysis.
XI	Move the machine in the positive direction of the z-axis to remove the adjusting ball
XII	Remove the adjustment ball.
XIII	Move the machine to the initial test coordinates, Fig. (1).
XIV	Perform parameterization of the software test.
XV	Generate G-code.
XVI	Load G-Code into the machine tool.
XVII	Wait for reading the G-code until the table positioning at the programmed point.
XVIII	Load the Ballbar in the given configuration, Fig. (1).
XVIX	Perform capture.

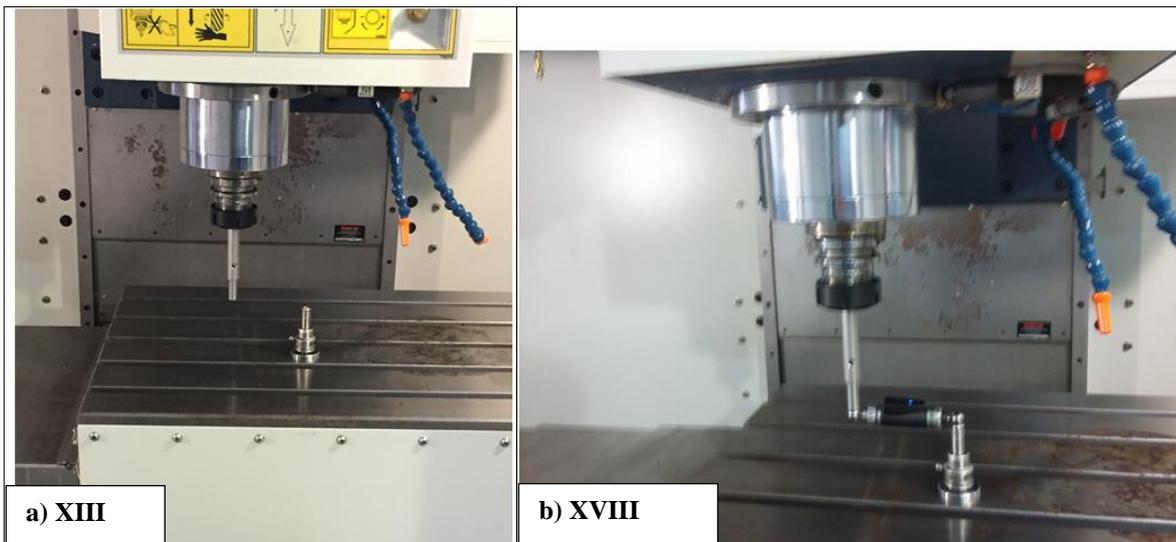


Figure 1. Stages of the Ballbar positioning setup: a) XIII - Machine movement for the initial test coordinates. b) XVIII - Loading of the Ballbar in the predetermined configuration.

In the parameterization step, the data were selected for execution of the TBS system and evaluation of the machining center performance in low speed forward condition: Test Plan: XY; feed rate 500 mm / min; test radius: 100 mm; number of spindles: 1; angular displacement 360°; overshoot angle 180°; capture direction: Counterclockwise (CCW), Clockwise (CW); The TBS is ready to perform the circularity test and to diagnose any errors according to ISO 230-4.

3. RESULTS AND DISCUSSION

The results presented in the diagnosis present the five errors with the highest percentages that provides the total error of non-circularity that can be attributed to the diagnosed errors, see Fig. (2). Thus, the Backlash error in Y is the most responsible when dealing with this item with a 22% indicator differentiating in only 1% of the Backlash in X. These errors can be caused due to the slacks in the drive system of the machine that is usually caused by a failure in worn ball screw bearings or spindle nuts, and there may be slack in the linear guides of the machine causing a stop of movement when the drive direction is reversed.

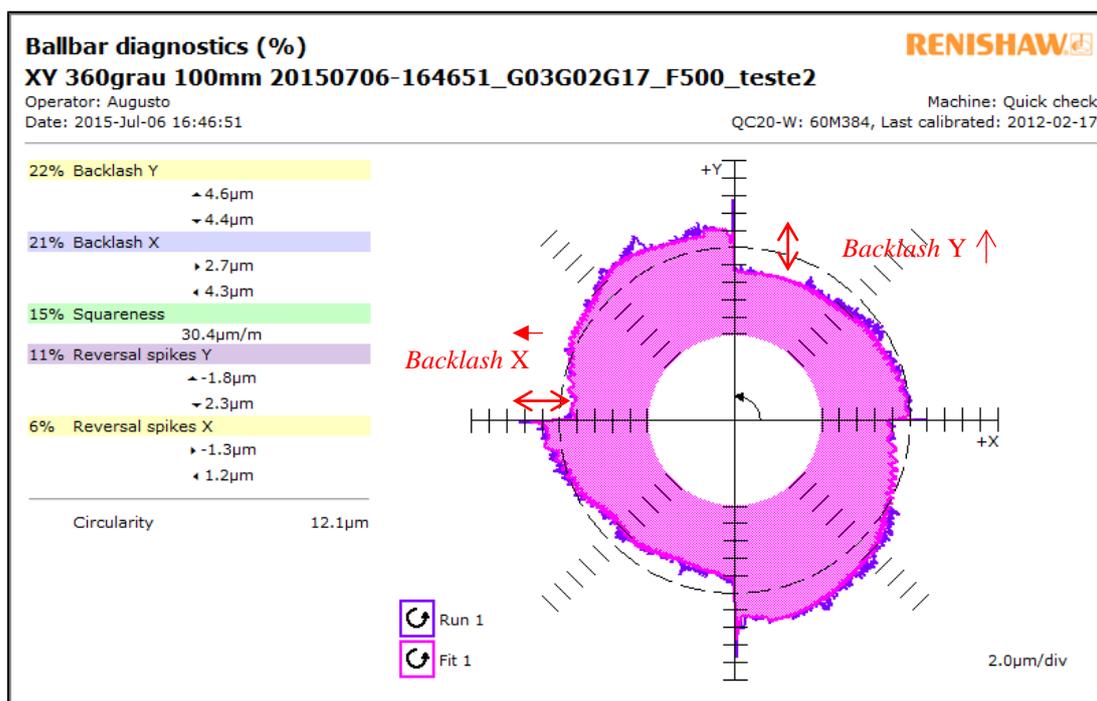


Figure 2. Ballbar diagnostics for backlash errors.

The importance of measuring them is because of the effect these errors can generate during the machining process. In the machining process, this positive backlash error can generate a small plane during the interpolation process. For the values found of 4.7 mm in the positive y-axis, 4.4 μm in the negative y axis, 2.7 μm in the positive x-axis and 4.7 μm in the negative x-axis, respectively, the plane length generated for a linear interpolation of 100 mm around 0.68 mm, 0.66 mm, 0.52 mm and 0.68 mm. The effect of the backlash error on the positive y-axis can be seen on a larger scale in Fig. (3).

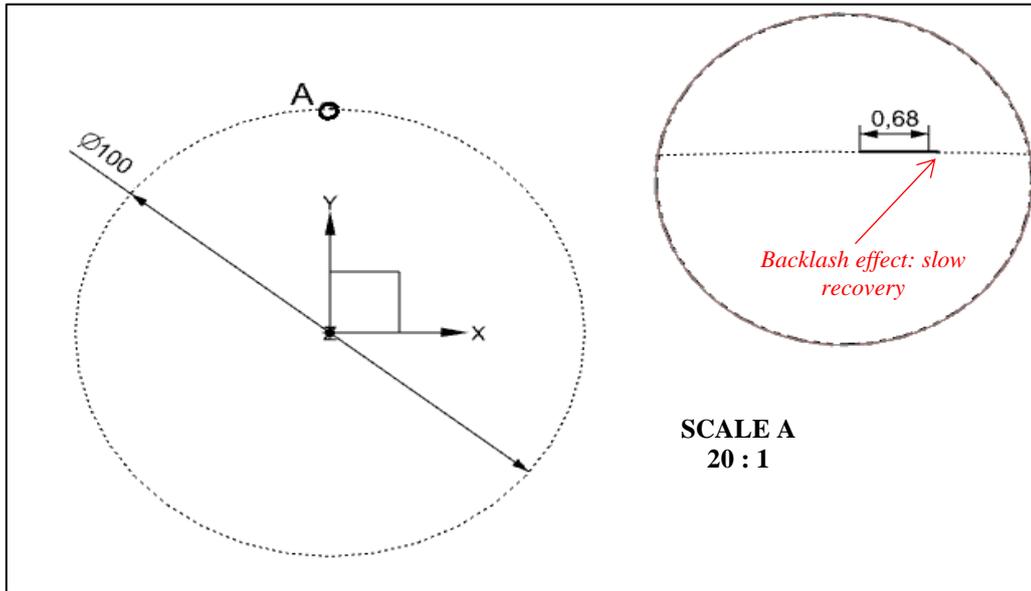


Figure 3. Generation of the plane length caused by the backlash effect.

It is also important to highlight the perpendicularity error that corresponds to be the third most influential in the diagnosis, having a value of 30.4 μm / m (0.00174°). The value of the perpendicularity error is positive; this means that the angle exceeds 90° of the perpendicularity between the evaluated plane. The Figure (4) shows the perpendicular error measured in this measurement; to calculate in degrees the perpendicularity error measured by the Ballbar system, we calculate the arc tangent of the expressed value, such that $\theta_{xy} = \arctg(30.4 \mu\text{m} / \text{m}) = 0.00174^\circ$, where θ_{xy} is the perpendicularity in the xy plane.

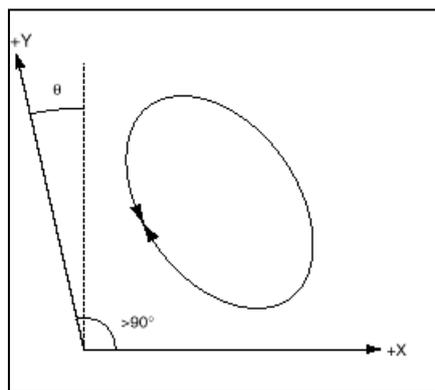


Figure 4. Characterization of the positive perpendicularity error.

The perpendicularity error is caused when the X and Y axes are not at 90° at the place where the test was performed, and it is important to investigate whether these errors are local, specifically where the Ballbar was installed, or if it is due to a general misalignment of the machine; such fact can only be investigated when performing several sweep tests on the table. Another factor that can cause perpendicularity (orthogonality) errors is the wear of the guides that can generate slacks in the axes when they move during machining. Because of this, the parts to be machined can be out of the square. It can be verified in Fig. (5) by means of the reference line, since the circle tends to distort in the direction of 135° for the positive square.

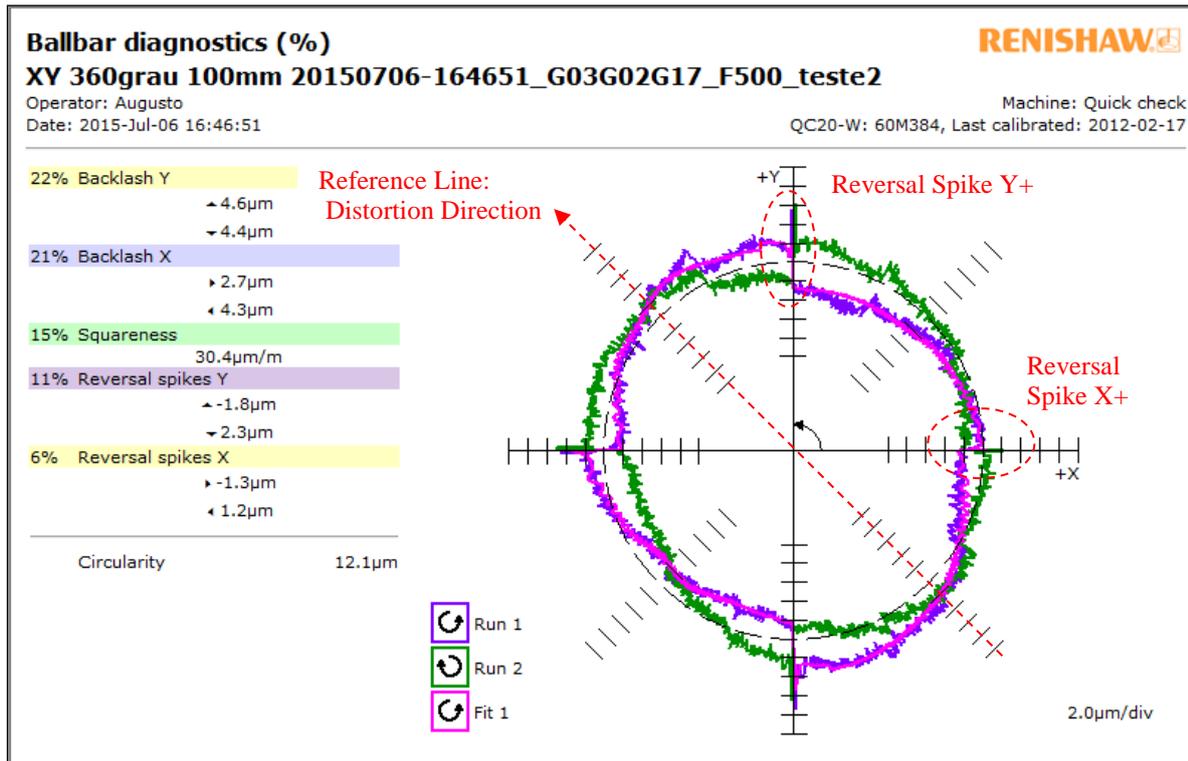


Figure 5. Direction of distortion generated by the effect of the positive orthogonality error on circular interpolation.

The reversal spikes correspond to the fourth and fifth most significant errors, presenting percentages around 11% for Y spikes and 7% for X, see Fig. (5). It's important to be careful not to confuse backlash errors with the spikes reversion errors, although both generate plans during the circular interpolation of the tool, the reversal spikes errors present a much faster recovery of the error than the backlash errors, and are also generated due to other factors, such as improper torque applied by the servomotor at the time of reversal of the axis direction, causing momentary adhesion at the reversal point, or the servos response at the time of reversal of the axis direction is poor, causing a small stop in the direction reversal of the shaft. As the advances greatly influence this type of error, therefore, it tends to find a certain value of advance that minimizes these peaks, and then, to perform the operations of finishing - that require tight tolerances - with the advance that presents/displays low reversal spikes errors.

The circularity presented for the machining center is 12.8 µm, and the analysis according to ISO 230-4: 2005 for circular deviations are organized in Tab. (4), and its graphs are shown in Fig. (6). It should be noted that it was not possible to determine the radial time offset, counterclockwise and the bidirectional radial mean deviation, since their identification requires the Ballbar to be calibrated.

Table 4. Circular deviation of ROMI D600: Rt = 100 mm and vf = 500 mm / min.

Circular deviation	
G (CW)	10,5 µm
G (CCW)	11,8 µm
Bidirectional G (b)	12,8 µm

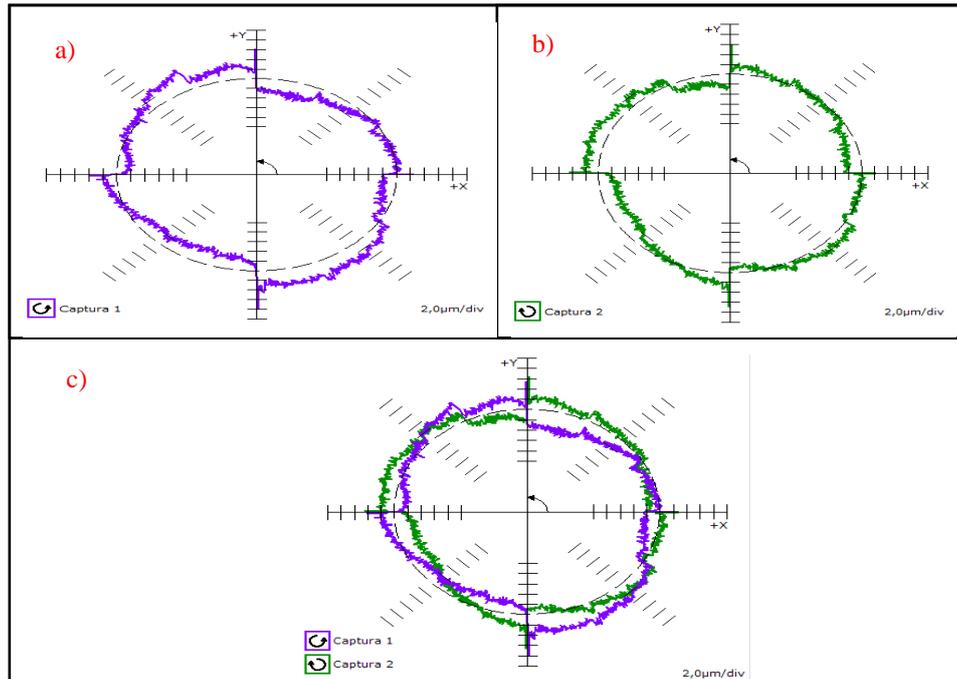


Figure 6. Evaluation of the circular deviation of the Machining Center: a) CounterClockWise b) ClockWise c) Bidirectional Average.

4. CONCLUSION

The results of machining center errors for the proposed test condition, show that:

- The mains errors of contours are: Backlash error, Reversal spikes error, Squareness error and Circularity
- Corrective actions are necessary in the machining center.
- Backlash errors as major sources of errors, and thus requires fast maintenance on guides and ball screws.
- Due to slow recovery of effect of backlash, planes are generated in circulars interpolations machining.
- Tests should be performed at several points on the machining center table to identify whether the squareness error is common or is punctual.
- It is recommended to perform tests for other levels of the feed rate in order to optimize the errors of reversal spikes from the feed rate which promotes the best finishing condition.

5. ACKNOWLEDGEMENTS

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