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RESEARCHES REGARDING ROTARY-TILTING TABLE PRECISION EVALUATION METHOD USING THE BALL-BAR SYSTEM

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The paper presents o method of precision evaluation of rotary – tilting table using the ball-bar. These types of tables are usually employed in 5 axis CNC machine tools. Starting from 3D modelling of the measurement system and simulating the measurement process, the trajectory of the point on an interpolation circle had been found when the interpolation is made by two rotation axes. The correlation between the motions of two axes had been demonstrated analytically in order to have the characteristic point moving on a reference circle which can be used to reveal different types of errors occurring during the motion of the two rotation axes. Using the analytical method the CNC program has been developed and the evaluation of precision had been made experimentally. Appling the method the causes of errors had been found and eliminated in the case of a real CNC machine tool.

Key words: 5 axis machining, ball-bar system, circular interpolation by two rotation axis.

1. INTRODUCTION

Dimensional precision of manufactured parts is influenced by a series of factors as: elastic and thermal deformations of the technological system, mechanical vibrations, wear of the technological system elements, manufacturing errors.

If we suppose that measures had been taken to eliminate vibrations, elastic and thermal deformations and manufacturing errors of the machine tool, it can be said that the precision of the devices directly impacts the surface quality and the dimensional precision of the manufactured part.

There is a small coverage of 5 axis machining in general and of manufacturing precision in particular in the reference literature.

The NAS 979 [10] American standard describes manufacturing tests for conventional and NC machine tool evaluation excepting drilling machines and lathes and gives a standard form for test results documenting and reporting. This standard describes a testing procedure of 5 axis CNC machines (3 translations and 2 rotations), which considers the manufacturing of a truncated cone.

In [1] evaluations of different configurations of 5 axis manufacturing centers are presented from geometric, cinematic and dynamic point of view.

The paper [7] presents the modified DBB measurement device, where master balls are supported from the 45° direction to the spindle axis. It can perform all the circular tests on *XY*, *YZ*, and *ZX* planes without changing the setup.

An automated control system for error compensation, which uses mathematical models of the 5 axis, tool path models and cinematic models associated with the 5 axis, is presented in [9].

In [3] a generalized cinematic model is presented which allows automated obtainment of a specific configurations of a 5 axis using screw theory.

The paper [6] studies the problem of avoiding collisions during cutting on 5 axis machining considering a numeric algorithm which allows the modelling of obstacles. As results of the algorithm which simulates tool paths the adjustment times are cut short.

In [8] a geometric error compensation method is proposed using two different setting of the ball-bar system, simultaneously on three axis.

Another method to compensate for deformation errors generated by temperature variation is presented in [2].

Our paper proposes the description of an evaluation method of the precision of a rotary-tilting table which is a component of a 5 axis machining center. It starts from the mathematical modeling, numeric simulation and 3D simulation. At the end the procedure is implemented on the machining center, the measurements are made, errors are discovered and the causes of errors are finally eliminated.

2. THE ANALYTIC METHOD

For precision testing of two rotation axis (named B and C) of rotary-tilting table a method which uses the ball-bar system (Fig. 1) is proposed in this paper. In Fig. 1, the 3D model of the ball-bar system mounted on the rotary-tilting table is presented.

In case of two linear axes the ball-bar system is testing the errors of circularity of the path programmed using circular interpolation functions. This circular path is used because it gives information about how well each of the two axis are operating and also how well the two axis can synchronize their motion in order to generate a circle. Furthermore the ball-bar system can track very easily the circularity errors. Circular interpolation functions are predefined in all NC equipment as G code functions G2 or G3. However there are no circular interpolation functions for circular path generated by two orthogonal rotation axis as it is the case of the rotary-tilting table. In order to test the rotation axis we have to demonstrate that circles can be generated in such way that it will result as the combined motion of the two rotation axis and also find the relation between the two rotary axis motions in order to generate the circle.

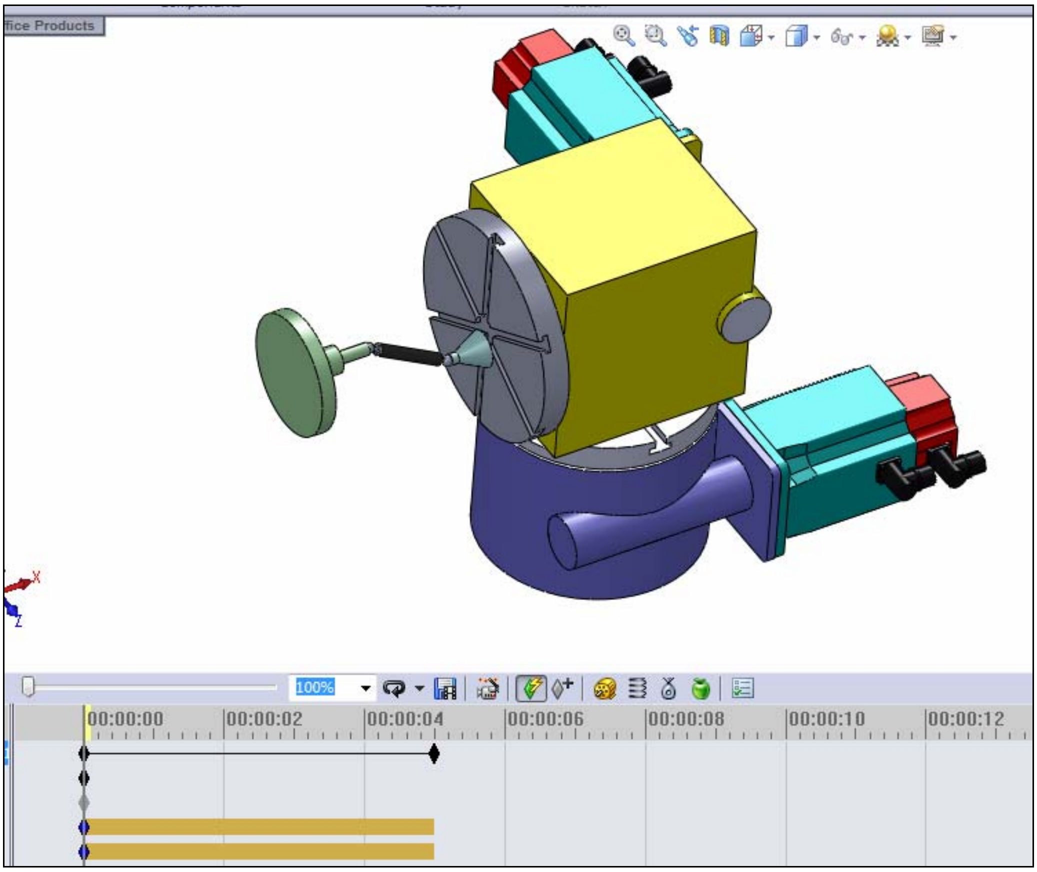


Fig. 1 – Verification of precision of two rotation axis (B and C) using the ball-bar system.

In order to establish the path of point M the scheme shown in Fig. 2 is used.

We denote with M the centre of the ball mounted on the vertical table surface of the rotary – tilting table.

As we stated before we will have to find the correlation between the angle of rotation of the horizontal plateau (angle B) and the angle of rotation of the vertical plateau (angle C) so that the geometric place of the positions of point M have to be a circle.

To achieve this goal, some tri-orthogonal coordinate systems must be defined, each of them linked to an element in the measurement process:

– fixed system $OXYZ$ linked to the centre of the ball-bar ball mounted on the spindle of the machine tool. The Z axis is identical with the spindle axis;

– fixed system $O_1X_1Y_1Z_1$ linked to the centre of the horizontal plateau;

– mobile system $O'_1X'_1Y'_1Z'_1$ linked to the centre of the horizontal plateau;

– mobile system $O_2X_2Y_2Z_2$ linked to the centre of the vertical plateau.

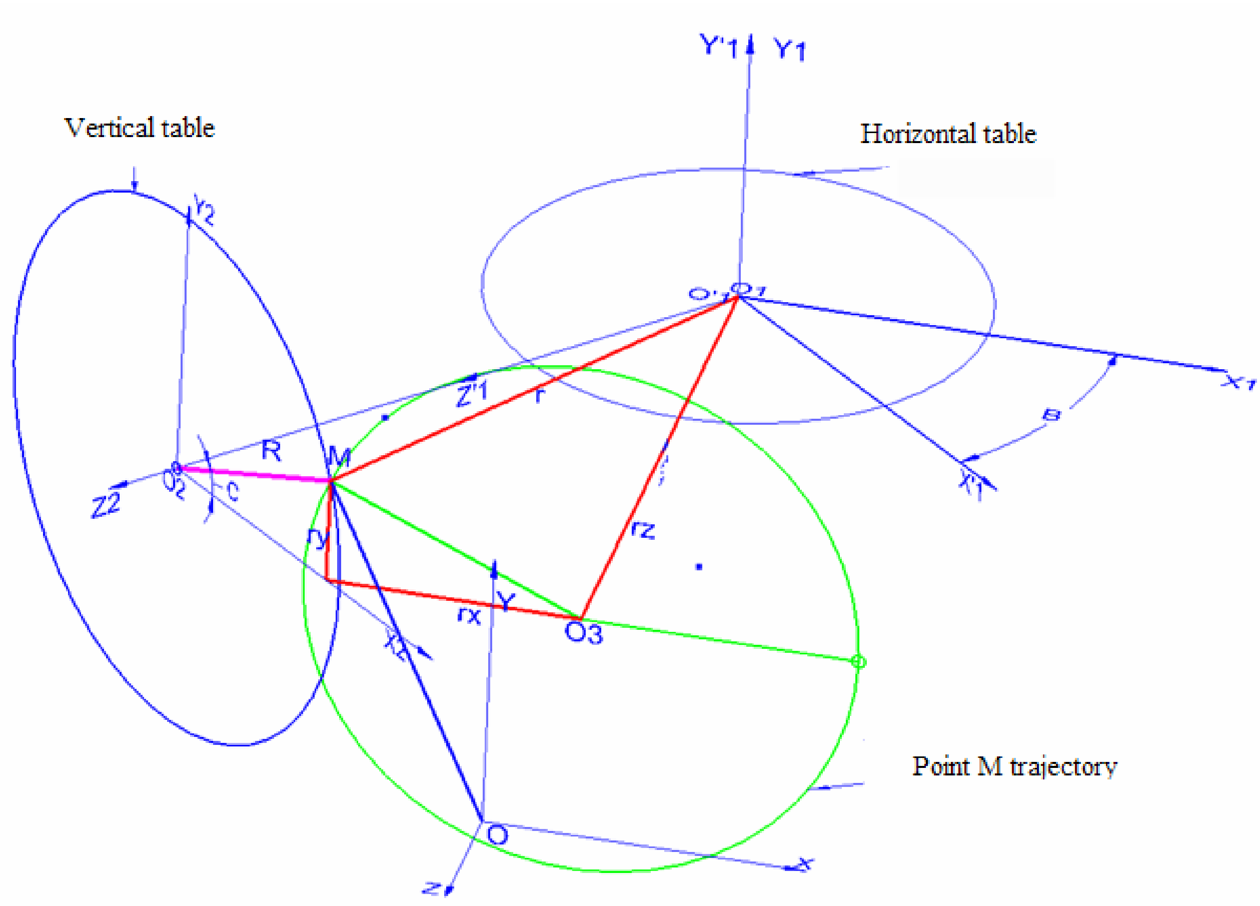


Fig. 2 – Schematics for computing point M trajectory.

Point M coordinates related to $O_2X_2Y_2Z_2$ system are given by the following equations:

$$r_{2M} = \begin{cases} r_{2x} = R \cdot \cos C \\ r_{2y} = R \cdot \sin C \\ r_{2z} = 0 \end{cases}. \tag{1}$$

In $O'_1X'_1Y'_1Z'_1$ mobile system the equations of point M are:

$$r'_M = M_{O'_1O_2} r_{2M}. \tag{2}$$

In homogenies coordinates the transfer matrix is as follows:

$$M_{O'_1O_2} = \begin{Vmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d \\ 0 & 0 & 0 & 1 \end{Vmatrix}, \tag{3}$$

$$r'_{1M} = \begin{cases} r'_{1x} = R \cdot \cos C \\ r'_{1y} = R \cdot \sin C \\ r'_{1z} = d \end{cases}. \tag{4}$$

In the fixed system $O_1X_1Y_1Z_1$, the equations of point M are:

$$r'_{1M} = M_{O_1O'_1} r'_{1M}. \tag{5}$$

The transfer matrix is:

$$M_{O_1O'_1} = \begin{Vmatrix} \cos B & 0 & -\sin B & 0 \\ 0 & 1 & 0 & 0 \\ \sin B & 0 & \cos B & 1 \\ 0 & 0 & 0 & 1 \end{Vmatrix}. \tag{6}$$

After computation, the following expressions results:

$$r_{2M} = \begin{cases} r_{1x} = R \cdot \cos B \cdot \cos C - d \cdot \sin B \\ r_{1y} = R \cdot \sin C \\ r_{1z} = R \cdot \sin B \cdot \cos C + d \cdot \cos B \end{cases}. \tag{7}$$

From the condition that the trajectory of point M has to be in a plane:

$$r_{1z} = d, \tag{8}$$

and replacing in the third equation of relations (7) we will obtain:

$$C = \arccos\left(\frac{d - d \cdot \cos B}{R \cdot \sin B}\right). \tag{9}$$

Relation (9) expresses the correlation between the rotation and tilt angles, which can be used to generate an NC (G code) program, giving a set of values for angle B (for example from 1 to 360 with a step of 0.01 degrees) we will obtain the corresponding values for angle C.

3. NUMERIC RESULTS

Knowing the geometric elements of the rotary-tilting table, the authors developed a program to test the computation of angles B and C versus the trajectory of point M.

The flowchart of the program is given in Fig. 3:

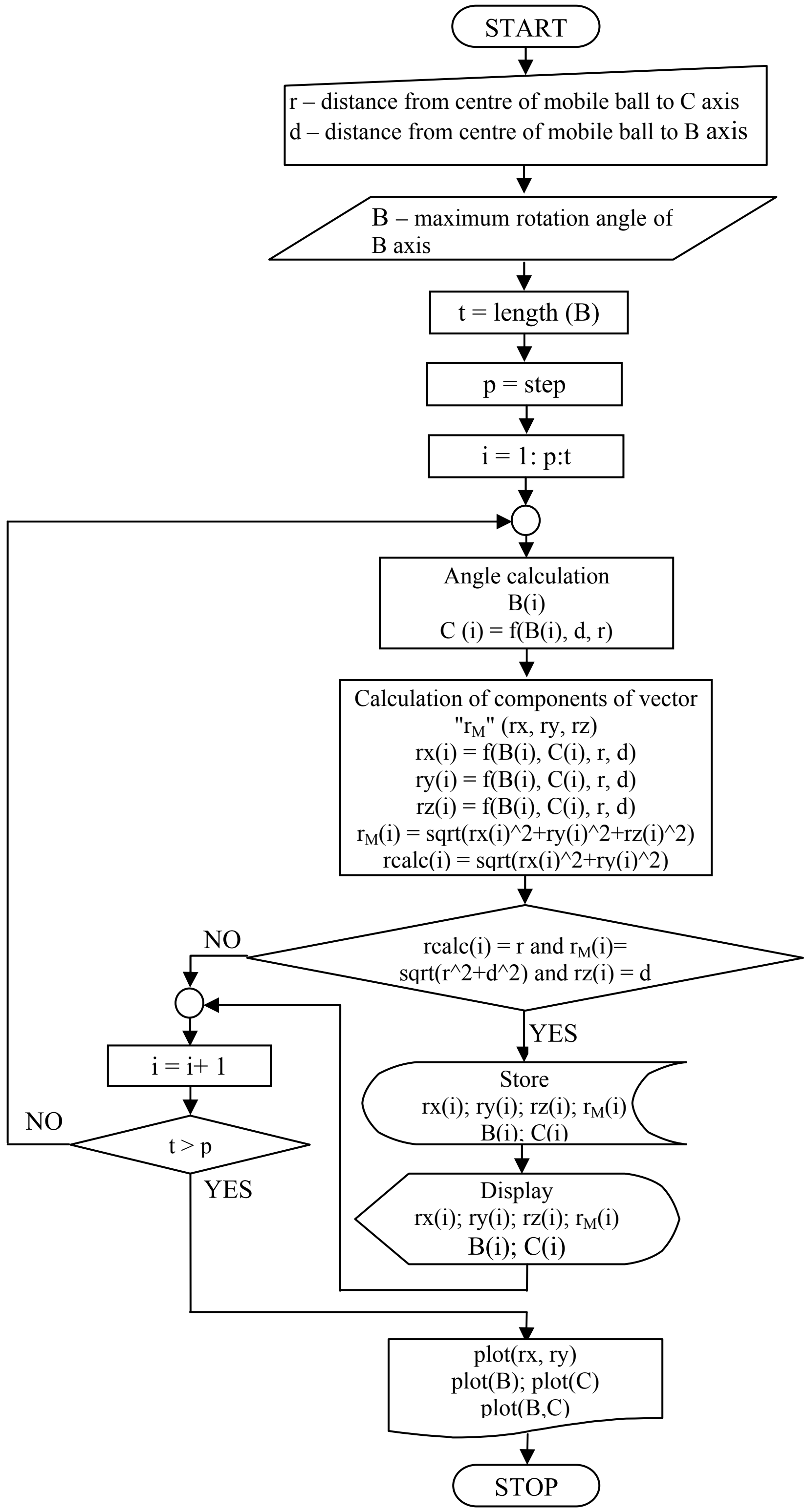


Fig. 3 – Flowchart for determination of point *M* trajectory.

– the radius of ball centre on the vertical plateau is $R = 100$ mm.
– distance from the centre of the ball to the centre of the horizontal plateau:

$$d = 239.433 \text{ mm};$$

– range of horizontal plateau angle (*B* axis)

$$B = – 45:1:45 \text{ degrees.}$$

Graphical representation of point *M* trajectory is given in Figs. 4–5 the dependence of *C* axis rotation angle on the *B* axis rotation angle is shown.

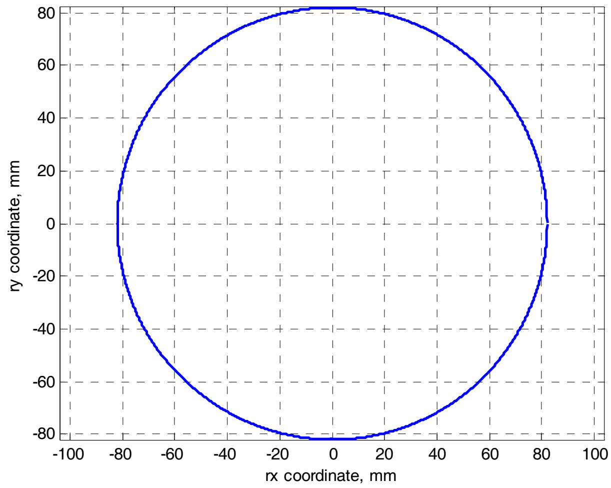


Fig. 4 – Trajectory of point *M* generated by the program.

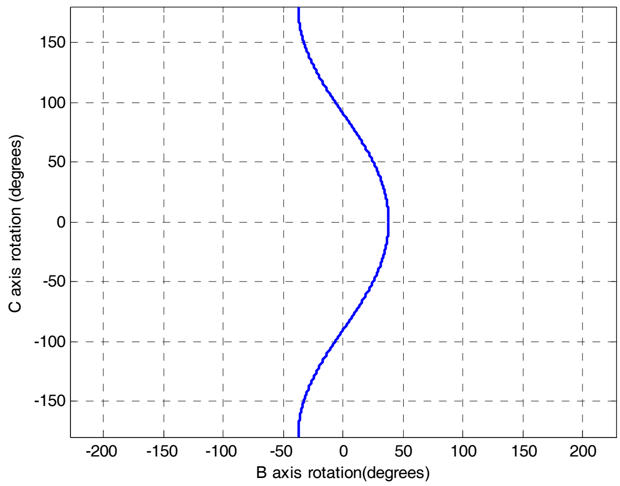


Fig. 5 – *C* axis rotation versus *B* axis rotation generated by the program.

In Fig. 6 evolution of *B* and *C* axis rotations are presented as fucntion of points on the generated circle.

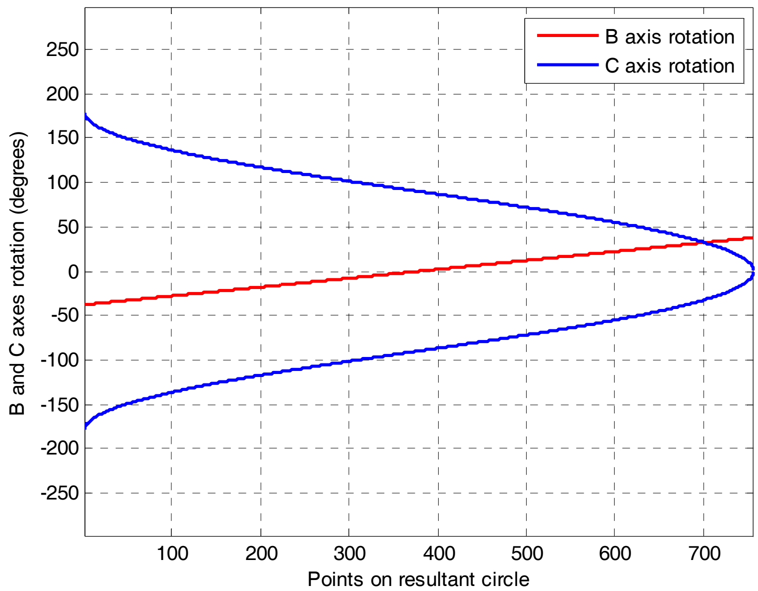


Fig. 6 – *B* and *C* axis rotation versus points on the generated circle.

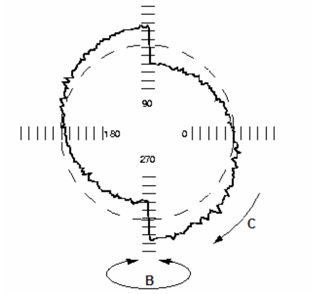
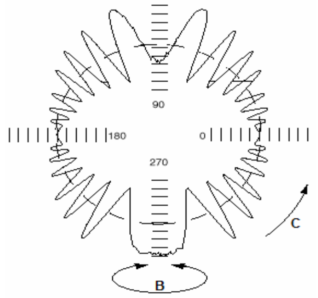
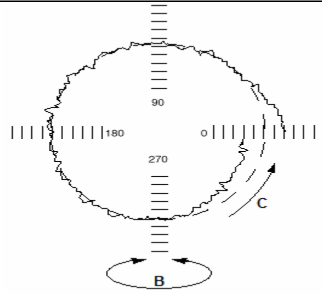
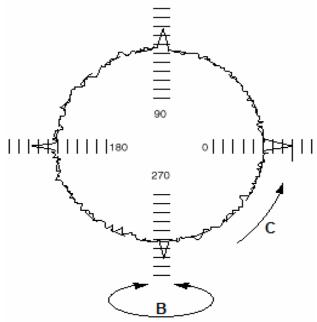
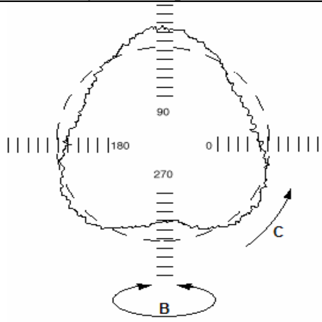
4. EXPERIMENTAL STUDY

4.1. TYPICAL ERRORS REVEALED BY THE BALL-BAR SYSTEM AND THEIR CAUSES

In Table 1, the typical possible error diagrams generated by the ball-bar system during testing are presented with their causes.

Table 1

Errors and their causes

Diagram shape			
Cause	1. There may be play in the drive system of the machine. This is typically caused by worm end float or a worm drive nut.	2. An axis worm gear (in this case, the *C* axis) has a cyclic error problem or there may be an eccentricity in the encoder or worm gear mounting.	3. Can by an error of the ball-bar mounting, the spindle may be unlocked and rotating, the part program may not match the software setup. In some cases, what appears to be a spiral plot can actually be unequal backlash.
Diagram shape			
Cause	4. When an axis is being driven in one direction and then has to reverse and move in the opposite direction, instead of reversing smoothly it may pause momentarily at the turnaround point. There are several possible causes of this problem: – an inadequate amount of torque has been applied by the axis drive motor at the axis reversal point causing it to stick momentarily at the reversal point, as the frictional forces change direction; – the servo response time of the machine is inadequate on backlash compensation. This means that the machine is unable to compensate for the backlash in time; causing the axis to stop while the slack caused by the backlash is being taken up.		5. The error is caused by the fact that the *B* axis of rotation is not vertical but tilted with a very small angle (misalignment of *B* axis).

4.2. EXPERIMENTAL RESULTS ON THE ROTARY-TILTING TABLE

At the University of Oradea, Faculty of Management and Technology Engineering a 5 axis horizontal machining center had been developed. This machine is equipped is a rotary-tilting table which adds two rotation axis (*B* and *C*) to the machines linear axis *X*, *Y* and *Z*. The configuration of the 5 axis is presented in Fig. 7 and the mounted ball-bar system is presented in Fig. 8.

After making the first set of measurements, the resulting ball-bar diagrams had shown large errors which had been identified (based on cases presented in Table 1) as unequal backlash in the worm gear assembly (Fig. 9).

Another measurement had proved that there is also an error of misalignment of *B* axis in the vertical direction (Fig. 10).

Having indentified the causes of errors, measures had been taken to correct these errors and the ball-bar tests had been made again. Resulting diagrams after the correction had been made shows that the errors had been eliminated as it is clearly shown in Fig. 11.

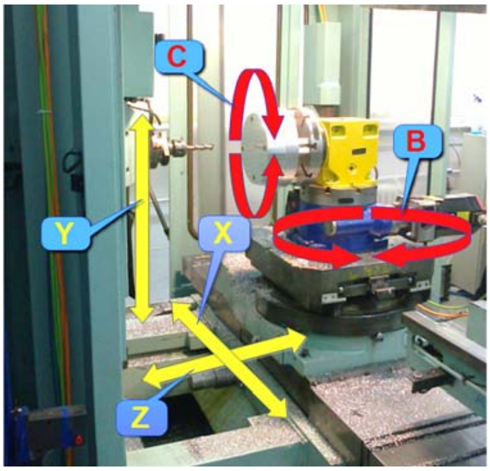


Fig. 7 – Five axis CNC machining center.

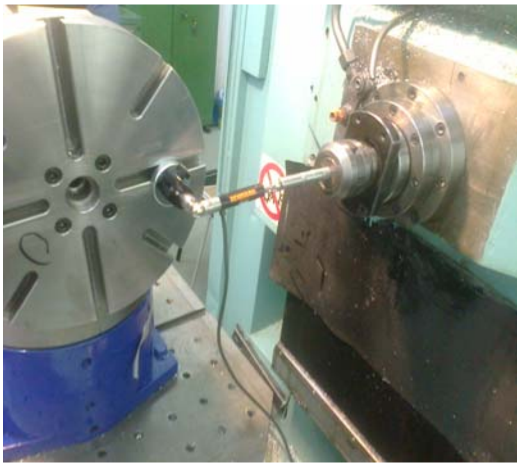


Fig. 8 – Mounted ball-bar system for *B* and *C* axis testing.

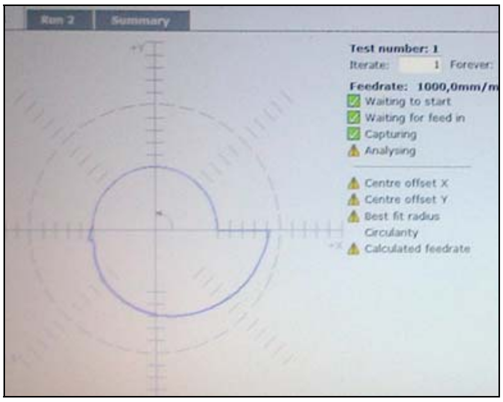


Fig. 9 – Errors caused by large unequal backlashes in the worm gear assembly.

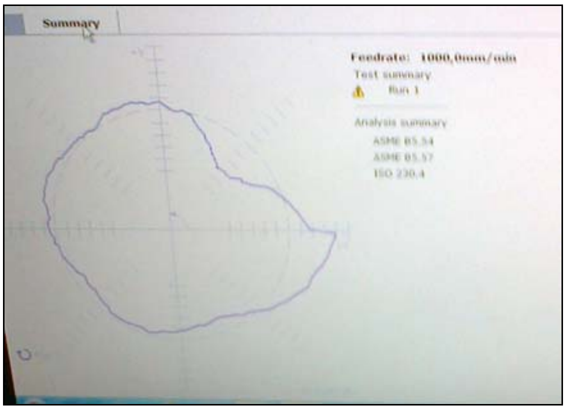


Fig. 10 – Error of misalignment of *B* axis in the vertical direction.

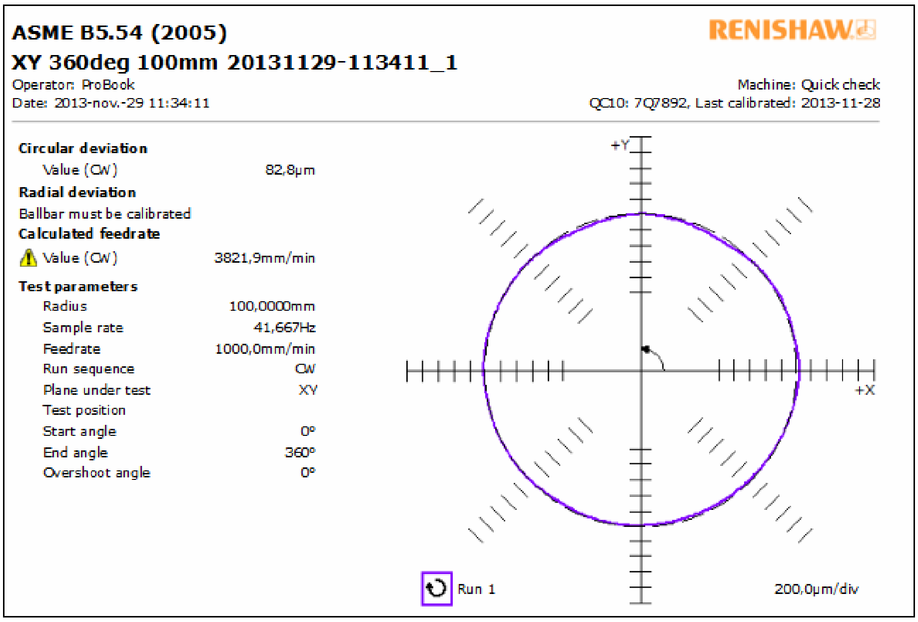


Fig. 11 – Error diagram for circular interpolation on *B* and *C* axis after the correction of worm gear assembly backlash.

5. CONCLUSIONS

Evaluation of precision of simultaneous 5 axis machining centers is a complex problem which presumes the development of new procedures based on mathematic relations defining correlations of two rotation axis.

Our paper proposes a method of evaluation of geometric precision of a rotary-tilting table using the ball-bar system. Development of the method is made by establishing the correlation between the two rotations (by the axis *B* and *C*). In order to check the correctness of the method a numeric simulation model, 3D measurement system and also experimental measurements had been made. Using the proposed method the geometric errors of the rotary-tilting table had been corrected.

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