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GEOMETRIC ERRORS ANALYSIS IN MACHINING ON CNC MACHINE TOOLS

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Abstract: *In this paper the geometric volumetric accuracy of the machine tools is defined. A NC milling machine with three axes X, Y, Z is considered and a methodology is proposed for evaluating the geometric accuracy, important in the precise processing of parts. The application is based on the structure of a vertical milling machine, configured on computer. The deviations from the evaluation are useful in correcting the part NC program to control the machine tool. The geometric analysis of the machine tool is performed using components and assemblies that provide displacements in the three motion directions. For displacements, besides the deviations in the movement direction, spatial deviations exist. In each displacement direction, three deviations are defined for linear positioning* δ_x, δ_y, δ_z *and the roll, pitch and yaw errors,* ε_x, ε_y, ε_z. *Finally, based on the determined values, it is presented how these deviations are applied to implement corrections in part NC program.*

Key words: *linear displacement, pitch, roll, geometric errors, volumetric accuracy, NC program, computer program.*

1. INTRODUCTION

Machines and modern technology are characterized by flexibility, simulation possibilities and adaptation to manufacturing complex parts, one of a kind or limited series [4]. In processing parts with high precision on NC machine tools, an important factor is the guide and actuators imprecision. To reduce or to eliminate this drawback regarding the processing imprecision, a pitch correction is applied to the feed screw along the motion direction.

The method of determining the guides configuration through the construction and adjustment diagram shows that the current measurement method does not characterize enough the table or saddle movements or movement errors [5].

An improved approach is proposed that is adequate for the accuracy of the geometric measurements [12, 13]. About this, the correction values of a NC program for processing a part on a NC machine tool can be determined with greater accuracy. The existing NC instructions make possible the application of corrections in the motion direction [15]. The parts surface generation is performed with smaller deviations.

The analysis of the possibilities of processing parts with complex surfaces shows that the use of advanced NC controlled machine tools is extended. The deviations resulting from the ideal motions of the machine tool assemblies can be determined and compensated [9, 17].

The theoretical support of this paper is based on the concept of a generalized machine tool consider as a model in computer. This concept was applied for the first time in the paper [6] and then completed in [7]. The concept of virtual machine tool is used and developed in previous papers of the authors (Constantin Sandu and Costin Sandu).

According to this concept, their configuration is analytically defined: the form of the cutting edges (Fig. 1), the position and movements of the machine tool moving elements, the displaying in time of the generating motions.

These generating motions are mainly performed along or around an axis (couple shaft-bearing or saddle-guides) of the coordinates system attached to each fixed or mobile element, which takes part into the generating process [1, 6, 7].

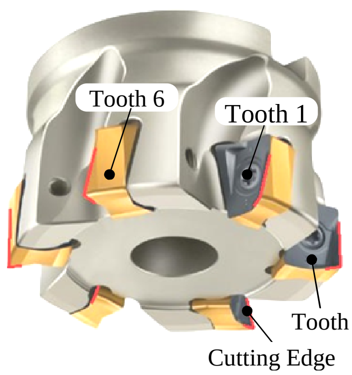

Fig. 1. Cutting tool with cutting edge definition used in generating theory.

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In practice it was found that some deviations from the motion paths of the machine tools assemblies are larger than others [8]. For example, those along a direction of movement are higher than those in the perpendicular direction. To increase the processing accuracy, corrections are applied by adding or removing an ammount of the measured value in the direction of the analyzed movement. For this, in the measurement system memory there is a table of corrections. This system needs tens of µs of the microprocessor time during execution and it fits in real time execution.

2. THEORETICAL ASPECTS

The basic elements of generating a curve are briefly presented in Fig. 2, where: T represents the cutting edge placed in its initial position (T_0), at moment w (T_w) and namely at moment $w + \Delta w$ ($T_{w+\Delta w}$); P – part, [S_T] – topographic area; $M_wM_{w+\Delta w}$ – fragment generated on surface [S_T] by the cutting edge, between moment w and moment $w + \Delta w$; S_P – the coordinates system attached to the piece and (C) – motion path of the cutting edge. In the analyzed case, this has one of the axes as an axis of a rotation of the machine [6, 11].

The cutting tool (Fig. 1) is characterized by one tooth or teeth having cutting edges analytically defined.

The movement along the curve (C) is provided by two branches, of the tool and of the part.

Another element is represented by the coordinate system XYZ. The next element which supports the virtual machine performing is the definition of the topographic planes of the part used in creation of generated surface.

The process of assessing the geometric accuracy takes into account that for the movement directions X, Y, or Z there are measured errors δ_x, δ_y, δ_z. These are processed and inserted in the NC part program as corrections. Numerous scientific papers present methodologies for the evaluation of the geometric accuracy [2, 16] during movement on an axes (e.g. X), where three linear errors δ_{xx}, δ_{xy}, δ_{xz}, and three rotation ones ε_{xx}, ε_{xy}, ε_{xz} [3, 4, and 14] are considered but not applied in the part NC codes.

Considering that the machine tool table (1) moves in X direction (Fig. 3), it is chosen a point M (x_M, y_M, z_M) in the workspace (2) which measures the linear motion

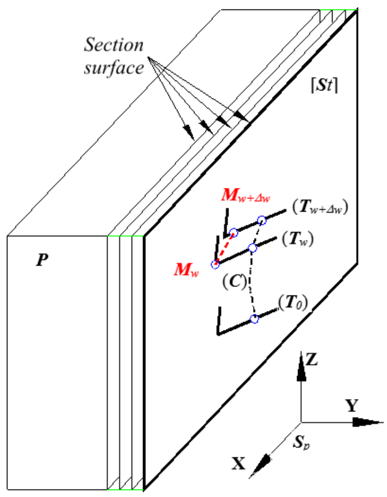

Fig. 2. Generation elements.

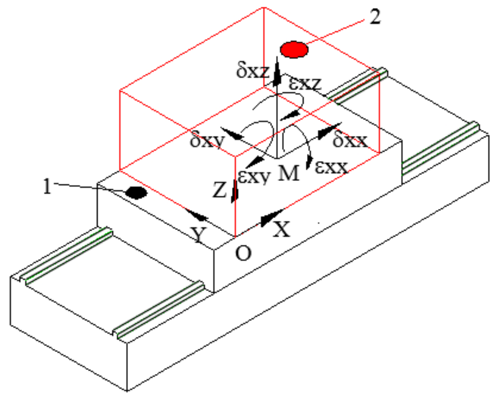

Fig. 3. Error definition in a point.

errors δ_{xx}, δ_{xy} and δ_{xz} along the coordinate axes X, Y, Z and the angular movement errors ε_{xx}, ε_{xy} and ε_{xz} around the respective axes. In Fig. 3, the frame origin coincides with the workspace origin O (0, 0, 0).

The measurement errors have indices composed of two letters, the first letter indicating the direction of movement, and the second one the direction of errors for the linear axes or around which axis the circular errors are measured. The term δ indicates the linear errors and ε the circular ones.

This paper proposes the approach of the motion errors of each moving element (table, saddle, and head) in the longitudinal direction X, transversal Y and vertical Z, namely:

- for the movement in the X direction, two more linear errors δ_{xy} and δ_{xz} and three rotational errors ε_{xx}, ε_{xy}, ε_{xz} are added to the error δ_{yy};
- for the movement in the Y direction, two more linear errors δ_{yx} and δ_{xz} and three rotational errors ε_{yx}, ε_{yy}, ε_{yz} are added to the error δ_{yy};
- for the movement in the Z direction, two more linear errors δ_{yx} and δ_{xz} and three rotational errors ε_{zx}, ε_{yy}, ε_{yz} are added to the error δ_{yy};

The basis of the virtual machine construction consists of an ample computing program elaborated and checked in time on various practical applications. The program is modularly created, having interfaces communicating with the operator and machine.

3. APPLICATION

In operation of the machine tools, their table movements must be done accurately. This aim is enabled by the machining accuracy of machine parts, alignment and fastening of the guides. The table motion is influenced by the guide geometric shapes achieved by processing and aligning during mounting, and also by positioning some adjustment elements of the machine tool with regard to the foundation.

3.1. The measuring method

To measure the geometrical precision of the machine tool [5, 11] standard devices (rulers, angles, prisms, and columns), levels, optical devices (telemeters, laser) are used.

An example of using the level is represented in Figs. 4,*a* and 4,*b* where the motion precision measurement in

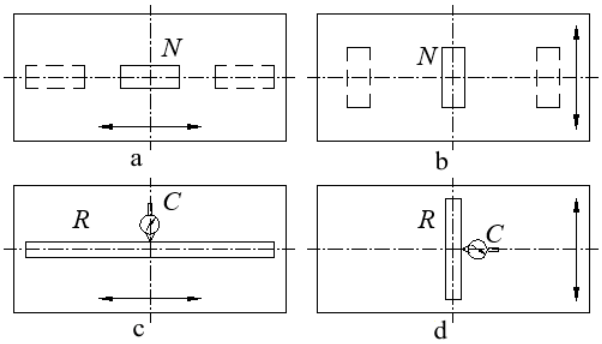

Fig. 4. Actual accuracy test: *a*, *b* – level; *c*, *d* – ruler.

two perpendicular directions is done using a level (*N*), placed and positioned successively in different locations on the machine table.

In Figs. 4,*c* and 4,*d* the measuring scheme of the motion precision using a standard ruler (*R*) (with two surfaces perpendicular, respectively parallel to the movement direction) is presented. The reading is performed on both surfaces with a dial gauge *C* placed in a fixed position on the bed frame.

During the experimental determinations made over a period of time it was found that this measurement method does not fully characterize the precision of table motions.

The construction of each table is characterized by three bearing surfaces. The geometric accuracy is determined by the precision of machined surfaces, assembling accuracy, or by the deformation introduced by the fastening components.

For assessing the precision of the machine tool, a measurement scheme is proposed in the analyzed case (Fig. 5).

It is considered the measuring precision of the table 5 motion and of the transversal saddle 14.

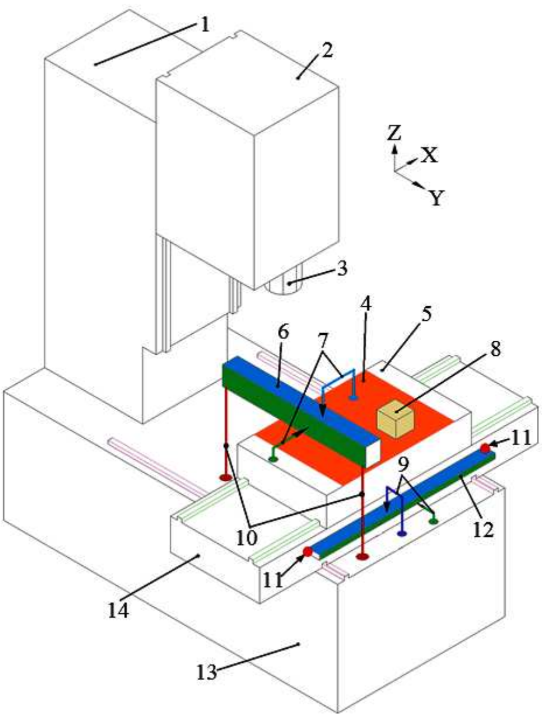

Fig. 5. Proposed accuracy test.

The measurement reference elements consist of surfaces of some assemblies or structural elements of the machine tool or standard rulers.

Thus, for each direction of movement, the standard rulers are mounted, namely: ruler 12 for motion in *X* direction, and ruler 6 for *Y* direction. Ruler 12 is fixed in the transversal saddle 14 through the elements 11 and ruler 6 is fixed by the elements 10 on the bed 13. Each ruler is palpated on the two surfaces by dial gauges 9 and 7. To measure in an optical way, it is used the prism 8 mounted on the machine tool table in selected points. The vertical saddle (head) 2, containing the main shaft 3, is moving in the *Z* direction on column 1. The transversal saddle 14 is moving on the bed frame in the *Y* direction. Surface 4 is the working surface on level $Z = 0$.

There are supplementary errors due to inaccuracies of motion in the three directions *X*, *Y* and *Z*, measured by the optical prism 8. These errors are caused by the transformation mechanisms of the rotation into translation or by imprecision of the linear electric motors.

3.2. Results analysis

For example, the measurement was made on the NC machine tool shown in Fig. 5. Three measuring points *A*, *B* and *C* are considered on the machine table and three more points D, E and F on the vertical saddle. In the established measuring points the deviations of each one in *X*, *Y* and *Z* directions are determined. The measurement phases correspond to the machine table movement in *X* direction (500 mm) and the *Y* direction (400 mm) on the length of their movement. For the vertical head motion on along the column, the measurement is done in *Z* direction (350 mm).

The cause of the errors is the imprecision of guides and deformations that occur due to the weight of some assemblies and of structural elements that compose the machine tool [10]. The measured data result in diagrams of displacement errors.

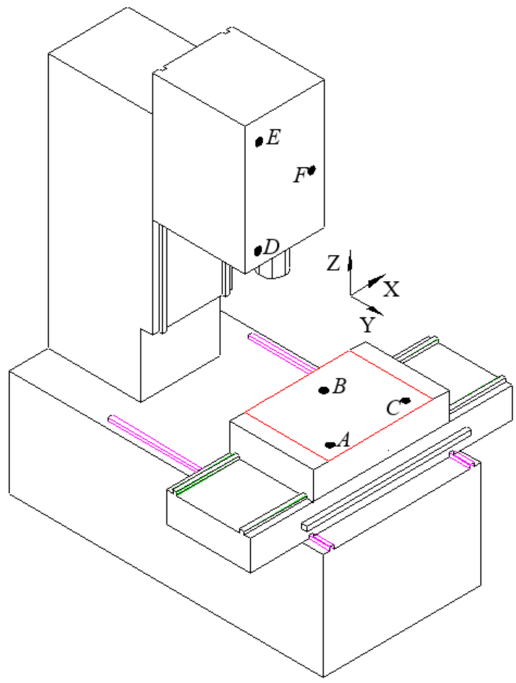

Fig. 6. Positions of the measuring points *A. B, C, D, E, F*.

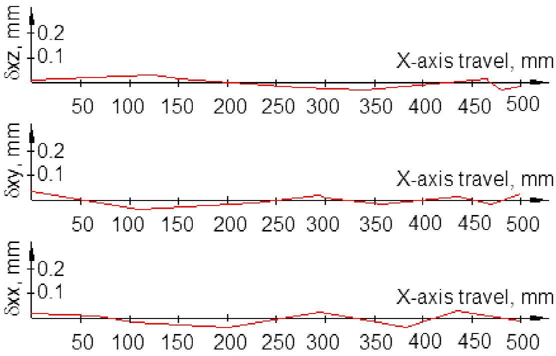

Fig. 7. Linear errors for point *A*.

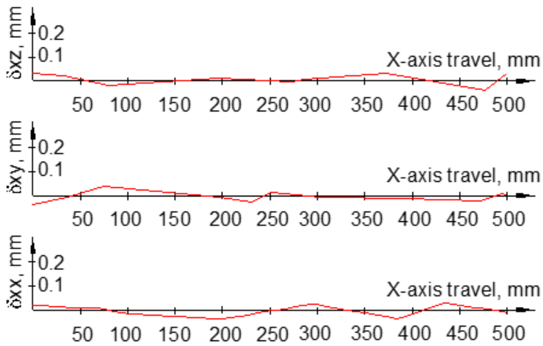

Fig. 8. Linear errors for point *B*.

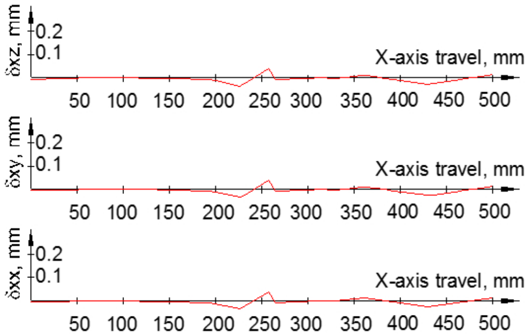

Fig. 9. Linear errors for point *C*.

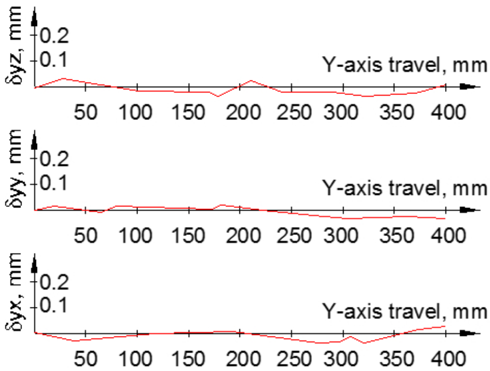

Fig. 10. Linear errors for point *A*.

According to the measurement data and calculation methodology the geometric motion errors on three axes were determined: *X* (Figs. 7, 8, 9), *Y* (Figs. 10, 11, 12) and *Z* (Figs. 13, 14, 15).

In these figures the corresponding errors for the mentioned movements are represented in the limits of the motion strokes.

Points *A*, *B*, *C*, and *D*, *E*, *F* determine a plane of the machine tool table or of the vertical head respectively. During the movement, these two planes are rotating about the axes, resulting the well errors pitch, roll, and yaw.

Values of the respective errors may be determined by calculation and are represented in Fig. 16.

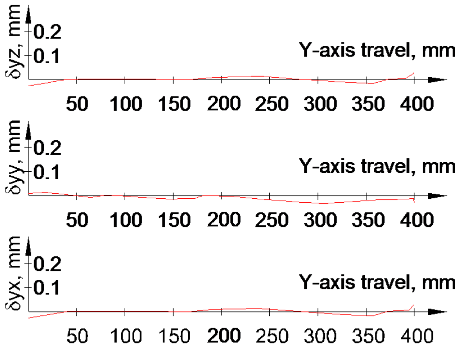

Fig. 11. Linear errors for point *B*.

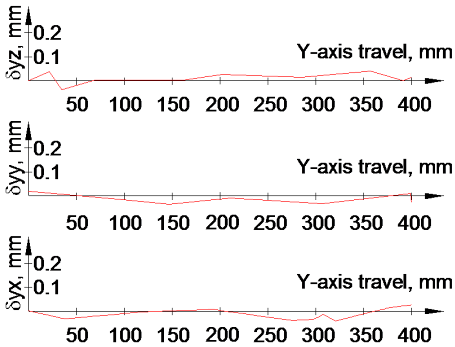

Fig. 12. Linear errors for point *C*.

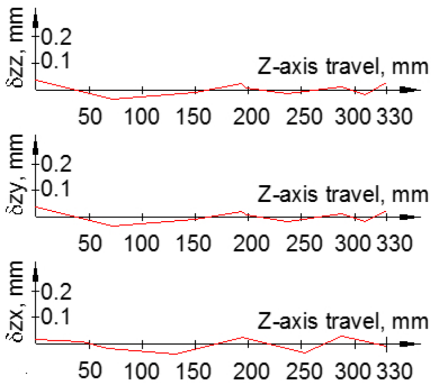

Fig. 13. Linear errors for point *A*.

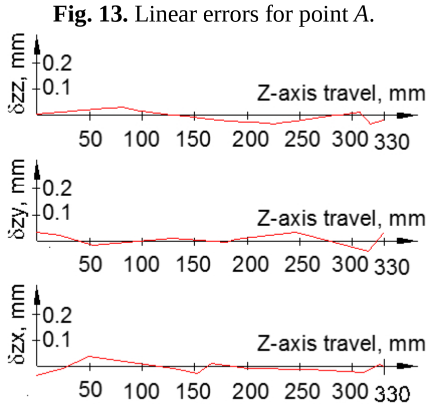

Fig. 14. Linear errors for point *B*.

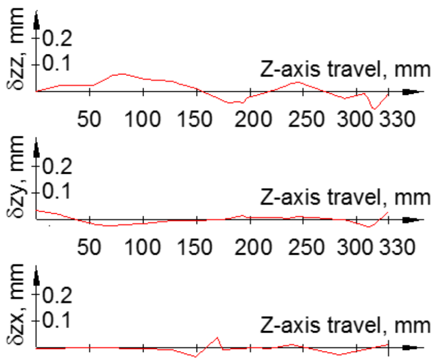

Fig. 15. Linear errors for point *C*.

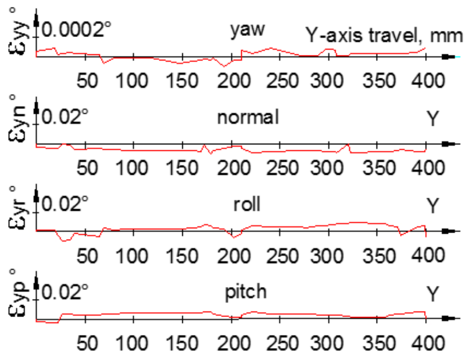

Fig. 16. Angular errors for *X* = 0.

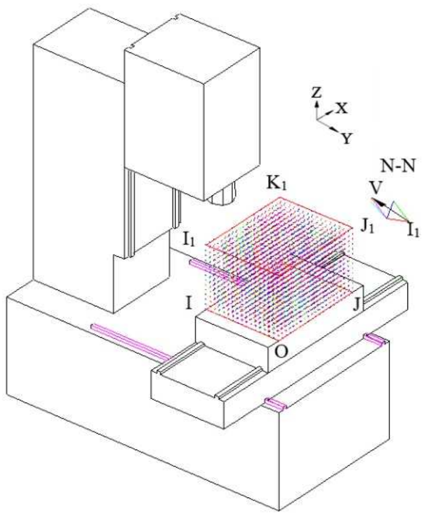

Fig. 17. Correction vectors in the workspace.

To determine the positioning deviations in the workspace of the considered machine tool, the theory of generating surfaces given by [1, 5, and 6] is applied. In machining, a cutting edge intersects theoretically or according to the NC part program a topographic surface of the workpiece (Fig. 2) after a curve $M_wM_{w+\Delta w}$. In real cutting, due to the motion errors the theoretical curve becomes $M'_wM'_{w+\Delta w'}$. Therefore, by determining the vectros $M_wM'_w$ and $M_{w+\Delta w}M'_{w+\Delta w'}$, the real position of the generating point is established.

Deviations representation is done as spatial correction vectors (Fig. 17) in the workspace shown by the cuboid *O* (0, 0, 0), *I*, *J*, I_1, K_1 (500, 400, 330), J_1. A set of points placed in the *Z* direction at a distance of 25 mm above the machine tool table were considered. The detail N-N contains the correction vectors in the point I_1.

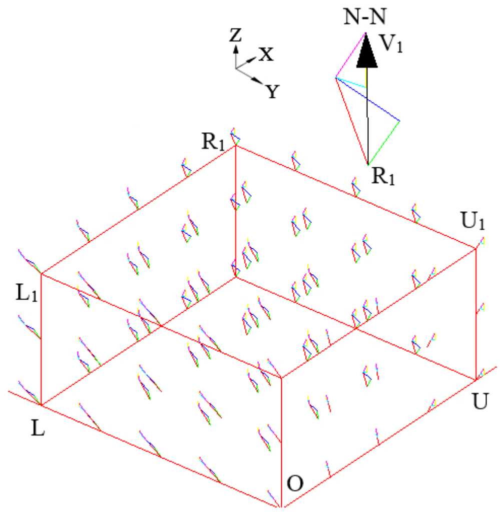

Fig. 18. Linear errors for point *C*.

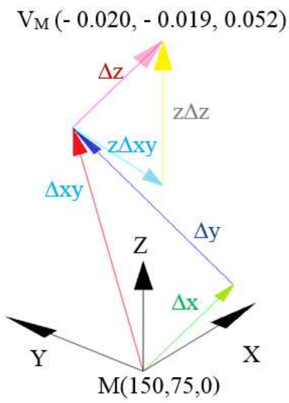

Fig. 19. Correction vectors in a point.

In Fig. 18 only the correction vectors in the workspace contained in the cuboid *O* (0, 0, 0), *L*, *U*, L_1, R_1 (200, 200, 150), U_1 are presented in a detail.

Thus, in Fig. 19, for example, in the point *M* (150, 75, 0) in the workspace, the error vectors defined by size and direction are represented.

The Δxy vector is the sum of vectors (δ_x) obtained by moving the machine tool table in *X* direction and (δ_y) in *Y* direction. The Δzxy vector is the sum of vectors obtained by moving the vertical head in *Z* direction, namely $z\Delta xy$ (deviation in the *XY* plane) and $z\Delta z$ (deviation in *Z* direction). Vectors are obtained in the workspace (0, 0, 0) ... (500, 400, 330), in mm. Also, in Fig. 18 there is a partial representation only for the vectors placed in the workspace (0, 0, 0) ... (200, 200, 150), values considered in the directions *X*, *Y* and *Z*.

The calculated deviations in the points situated in the workspace determine values of correction in the part NC program. As an example (Fig. 19), for the point *M* (150, 75, 0) the corrections are: –0.020 mm on X, –0.019 mm on *Y* , and 0.052 mm on *Z* axes.

Correction values determined for various analyzed points are introduced into the part program. Some examples of changes in phrases of the part program are:

N100 X150 Y75 Z0 F100 *becomes*
N100 X149.980 Y74.981 Z0.052 F100;
N100 X150 F100 *becomes*

N100 X149.980 F100;
N100 Y75 F100 *becomes*
N100 Y74.981 F100;
N100 Z0 F100 *becomes*
N100 Z0.052 F100.

4. CONCLUSIONS

The precision machining of parts requires knowing the linear and angular errors, measured in the motion directions of the machine tool, through successive movements of the table (on X and Y axes) and of the vertical head (on Z axis).

Even if the value of the angular errors is of thousandths of a degree, it is necessary to take them into account. Thus, it was numerically determined that for an angular error of ± 0.005°, in processing there will be a difference of ± 0.25 mm for a tool of diameter D_c = 50 mm and ± 0.05 mm for tool of diameter D_c = 10 mm. These errors may substantially exceed the permissible values accepted as corrections in processing on the analyzed machine tool of some medium or high precision surfaces.

For introducing the necessary corrections described above, it is necessary:

- to exist the possibility and an engineer specialized in using the CNC equipment of the machine tool;
- that in the NC equipment computer or in a computer connected with the NC equipment a special program is required to be loaded and run for modifying the point coordinates given in the original NC program by considering the corrections calculated on the basis of the errors measured on the machine tool.

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REFERENCES

[1] C. Sandu, *Contribuţii privind îmbunătăţirea calităţilor dinamice ale lanţului cinematic de rulare la maşina de prelucrat roţi dinţate* (Contributions to the improvement of dynamic qualities of rolling kinematic chain in gear processing machine.), PhD Thesis, Institutul Politehnic, Bucharest, 1987.
[2] G. Constantin, *Cercetări privind precizia geometrică a maşinilor-unelte cu comandă numerică* (Research on geometric precision of CNC machine tools), PhD Thesis, University "Politehnica" of Bucharest, 1995.
[3] D.A. Dornfeld, D.E. Lee, *Machine design for precision manufacturing*, Springer Science Business Media, LLC, New-York, 2008.
[4] L.N. Lopez de Lecalle, A. Lamikiz, *Machine Tools for High Performance Machining*, Springer-Verlag London Limited, 2008.
[5] M. Weck, Ch. Brecher, *Werkzeugmaschinen. Messtechnische Untersuchung und Beurteilung dynamische stabilitat* (Machine tools. Metrological inspection and assessment of dynamic stability), VDI-Buch, Springer, 2008.
[6] C. Sandu, Co. Sandu, G. Dobre, *New Principles for Surface Generation Starting from the System Machine Tools and Tools*, Scientific Bulletin of North University of Baia Mare, Series C, Volume XIV, pp. 233–238, România, 2000.
[7] C. Sandu, G. Dobre, Co. Sandu, *On contact of conjugated flanks generated in the system machine tools – tools*, International Conference on Manufacturing Systems, Edit. Tehnică, Bucharest, Journal TCMM, No. 41, 2000, pp. 263–268.
[8] N. Predincea, C. Minciu, G. Constantin, M. Zapciu, *Geometric accuracy of machine tools*, Journal TCMM, No. 11, 1995, Edit. Tehnică, Bucharest, pp. 138–150.
[9] M. Košinar, I. Kuric, Cr. Mohora, *Innovative method for measurement of geometric accuracy of machine tool*, Proceedings in Manufacturing Systems, Vol. 8, Issue 4, 2013, pp. 245–250.
[10] A. Ghionea, G. Constantin, I. Ghionea, L. C. Popa, *Aspects of kinematic structure configuration and working possibilities of milling machining centers*, Proceedings of the IMC 2013 International Multidisciplinary Conference, Bessenyei Publishing House, pp. 59–64, North University of Baia Mare România and University College of Nyiregyhaza Hungary, May 2013.
[11] W. Knap, *Measurement uncertainty and machine tool testing*, Annals of the CIRP, Vol. 51, Nr. 1, 2002, pp. 459–463.
[12] S. Sartori, G.X Zang, *Geometric erorr measurement and compensation of machines*, Annals of the CIRP Vol. 44, No. 2, 1995, pp. 599–609.
[13] H. Schwenke, W. Knapp, H. Haitjema, A. Weckemann, R. Schmitt, F. Delbressine, *Geometric erorr measurement and compensation of machine*, CIRP Annals, Manufacturing Technology, Vol. 57, No. 2, 2008, pp. 660–675.
[14] G. Chen, J. Yuan, J. Ni, *A displacement measurement approach for Machine geometric error assessment*. International Journal of Machine Tools & Manufacture 41, Pergamon, 2001, pp. 149–161.
[15] Z. Du, S. Zhang, M. Hong, *Development of a multistep measuring method for motion accuracy of NC machine tools based on cross grid encoder*, International Journal of Machine Tools & Manufacture, Elsevier, Vol. 50, 2010, pp. 270–280.
[16] ***, ISO International Standard Committee Draft ISO/CD 230/1.4: *Test Code for Machine Tools*. Part 1. *Geometric accuracy of machines operating under no-load or quasi-static conditions*, Part 2. *Determination of accuracy and repeatability of postioning of numerically controlled axes*, ISO, Geneva, 2006.
[17] ***, ISO 10791-2: 2001, *Test Conditions for machines Centres*. Part 2: *Geometric Tests for machines with Spindle on Universal Heads with Vertical Primary Rotors, Axis*, ISO, Geneva, 2001.