RESEARCHES REGARDING THE ASSESSMENT OF MANUFACTURING ACCURACY OF NUMERICALLY CONTROLLED MACHINE-TOOLS

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ABSTRACT: The manufacturing technology evolves rapidly, nowadays most of the manufacturing processes being unfolded on numerically controlled machine-tools (NCMT). In order to use properly this kind of equipment, some characteristics have to be accurately assessed. This work presents some experimental researches unfolded on NCMT in order to assess their manufacturing accuracy. The manufacturing accuracy of NCMT has a major influence upon the shape and dimensional accuracy of the manufactured parts. The results obtained within this work will be further used to build a knowledge database used for improving the manufacturing accuracy on NCMT.

KEY WORDS: manufacturing accuracy, positioning accuracy, contouring accuracy, errors.

1 INTRODUCTION

The accuracy of a numerically controlled machine-tool (NCTM) is assessed taking into consideration both the positioning accuracy (no-load movements of a single axis) and the contouring accuracy (coordinated simultaneous movements on two or more axes). There are some standardized methods for assessing both types of accuracies.

The positioning accuracy may be assessed using the norm "Numerically controlled machine-tools. Method of assessing the positioning accuracy", developed by ICPMU, Bucureşti, 1978. The contouring accuracy in no-load conditions is assessed using the high-precision inductive transducer Renishaw QC 10 Ballbar.

2 ASSESING THE POSITIONING ACCURACY

2.1 Manufacturing accuracy

The manufacturing accuracy is expressed by means of the manufacturing error seen as the difference between the nominal dimension, imposed by the designer and the current dimension of the part. It is **known** that the manufacturing accuracy and is heavily influenced by the accuracy of the NCMT.

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2.2 Positioning accuracy

In order to test the positioning accuracy of an NCMT, for X and Y axis, no-load test were performed, choosing an usable length of 500 mm on each axis.

The moving space of each axis was split in 10 intervals of 50 mm. The first and the last interval were reduced (5 mm and 40 mm).

Each slide was moved from initial to the final position, going through the same points in both directions.

The differences between the programmed position and the real positions were determined, for a BLU (basic length unit) of 5 µm. The measurements were repeated five times for each position. A laser interferometer was used as measuring device.

The deviation Δx_j^i for each position may be calculated as:

$$\Delta x_j^i = x_{Rj}^i - x_{Pj} \tag{1}$$

The standard deviation S_j, for each movement direction may be expressed as:

$$S_j = a_i x \overline{D}_j,\ 10 \geq i \geq 5 \tag{2}$$

According to the norm mentioned in paragraph 1, a_5=0.4299. The maximum width of the spread R_j, also known as repeatability for each movement direction may be expressed as:

$$R_j = 6S_j \tag{3}$$

After the calculations of this parameters two pairs of curves (one pair for each direction) are plot. These curves are obtained by translating the points from the curves $\overline{\Delta x}_j$ by a distance equal with $\pm 3S_j$.

The positioning tolerance M, may be determined either graphically, or calculated using the relation:

$$M = \max(\overline{\Delta}x_j + 3S_j)\uparrow or \downarrow - \min(\overline{\Delta}x_j - 3S_j)\uparrow or \downarrow \quad (4)$$

The insensibility N may be calculated with the relation:

$$N = \max(\overline{\Delta}x_j \uparrow - \overline{\Delta}x_j \downarrow) \quad (5)$$

The resulting values, calculated according to the relations presented above are displayed in figure 1, for Y axis.

The values for *M* and *N* are:

M ↑ =19.08µm

M ↓ =15.508µm

N = 4.2 µm

The resulting values, calculated according to the relations presented above are displayed in figure 2, for X axis.

The values for *M* and *N* are:

M ↑ =16.71µm

M ↓ =14.219µm

N = 4.0 µm

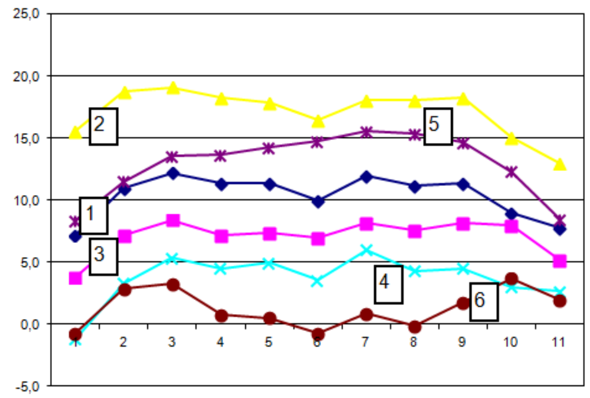

Figure 1. Checking diagram for Y axis

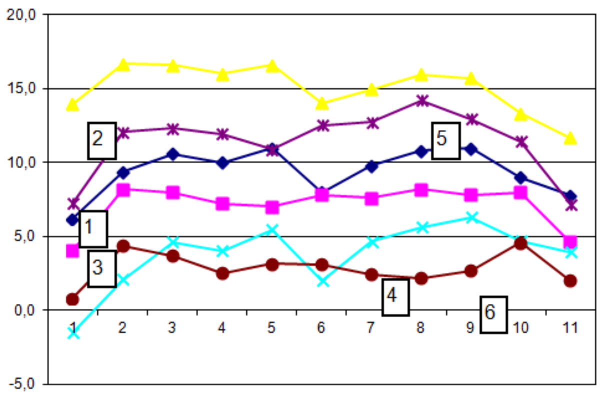

Figure 2. Checking diagram for X axis

The measurements had shown similar results regarding the positioning accuracy on both X and Y axis.

The results on Y axis were presented first, because it supports the weight of X axis. However, the effect of the weight and inertia of X axis upon Y axis proved to be insignificant.

3 EXPERIMENTAL RESEARCHES REGARDING THE CONTOURING ACCURACY IN NO-LOAD AND LOAD CONDITIONS

3.1 Experimental researches regarding the contouring accuracy in no-load conditions

The high-precision inductive transducer Renishaw QC10 Ballbar and the corresponding software package is used for assessing the errors of a NCMT running a circular interpolation in no-load conditions. The QC10 Ballbar system is extremely versatile and it can be used on great variety of equipments.

The standard system can be used for testing 3 axes NCMT, such as vertical and horizontal machining centers. The measurement data are captured, stored and analyzed while the machine unfolds a circular test. During this test, the machine slides are moving simultaneously on X and Y axis, the circular path resulting as a combination of these linear movements by means of an interpolation algorithm. Circular interpolation regime is available on most NCMT.

For the measurements unfolded during this research a 100 mm QC 10 Ballbar device was used for assessing the interpolation errors in no-load conditions for a 3 axes CNC milling machine.

The first step was to install the Ballbar system on the machine table and to connect it with the PC by means of an USB connector. During the measurement, the transducer performs both a clock-wise and a counter clock-wise movement.

The user has to load in the memory of the CNC controller a specific NC program, which controls the movements of the machine slides, driving them on a preset movement cycle, consisting of two full-circles.

The main types of errors which can be highlighted are: backlash, reversal spikes, lateral play, scaling mismatch, squareness error, servo mismatch.

The backlash may be either negative or positive. When he backlash occurs, the plot has a step inwards towards the centre of the plot which starts on an axis.

The size of a backlash step is usually unaffected by the machine feedrate.

The possible cause for backlash is play in the guideways of the machine, causing a jump in motion when the direction in which the machine is being driven changes. Another cause may rely in the fact that the amount of backlash compensation being applied to the machine to cure an existing backlash problem in the machine is too large. This causes a machine which previously had a positive backlash problem to exhibit negative backlash.

The effect of positive backlash on a machine is that a circular interpolated cutter path will show a short flat. The effect of negative backlash on a machine is that a circular interpolated cutter path will show an inward jump.

When reversal spikes occur, the plot has a short spike which starts on an axis. The size of the spike often varies with the machine feedrate. 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. In the example plot the Y axis has paused.

One off the possible causes is 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.

When lateral play occurs, the plot has a symmetrical peach/stone shape. Lateral play type plots are unaffected by the machine feedrate, however they are affected by direction. If clockwise and counter-clockwise runs are displayed at the same time then one plot will appear inside the other. Which plot appears inside the other depends on the whether the Lateral play error has a positive or negative value

The main cause of tateral play is play or slop in machine guideways. This allows the axes of the machine to move at right angles to their guideways as the axis reverses. This should be contrasted with a backlash step, which is also caused by play, but in line with the axis. As seen on a Ballbar circular test, backlash is a radial error, whereas lateral play is a tangential error.

When scaling error (mismatch) occurs, the plot has an oval or peanut shape distorted along the 0° or 90° axis. The axis of distortion is unaffected by the direction of data capture, i.e. clockwise or counter-clockwise. The amount of distortion caused by scaling error is usually unaffected by machine feedrate.

Scaling error is the difference in the measured travels of the axes during the test. For example, if the machine is performing a circle in the XY plane, the X and Y axes should move over exactly the same distance. If they do not, the difference in their movements is the scaling mismatch error.

One of the machines axes is either over travelling or under travelling relative to the other. There are a number of possible causes for this: if linear error compensation parameters are being used, these may be set incorrectly or the axis tape scale may be either over-tensioned or under-tensioned, rr rhe axis ballscrew may be faulty or overheating causing a ballscrew pitch error.

When squareness error occurs, the plot has an oval or peanut shape, distorted along the 45° or 135° diagonal. The axis of distortion is the same for both clockwise and counter-clockwise directions. The amount of distortion is unaffected by feedrate.

A squareness error is caused when the X and Y axes of the machine are not at 90° to one another at the position on the machine where the test is being performed. The axes may be bent locally or there may be an overall axis misalignment in the machine. The axes of the machine may be drooping causing them to misalign at certain locations. The machine guideways may be worn excessively causing a certain amount of play in the axes when they move.

Figure 3 shows the result of the measurements on the machine. The software has automatically synthesized the main type of errors which occurred and also has shown information regarding the share of each error in the overall error balance.

It can be noticed that the greatest influence is exerted by the scaling mismatch, which represents 18% from the overall balance. This means that during the circular interpolation, even the travels on X and Y axes should be equal, the travel on X axes was bigger.

The system also includes a simulator, which allows the user to highlight the influence of each type or error.

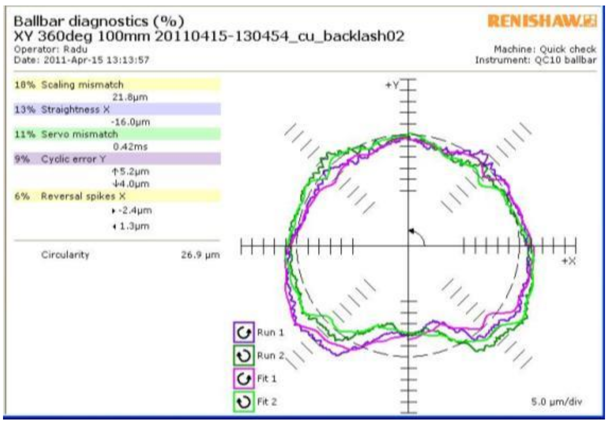

Figure 3. Measurement results

Using the simulator, the user is able to visualize either how the circle will look like if only a particular type of error occurs, or how the circle will look like if that type of error does not occur.

Figure 4 shows the shape of the circles in the absence of scaling mismatch error.

Figure 5 shows the shape of the circles in the absence of the squareness error.

The third most important error of the system was the servo mismatch error. When it appears, the plot has an oval or peanut shape, distorted along the 45° or 135° diagonal. The axis on which the plot is distorted switches if the feed changes from the clockwise direction to the counter-clockwise direction; both directions are shown on the plot below. The amount of distortion usually increases with increasing feedrate.

Figure 6 shows the shape of the circles in the absence of the servo mismatch error.

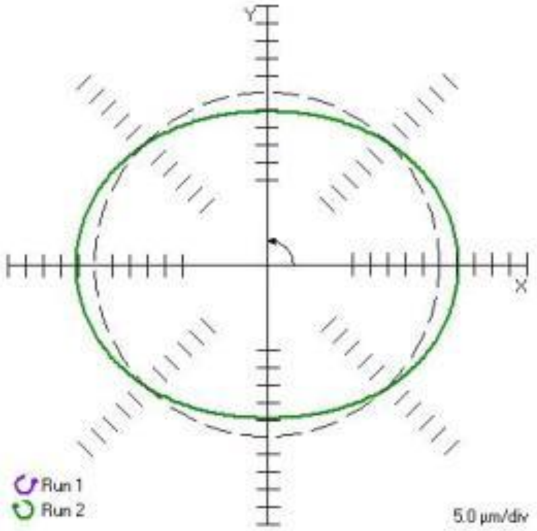

Figure 4. The circles without scaling error

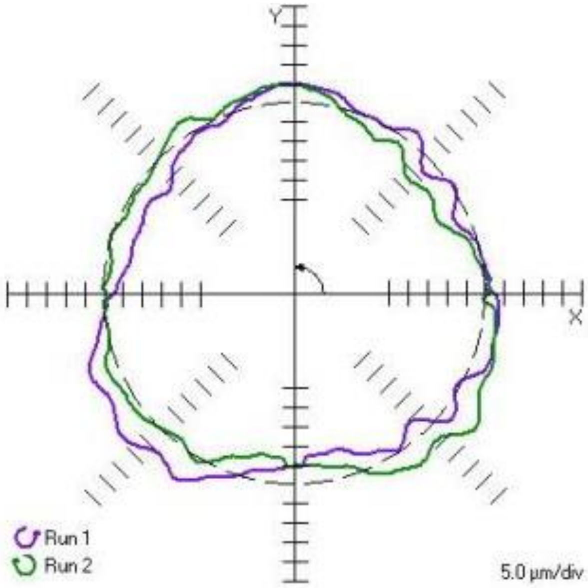

Figure 5. The circles without the squareness error

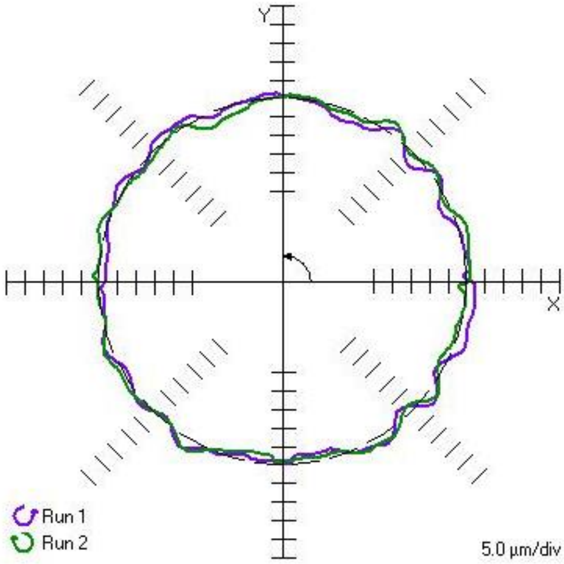

Figure 6. The circles without servo mismatch error

The results of the experimental tests unfolded with the QC 10 Ballbar have indicated that the contouring accuracy of the machine in no-load conditions is acceptable

The tests also allowed the users to identify the main errors (scaling mismatch error, squareness error and servo mismatch error) and find some ways to eliminate them.

3.2 Experimental researches regarding the contouring accuracy in load conditions

In order to assess the contouring accuracy of the machine-tool in load conditions, a method which involves the manufacturing of four identical circular contours on a CNC milling machine, using different control parameters of the CNC equipment was developed by the authors.

The cutting process is followed by measuring the circular error of each contour on ZEISS PRISMO 7 S-ACC coordinate measuring machine. The machine uses the CALYPSO software package for processing and displaying the measurement data.

In order to assess the contouring accuracy in load conditions, during the cutting process, four circular contours with a diameter of 30 mm were machined, at a total cutting depth of 2 mm, in a low-alloyed steel workpiece, using a 8 mm diameter cylindrical mill. The feedrate during the milling operations was set to 200 mm/min and the spindle speed was set to 2500 revs/min.

A schematic diagram of the processed circular contours is presented in figure 7.

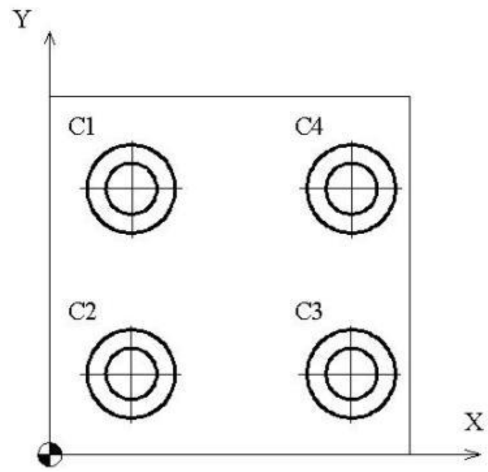

Figure 7. Schematic diagram of the machined circular contours

The simplified schematic diagram of the motion control system of the CNC machine tool is presented in figure 8. From the figure it can be noticed the main position control loop and the secondary velocity and feed-forward control loops.

After the digital control action is applied, the resulting digital control output is applied at the input of a digital-to-analog converter (DAC), defined by the gain K_c.

A control voltage is generated at the output of the digital-to-analog converter (DAC), which acts an input to the velocity control loop, a secondary control loop of the motion control system.

The control parameters taken into consideration during the experiments were:

- the overall gain on each axis (which represents the proportional gain of the PID controller from the main position loop of the motion control system)

- the feed-forward gain (which represents the gain from the supplementary feed-forward loop, which has the role to make the overall transfer function of the motion control system as close as possible to unity).

For each circular contour 1965 points were measured and processed (figure 9).

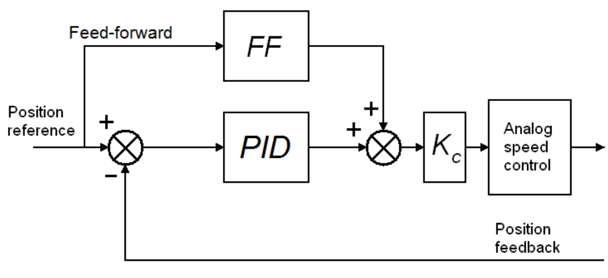

Figure 8: Schematic diagram of the motion control system

The first circular contour was machined using the initial control parameters of the CNC equipment, without any changes. The maximum measured circular error was 26.7 µm.

The second circular contour was machines after eliminating the feed-forward gains on each axis (setting them equal to zero). The maximum measured circular error was 14.5 µm.

The third circular contour was machined using an overall gain on Y axis 1.5 bigger than the one X axis (which kept its initial value). The feed-forward gains were set zero. The maximum measured circular error was 14.5 µm.

The fourth circular contour was machined using an overall gain on Y axis 1.5 bigger than the one X axis (which kept its initial value) and the initial values for the feed-forward gains. The maximum measured circular error was 19.1 µm.

From figure 5 it can be noticed that the first circular contour shows a maximum circular error approximately equal with the maximum error measured in no-load conditions with the QC 10 Ballbar device, and the most favorable situation appears when using the control parameters for machining the second circular contour.

Consequently, the experimental tests had shown that the contouring accuracy in load conditions is quite similar with the one in no-load conditions. Also, some recommendations regarding the setting of control parameters were issued.

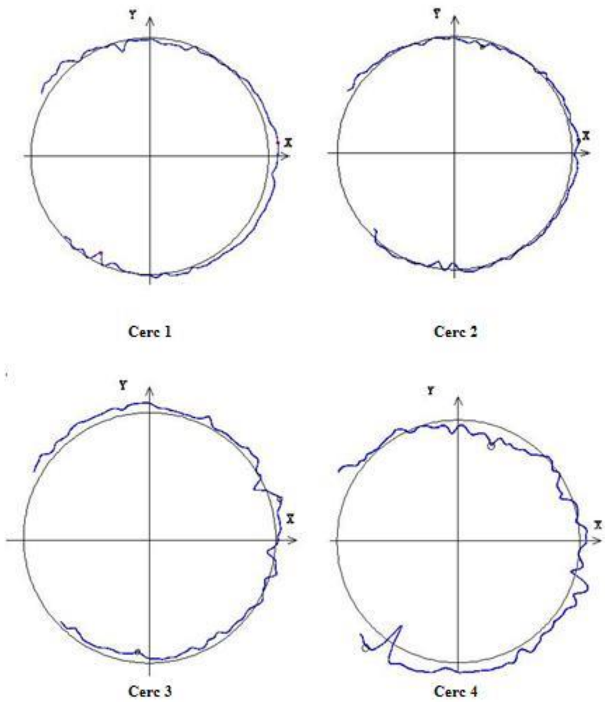

Figure 9. Measured circular errors

4 CONCLUDING REMARKS

Positioning accuracy at single axis movements and contouring accuracy in no-load and load (cutting) at simultaneous multi-axis movements had a significant influence upon the manufacturing accuracy of a numerically controlled machine-tool.

This work presented experimental methods for evaluating these accuracies. For the assessment of the positioning accuracy and of the contouring accuracy in no-load conditions, widely known and accepted methods were used, while for the assessment of the contouring accuracy in load conditions a method proposed by the authors was used.

Thus, the overall gain on each axis and the feed-forward gain on each axis were taken into consideration as the main control parameters of the motion control system. Assessing the contouring accuracy in load conditions involved the machining of several circular contours using different setting of the above mentioned control parameters.

The experimental tests allowed the elaboration of some useful conclusion regarding the influence of these parameters upon the circular errors in machining conditions.

The presented methods of assessing different types of accuracies for the numerically controlled machine-tools can provide very important data and knowledge regarding the ability of the machines to process complex parts, with high dimensional and shape accuracy. These methods will be further used for building a knowledge database which will be used for improving the NCMT manufacturing accuracy.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

► Biriş, C., Tera, M., Serb, S., (2008), *Considerations on the Precision of NC Machine-Tools Used For Non-Conventional Cutting Operations*, 17th International Conference on Manufacturing Systems – ICMAS 2008, Bucureşti;

► Breaz, R., (2007), *Automatizări industriale. Controlul mişcării şi automate programabile*, Editura Universităţii “Lucian Blaga” din Sibiu;

► Breaz, R.E., Bologa, O., Oleksik, V. and Racz, G., (2007), *Computer Simulation for the Study of CNC Feed Drives Dynamic Behavior and Accuracy*, Proceeding of the IEEE Region 8 EUROCON 2007, International Conference on “Computer as a tool”, Warsaw, Poland, pp. 2229-2233, September 2007;

► Gordon, S., Hillery, M.T., (2005), *Development of a high-speed CNC cutting machine using linear motors*, Journal of Materials Processing Technology, 166, 3, pp. 321-329, 2005;

► Hecker, R.L., Flores, G.M., Xie, Q. and Haran, R., (2008) *Servocontrol of Machine-Tools: A Review*, Latin American Applied Research, 38, pp. 85-94, 2008;

► Koren, Y., (1991), *Advanced Controllers for Feed Drives*, CIRP Annals, Vol.41, No. 2, pp. 689-698, 1991;

► Morar, L., (2006), *Programarea sistemelor numerice CNC*, Editura Utpress, Cluj-Napoca;

► Ramesh, R., Mannan, M. A., Poo, A.N., (2005), *Tracking and contour error control in CNC servo systems*, International Journal of Machine Tools and Manufacture, Vol. 45, pp. 301-326;

► Saturley, P.V., Spence, A.D., (2000), *Integration of milling process simulation with on/line monitoring and control*, International Journal of Advanced Manufacturing Technologies 16;

► Timar, S.D., Farouki, R.T., Smith, T.S. and Boyadjieff, C.L., (2005), *Algorithms for time-optimal control of CNC machines along curved tool paths*, Robotics and Computer-Integrated Manufacturing, 21, 1, pp.37-53, 2005;

► *** PowerMotion® Products, (1998) *Servo Products Specification Guides, GFH-001B*, GE Fanuc Manual, September 1998.

7 NOTATION

x_{Rj}^{i} – current position;

x_{Pj} – programmed position;

K_c – digital to analog (DAC) converter gain.