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THE INFLUENCE OF GEOMETRIC ERRORS COMPENSATION OF A CNC MACHINE TOOL ON THE ACCURACY OF MOVEMENT WITH CIRCULAR INTERPOLATION

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S u m m a r y

In the paper set of the experimental tests was presented in order to determine the cyclic pitch error of the feed screw in CNC machine. Laser interferometer with feedback from rotary encoder was used in the experiment. The results of the cyclic pitch error compensation were presented in the circular interpolation test performed using a telescopic ball bar. Results of the circular interpolation in the mutually perpendicular planes XY, YZ, ZX with and without error compensation were presented. The increase of the axes positioning accuracy in dynamic tests can be determined basing on the experimental results. Moreover, the backlash compensation, positioning and squareness errors are discussed in the paper.

Keywords: cyclic pitch error, machine tool

Wpływ kompensacji błędów geometrycznych obrabiarki CNC na dokładność odwzorowania ruchu z interpolacją kołową

S t r e s z c z e n i e

W artykule przedstawiono analizę wyników badań doświadczalnych, prowadzonych dla określenia wartości cyklicznego błędu skoku śruby pociągowej w obrabiarce sterowanej numerycznie. Badania wykonano z użyciem interferometru laserowego z możliwością bezpośredniego odczytu pozycji zadanej z impulsowego przetwornika pomiaru położenia obrabiarki. Wyniki próby kinematycznej z interpolacją kołową umożliwiły ocenę skutków kompensacji cyklicznego błędu skoku śruby oraz innych błędów obrabiarki. Uzyskane wyniki badań pozwoliły na ilościową ocenę zwiększenia dokładności pozycjonowania osi obrabiarki.

Słowa kluczowe: cykliczny błąd skoku, obrabiarki

1. Introduction

One of the major functional tasks which should be realized by a numerically-controlled machine tool is the exact positioning of the tool relative to the workpiece. The accuracy of the positioning depends on many factors such as geometric errors of the drive components and linear guides connections [1],

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thermal deformations, errors associated with the deformation of: linear guide components [2], cutting tools [3], static [4] and dynamic [5] machine tools carrying system, and the errors that result from assembly of machine components. With respect to the accuracy of positioning, geometric errors can be characteristic depending on the specific design of the carrying system and on the method of measuring the position of the machine elements. An example of this situation is the occurrence of so-called cyclic feed screw pitch error in machine tools where indirect measure of the position of the machine executive elements is used. The indirect measurement is understood as the appliance of a rotary pulse transducer mounted directly on the motor shaft of the drive instead of a linear scale mounted on the body elements of the machine. In such solution, the cyclic pitch error of the screw appears as "pulsing" on axes positioning accuracy characteristics (according to the standards [6]) or on the test of kinematic characteristics with circular interpolation (according to the standards [7]) as a radial deviation modulated with harmonic course. The characteristic feature of this error source is its reproducibility, which means that this error can be considered as systematic. Therefore, the knowledge of the parameters of the cyclic pitch error of feed screw can be used in practice to increase the positioning accuracy of machine tools. Another source of feed screws errors are their thermal deformations. The authors [8, 9] are among others involved in the compensation of this error.

The final result of the work is the comparison of the kinematic tests with circular interpolation before and after the compensation of typical machine tool errors. These comparisons were intended to check the effects of the compensation of the feed screw cyclic pitch errors.

2. Cyclic pitch error of the feed screw

Cyclic pitch error of the feed screw occurs most often in machine tools where the indirect measure of the position with rotary encoders mounted on the motor shaft of the feed drive axis is used. This error occurs because of the geometrical errors of feed screw helical line and / or metrological characteristics of the rotary encoder (the resolution of the encoder has an impact on the value of the cyclic pitch error of the feed screw). A characteristic feature of this error is its independence from the axis feed during the tests conducted on the machine.

Below a research program, using a laser interferometer, which allowed to identify the effects of the cyclic pitch error of the feed screws of three axes of a medium sized milling machine, has been presented. The acquaintance of the error and its sources allowed to determine the values of correction for the position set in the machine control system.

3. Experimental study of positioning accuracy and repeatability of machine axis considering the cyclic pitch error of the feed screw

Below are examples of experimental results of positioning accuracy and repeatability of the prototype machine tool (the main body of a triaxial milling center with rolling linear guides and machining space with dimensions 600x400x400 mm). These studies were carried out at the Institute of Mechanical Technology of West Pomeranian University of Technology. The prototype machine is new and after its running-in process. It has an open CNC control system, which makes it possible to test newly developed compensation algorithms. Before the tests an adequate warm-up cycle was carried out on the machine tool to stabilize it thermally. The accuracy and repeatability of positioning was measured with a laser interferometer [10]. According to the manufacturer of this interferometer the measurement accuracy (without the amendments resulting from thermal expansion) of the linear displacements is MPE = ± 0.5 ppm. Detailed analysis of the uncertainty of this measurement allowed to estimate its expanded uncertainty (k = 2) at about 6μm per meter of the axis length at 5°C temperature difference relative to the normal temperature. During the measurements a compensation of laser wavelength due to temperature, pressure and humidity changes was applied, allowing more accurate measurement. The interferometer and reflector relative location and the distribution of temperature sensors during the X-axis tests is shown on Fig. 1.

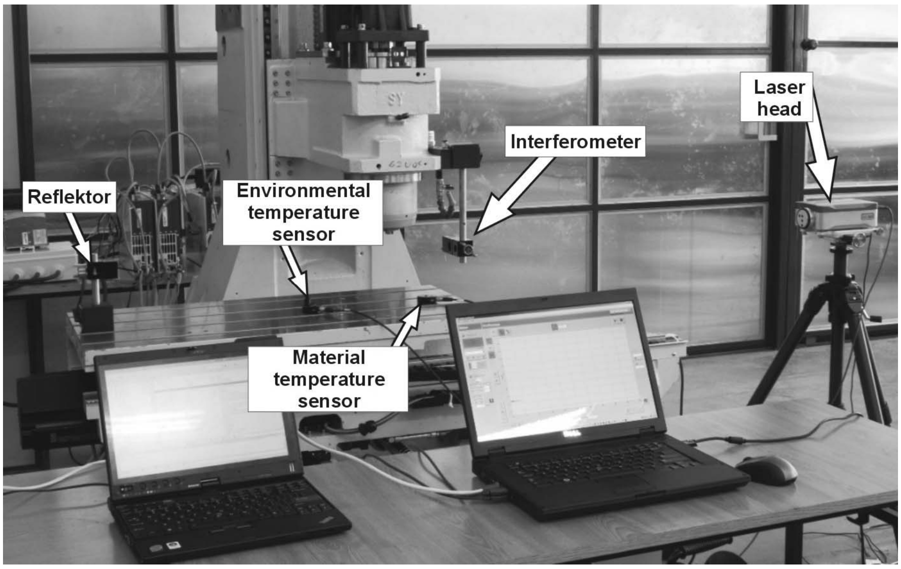

Fig. 1. View of the machine during the accuracy and repeatability of positioning of the X-axis test

Figure 2 shows examples of measurement results of positioning accuracy and repeatability. The graph was drawn for the measurement before compensation of the specified position in the machine control system. Indicators (and their uncertainty) shown in the drawing area were calculated according to the standard [6].

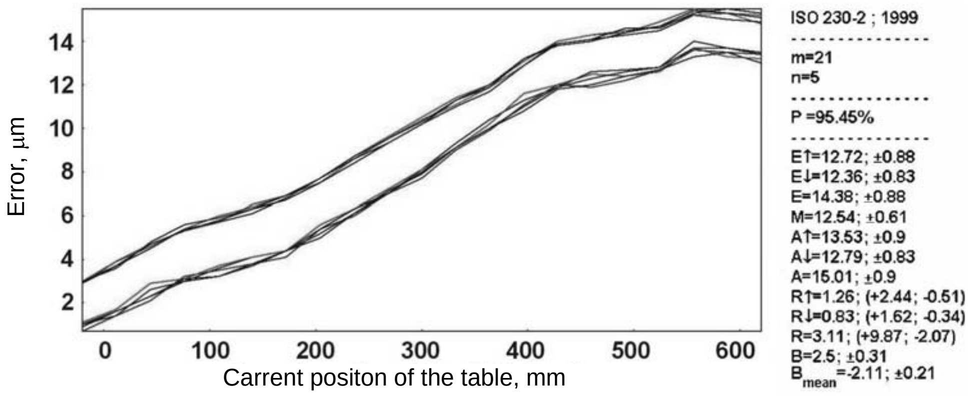

Fig. 2. Characteristics according to [6] two-way accuracy and repeatability of the X-axis positioning

Figure 3 shows the characteristics of the X-axis positioning accuracy, which was measured during movement of the axis with feed at 300 mm/min (to clarify the figure only one cycle of the measurement: push – pull have been shown). The measuring points were recorded with increments of the position set at 1 mm. This measurement was performed using a trigger – device which synchronized machine axis position transducer with the laser interferometer. In such system the position measured by the transducer is the position against which the deviation of the positioning is measured using a laser interferometer.

The comparison of Fig. 2 and 3 showed that the trend of axis positioning accuracy of the tested machine is similar regardless of whether the study was conducted when stopping as the norm [6] or when moving the feed axis. Premising that the main source of positioning error are geometric inaccuracies of the machine components result of this was to be expected. However, conducting the study with an increment of the set position of 1 mm the cyclic pitch error of the feed screw can be seen as harmonics imposed on the characteristics of the positioning accuracy – Fig. 3.

The tests were repeated for the Y and Z axes. Information for all three axes of the machine tool have been obtained not only of accuracy and repeatability of axes positioning and the backlash, but also of amplitude of the feed screw cyclic pitch error and phase shift of harmonics of this error in the machine coordinate system. These characteristics were used for making an array of axes positioning amendments with the cyclic pitch error of the feed screw taken into account. This table was used to compensate the position set in the machine tool control system. The question arises whether the inclusion of the amendment of cyclical pitch error compensation has a technical sense, is there a way to effectively compensate this error? To answer this question, it was decided to conduct a kinematic test of the machine tool (with circular interpolation in planes XY, YZ and ZX). This test was carried out before and after the compensation of machine tool errors. The results are shown below.

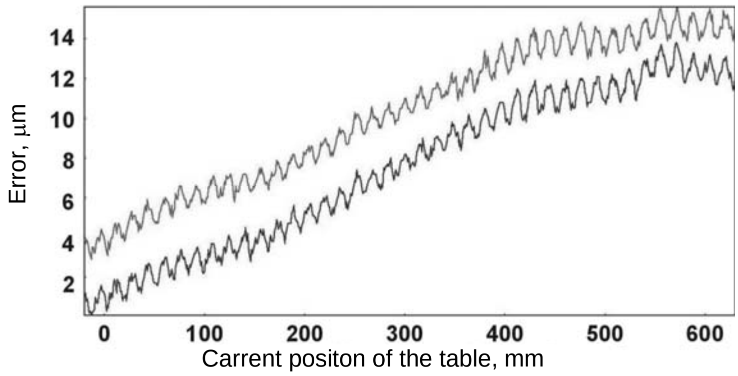

Fig. 3. Characteristics of the X-axis positioning accuracy with feed screw cyclic pitch error taken into account

4. Kinematic test with circular interpolation before and after compensation of the machine tool errors

Kinematic test with circular interpolation by [7] was carried out using telescopic ball bar – Renishaw QC10 [9]. The results presented in this paper are the effect of visualization and calculations obtained from the software provided by the equipment manufacturer. Fig. 4a presents pictures that were made during the test in machine planes XY, YZ and ZX. The study was conducted using a bar with a length of 150 mm. Test center of the circle was placed in the middle range of the tested axes. The test was carried out in two passes. First one anti-clockwise and the second one was carried out in clockwise direction. The results of measurements include temperature compensation of the machine elements. The temperature was measured on the surface of the table. To compare the results of all axes tests only one value of feed at 500 mm/min has been used to implement the circular interpolation. Measurements were carried out in two stages. In the first stage a roundness test was performed for the machine, with compensation only for backlash error used in the control system. These measurements were repeated five times for each of the test planes. An example of raw results of such studies are shown in Fig. 4b. Interpretation of the plots are as follows [9]: In the XY and YZ planes dominant error is the error associated with axes positioning accuracy. This is evidenced by the elliptical shapes of graphs, which semi-axes are parallel to the tested axes of the machine tool. The graph in the ZX plane is elliptical and tilted relative to the machine axis at an angle of 45°, which reflects the dominant influence of the axes perpendicularity error. The axis relapse error has also revealed, a dominant radial deviation in quadrants of the roundness chart – in places where the feed direction changes. This is particularly evident for the vertical axis that is Z in the test plane YZ and ZX. The source of this error are the dynamic characteristics of servo drives. While the value of this error significantly depends on the settings of drives and the axes feed controls. By correcting the set position it is not possible to compensate the relapse error, so in further considerations the roundness graphs will be analyzed without this error. It should be noted that in each graph of Fig. 4b the effect of the presence of cyclic pitch error of the feed screw becomes apparent. The impact of this error is manifested in a characteristic way as a harmonic modulation of the radial deviation. Therefore, it has been confirmed with other measuring method than the test of positioning accuracy using a laser interferometer, that the tested machine tool has a cyclic feed screw pitch errors.

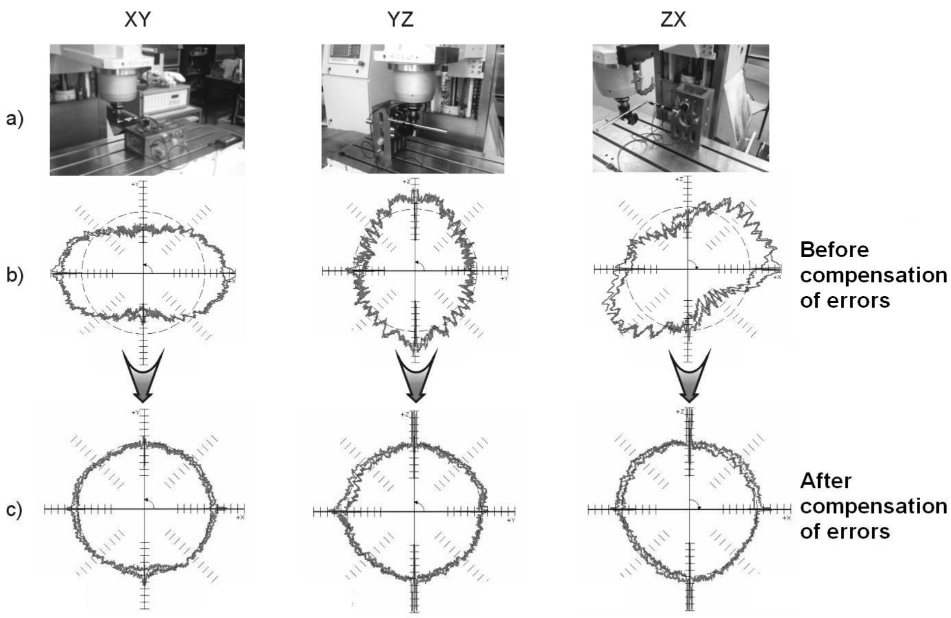

Fig. 4. Kinematic test setup (a) results and with circular interpolation in planes XY, YZ and ZX before (b) and after (c) machine tool errors compensation

The results of the second stage of the kinematic test with circular interpolation are illustrated on Fig. 4c (the scale of the graphs in Fig. 4b and 4c is identical). The graph of the radial deviation are made during the test of the machine tool, in which the compensation of the set position is used. The compensation is made with the feed screw cyclic pitch error, the backlash error and the axes squareness errors taken into account. The numerical values of the compensation corrections were calculated using the homogeneous matrix transformation model according to [1]. The comparison of the roundness charts, which were obtained for the machine tool before compensation (Fig. 4b) with the graphs obtained after the compensation of its errors (Fig. 4c) allows to conclude that the accuracy of the circular trajectory implementation done by the machine elements has increased. It is also evident that the compensation of errors has minimized the impact of the feed screw cyclical pitch error on positioning accuracy of tested milling machine. To compare quantitatively the effects of increased accuracy of the machine tool bar graphs – Fig. 5 and Fig. 6 have been made. The height of the bar for a particular source of error (that is the feed screw cyclic pitch error, axes positioning deviation and the deviation of the axes squareness) shows the roundness error determined independently of the existence of other sources of errors, this means that the roundness error is calculated in the presence of only one machine error. While the height of roundness deviation bar corresponds to the value designated as the synergistic effect of considered sources of errors. Fig. 5 shows the measurement results before compensation, while in Fig. 6 the results which were obtained after the

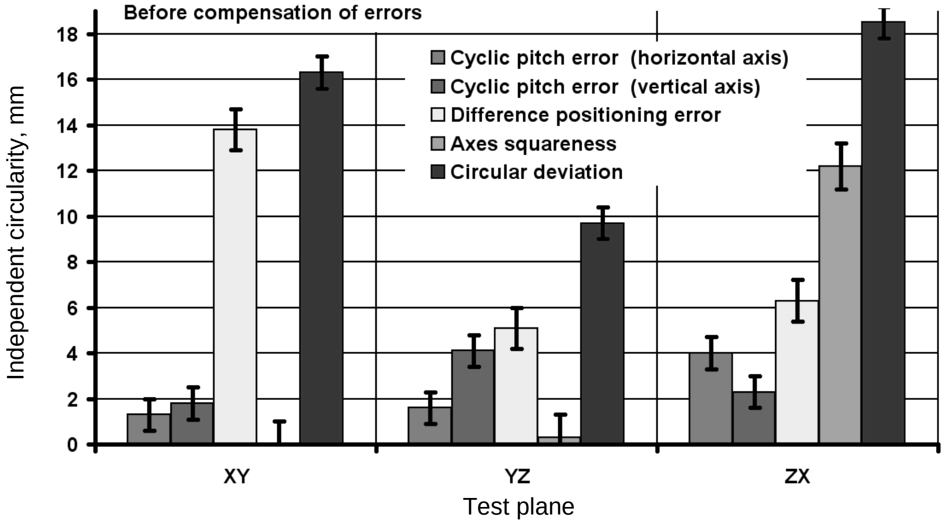

Fig. 5. The results of kinematic test with circular interpolation before the machine tool error compensation

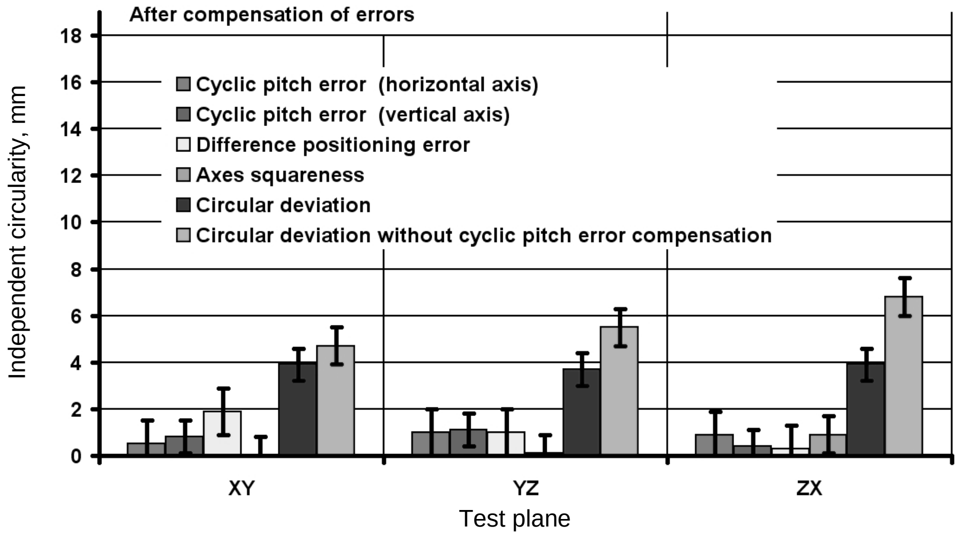

Fig. 6. The results of kinematic test with circular interpolation after the machine tool error compensation

compensation of machine tool errors. Error bars shown in Fig. 5 correspond to the value of ±2σ, which are the measure of the measurements repeatability.

The bar chart in Fig. 6 shows the roundness deviation bar twice. First for the measurement, during which considered sources of errors were compensated in the machine tool and the other for the measurement, during which errors were compensated except for the feed screws cyclic pitch error. Comparison of these bars was to investigate the effect and reasonableness of the feed screw cyclic pitch error compensation.

Conclusion

- After compensation of backlash, positioning error and the squareness errors the feed screw cyclic pitch error can be a significant source of geometric errors in machine tools with an indirect measurement of the executive parts position.
- Knowledge of the amplitude and phase shift of the feed screw cyclic pitch error, relative to the machine coordinate system, allows effective minimization of its effects by correcting the value of the set position.
- After the feed screw cyclic pitch error compensation the results of the kinematic test with circular interpolation showed that effects of its influence are on the level that exists in machine tools with direct measurement of the position of executive parts of the machine.
- The procedure of machine tool error compensation required an earlier measurement of the positioning accuracy with the laser interferometer in

increments smaller than the feed screw pitch. This measurement, if it is to be effective in the time-consuming sense, requires additional equipment for the laser interferometer (trigger). Such devices are not cheap and are inconvenient for practical applications because of the need to adjust the standard of communication of the pulse position encoder with the laser interferometer. These standards are different for different manufacturers of the encoders. The question arises whether such devices can be eliminated from the measurement procedures presented in the article? This seems to be feasible on the basis of fast and inexpensive kinematic roundness test using a ball telescopic rod. The work in this area requires further study.

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