Investigation of the causes of shape deviations in contour milling

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Abstract. The article discusses the variety of deviation causes from the shape and relative position of the surfaces by contour machining. The most accurate and operational measuring method has been determined and a qualitative assessment method has been selected for diagnostics the fault causes. The value of the drive mismatch on metal-cutting machines with Heidenhain CNC at different feed rates has been investigated. The linear dependence of the drive mismatch on the feed and the constancy of the non-squareness of the axes were experimentally approved. An algorithm for equipment diagnostics is presented to determine the causes of the contour error without special measuring devices.

1. Introduction

The accuracy of modern engineering products largely depends on the accuracy of the equipment on which processing is performed. Most of the precision engineering products are made at various CNC machining centres. Herewith the occurrence of various geometrical and dynamic inaccuracies on the surfaces of a part can have both mechanical origin and inaccuracies in the subsystems of electric drive control and feedback [1].

In the production of parts with high dimensional accuracy and small tolerances on the shape deviation, the problems of discrepancy of cylindrical, prismatic or random surface with the requirements of the drawing are faced. The discrepancy of the contour can either have a local character (only by reverse) or have common features [2]. The most common variants of circle distortion are: reverse error, feedback errors, axes non-squareness or servo mismatch of the interpolating axis drives are presented in Figure 1. The circular diagram 1a corresponds to the misalignment of the scales at which the distances along two linear axes are not equal to each other. Plots 1b, c are caused by the presence of an acute or blunt angle between two axes. Figures 1 d, e show circular diagram distorted by the error of the linear axes reverse. “The gap in the mechanical part of the drive fundamentally differently affects the accuracy of the “circle” trajectory, depending on whether or not the mechanical part of the drive is covered by feedback on the position”[3].
2. Formulation of the problem

The purpose of this study is to determine the dependence of servo mismatch and non-squareness errors on the feed and the circle radius. In order to obtain the most complete picture, the widest range of 100-10000 mm / min is taken.

To achieve the purpose, the following tasks are set:
1. To determine the most accurate and operative measuring tool for diagnostics.
2. To determine the algorithm for identifying the cause of error without modern diagnostic tools.
3. To conduct a multifactorial experiment to study the quality of circular interpolation at different radiiuses and feed rates.

3. Theory

Indirect measurement systems are integrative, whereby this diagnostic can be performed as quickly and accurately as possible using a measuring system with magnetic spherical tips from point 6.63 of ISO 230-1:2012, for example, Ballbar QC-20W from Renishaw. The software allows you to visualize the circular deviation along the path of the circle, as well as to estimate the value of the majority of the inaccuracies of the studied axes of the machine [4]. Also, there are already many improved methods with similar devices for studying three-dimensional trajectories [5] as well as measurement under load [6]. With a small working area in multi-axis machines, reference spheres are used for kinematic and dynamic testing of equipment [7].

It is worth noting the impossibility of self-diagnosis of equipment with built-in systems, since the coverage of equipment feedback will always be less than the total machine tool system (machine-device-tool-part). On the example of the coordinate boring machine 2431SF10, upgraded by numerical program control, but having extremely high errors, we can observe the ratio of inaccuracies (Figure 2). Under position 1 is the actual trajectory recorded by the ballbar device. Position 2 - oscillogram of deviations recorded by the feedback subsystem. The feedback error of the drives, the scales and the deviation from the perpendicularity of the X and Y axes in 4° 9’ is not fully covered by the feedback. The total error of 75 ± microns with a 100 mm diameter and a feed value of 200 mm/min.
In order to determine the source of this error without this device, you can use the functional diagnostics method [8]. The basis of the method consists in the production of a test part containing structural elements with the required tolerances for the purpose of the following evaluation of investigated errors [9]. There are also separate methods for assessing the accuracy of positioning rotary tables of five-axis machining centers [10].

To determine the main fault causing arc movement deviation a test piece that has 3 elements located along the axis: a square island (flange) and two milled holes could be made. Each of these holes should be machined with a different direction of rotation of the spiral trajectory and preferably with a different tool to eliminate finishing counter-milling as a disturbing factor.

If the contour of the flange has a square cross-section (equal sides and diagonals), then the most likely cause is the mismatch of the drives. In the case of the presence of an ellipse forming the hole, it is worth determining the largest diameter direction. In case of its orientation along one of the physical axes, it is necessary to check and adjust the feedback subsystem, since this is due to a different scale along the axes due to the accumulated screw pitch error.

If the main axes of the ellipse are located at an angle of 45° to the drives (Figure 1 b, c), the necessary condition is to check the repeatability of this error depending on the trajectory direction. In the case of repeatability in any direction, the non-perpendicularity of the axes certainly is the source of this error.

If two holes have different distortions of the elliptical paths, then only in this case can the drive misalignment be diagnosed (Figure 1d, e). The elimination of this defect due to the lack of universal mathematical models in practice is associated with multiple test measurements. Since each of the above-described faults is extremely
rarely found isolated in the operated equipment, the test part method (Figure 2) is only suitable for the purposes of initial assessment of the accuracy of a CNC machine in the absence of measuring instruments. The final algorithm for functional diagnostics of the causes of shape inaccuracies and relative position of the surfaces is presented in Figure 4. In general, diagnosing and correcting a CNC system with a ballbar is operative and preferable.

![Figure 4. Algorithm for examination the causes of inaccurate contour reproduction during processing](image)

In general, diagnostics using a ballbar device are more preferable to the CNC system due to high measurement accuracy. It should be noted the possibility of a significant reduction of errors through repair and program corrections [11].

4. Experimental results

The 5-axis vertical machining center DMU50 with the Heidenhain CNC system was selected as the main object of study. The results of the most dynamically informative test with a radius of 50 mm and a circular feed of 10,000 mm/min are presented in Figure 5.

![Figure 5. Circle diagramm DMU50 Heidenhein machine with the highest possible feed and minimum radius](image)
The angle value between X and Y-axes is $90^\circ 29''$. However, its contribution to the total error, which invariably increases with an increase in the feed rate, is significantly reduced due to an increase in a number of dynamic inaccuracies such as reversal spikes, backlashes and cyclical error amplitudes.

**Figure 6.** The graph of the dependence of the drives mismatch on the contour feed rate

Figure 6 shows the linear dependence of the mismatch error contribution for drives based on stepper motors without correction. Absolute value of drives mismatch during the experiment varied from 10 to 15%.

5. **Results and discussion**

It was experimentally shown that linear drives of the DMU50 machine in normal operating mode could avoid misalignment up to a feed rate of 10,000 mm / min. The drive mismatch contributes less than 3% to the total error taking into account the peak values in certain modes. The main factor of inaccuracies at such high speeds of movement is reverse errors.

**Figure 7.** Graphs of the error of the mismatch of the DMU50 drives in $\mu$m (left) and non-perpendicularity in $\mu$m / m from the contour feed in mm / min at different radius of the arc.

Thus, it is shown if the subsystem of the drives and feedback on the linear position are set correctly, then the error associated with the mismatch of the drives does not correlate with the feed rate. However, on a modified universal machine tool with “Mayak” control system, the distortion of the trajectory by the error of the drives increases linearly with increasing feed rate. This mismatch can happen even with using linear position sensors: position accuracy and repeatability of investigated drives less than 3 $\mu$m. Nevertheless, that fact cannot provide accuracy of circle moving.

6. **Conclusions**
1. Determining the true correlation between the causes of movement deviations requires a careful approach to the choice of research methods and sufficient accuracy of the results.

2. Most operational diagnostics is capable of providing the technique of indirect measurement of movements using a telescopic sensor with spherical tips according to GOST ISO 230, in case of its absence the test can be performed using the presented test piece evaluation algorithm.

3. Correct functioning of the feedback subsystems on the position of the linear axes and the drive control subsystem may not have a significant effect on the final accuracy even at high feed rates (up to 10,000 mm/min). In the opposite case, the inaccuracies caused by mismatch between the drives (in µm) increase almost linearly with the feed rate.

7. References

[1] Serkov N.A The main directions of improving the accuracy of machine tools (In Russian) 2010 Prob. of mech. eng. and autom. 2 26–35.

[2] Kakino Y, Ihara Y, Nakatsu Y and Okamura K The measurement of motion errors of NC machine tools and diagnosis of their origins by using telescoping magnetic Ball Bar method 1987 CIRP Annals 36 377–80.

[3] Pas’ O V and Serkov N A Influence of the gap in the drives on the accuracy of the trajectory in a multi-axis CNC machine (In Russian) 2015 Prob. of eng. and mach. reliaib. 5 3–10.

[4] Blokhin D A, Koltzov A G and Wasil’eva I A Diagnostics of technical condition of CNC machine tools (In Russian) 2016 Science and youth in the XXI cent. 2 91–6.

[5] Kato N, Sato R and Tsutsumi M 3D circular interpolation motion equivalent to cone-frustum cutting in five-axis machining centers and its sensitivity analysis 2012 Procedia CIRP 1 530–5.

[6] Archenti A, Nicolescu M, Casterman G and Hjelm S A new method for circular testing of machine tools under loaded condition 2012 Procedia CIRP 1 575–80.

[7] Florussen G H J and Spaan H A M Dynamic R-test for rotary tables on 5-axes machine tools 2012 Procedia CIRP 1 536–9.

[8] Anikeeva O V Functional diagnostics of machine tools (In Russian) 2011 News of South-West State University 38 106–12.

[9] Givi M and Mayer J R R Validation of volumetric error compensation for a five-axis machine using surface mismatch producing tests and on-machine touch probing 2014 Int. Jour. of Mach. Tools and Manuf. 87 89–95.

[10] Ibaraki S, Ota Y A machining test to evaluate geometric errors of five-axis machine tools with its application to thermal deformation test 2014 Procedia CIRP 14 323–8.

[11] Majda P The influence of geometric errors compensation of a CNC machine tool on the accuracy of movement with circular interpolation 2012 Advances in manufacturing science and technology 36 59–67.