

Investigation of influence of errors of cutting machines with CNC on displacement trajectory accuracy of their actuating devices

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Abstract. In the article, the issue of increasing a CNC lathe accuracy by compensating for the static and dynamic errors of the machine is investigated. An algorithm and a diagnostic system for a CNC machine tool are considered, which allows determining the errors of the machine for their compensation. The results of experimental studies on diagnosing and improving the accuracy of a CNC lathe are presented.

1. Introduction

One of the tasks that is solved during machining on CNC lathes is to ensure a given accuracy in the size and shape of the treated surface. The accuracy of the size and shape depends on many factors, including the current state of the machine. During the operation of the lathe with CNC, its state changes, and as a result a partial loss of its accuracy takes place [3,5].

The physical wear and tear of the mechanical part can be eliminated by carrying out major repairs, including the restoration of the guides, replacement of the parts of the spindle unit, the running gear of the drives, etc. [2] The moral and physical wear of the control systems can only be eliminated by upgrading, including the replacement of the CNC control of electric drives of feeders and feedback sensors. To ensure the specified accuracy of a CNC lathe, after a major overhaul, it is necessary to determine its static and dynamic errors, such as gaps in mechanical transmissions, the error due to the presence of friction in rest, the accumulated error of the lead screw, servo gear and others. These errors can be fully or partially compensated for by the CNC by using a set of machine parameters that make it possible to compensate for static errors and reduce the dynamic errors of the machine and its control system [9].

2. Materials and methods

The accuracy of the part contour defined in the control program depends on the accuracy of the shaping movements of the machine's actuating devices. For a CNC lathe, the accuracy of a given contour depends on the accuracy of the transverse and longitudinal caliper movements along the X and Z coordinates, respectively. The cumulative error for each of the coordinates determines the magnitude of the contour error of the trajectory of the movement of the machine's actuating devices



[10]. The trajectory contour error (Figure. 1) is the shortest distance Δ_k from the point (1) on a given trajectory to the point (2) on the actual trajectory.

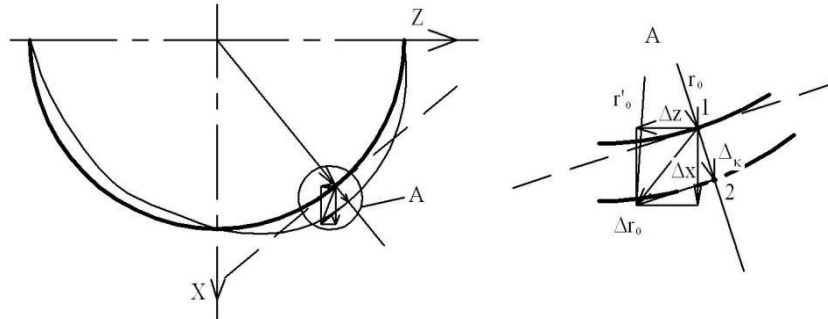


Figure 1. Determination of the contour error of the trajectory of motion of the machine's executive bodies: 1 - a given point of the trajectory; 2 - the actual point of the trajectory; r_0 - the radius vector of a given trajectory; r'_0 - the radius of the actual path; Δx , Δz - error along the X and Z axes respectively; Δr_0 - the error of the trajectory radius; Δ_k - the trajectory contour error; n - the normal to the spherical surface.

On CNC lathe such surfaces as cylindrical, end, conical, shaped (curvilinear), shaped end, cylindrical fist, as well as Archimedean helical surface, are machined. Therefore, depending on the type of motion trajectory of the machine's actuating devices, appropriate mathematical models are used to determine the contour error.

3. Obtaining the dependence of the working accuracy of CNC lathe on errors (static and dynamic) due to its condition and the algorithm for diagnosing the CNC lathe accuracy.

A circular trajectory was studied in the paper, since it is definite that during its development the effect of all static and dynamic errors is manifested. The contour error of the part can be represented in the form:

$$\Delta_K = \Delta r_0 \cdot n, \quad (1)$$

where Δr_0 - inaccuracy of the position of the actual surface point in space; n - the normal to the spherical surface (Figure 1).

Using the variational method of D.N. Reshetov, expression (2) was obtained, which makes it possible to determine the contour error of the displacement trajectory:

$$\Delta_K = (\delta_{x, pos} - \varphi_{z3}(y - y_{k3}) + \varphi_{y3}(z - z_{k3})) \cos \chi + (\delta_{z, pos} - \varphi_{x2}(y - y_{k2}) + \varphi_{y2}(x - x_{k2})) \sin \chi, \quad (2)$$

where $\delta_{x, pos}$, $\delta_{z, pos}$ - positioning error respectively along the X and Z axes; φ_{x2} - longitudinal support rotation angle with respect to the X axis; φ_{y2} - angle of the longitudinal support rotation with respect to the Y axis; φ_{y3} - angle of rotation of the transverse support with respect to the Y axis; φ_{z3} - angle of rotation of the longitudinal support with respect to the Z axis; x_{k2} , y_{k2} , y_{k3} , z_{k3} - the starting point coordinates; x , y , z - the current point coordinates; $\text{tg}(\chi) = \Delta x / \Delta z$; Δx , Δz - the error along the X and Z axes respectively.

Using expression (2), the trajectory contour error is determined, knowing the values of the position error of the transverse and longitudinal supports ($\delta_{x, pos}$, $\delta_{z, pos}$), the parallelism of the spindle axis in the direction of displacement of the longitudinal support in the vertical (φ_{x2}) and horizontal (φ_{y2}) planes, perpendicular to the spindle axis of the transverse support movement direction (φ_{y3}), skew of the motion plane during longitudinal displacement (φ_{z3}). The error data are determined by carrying out a complex of checks of the machine geometrical accuracy in accordance with [1, 4, 8] for machines. However, expression (2) does not take into account a number of errors in the machine that can be compensated with the help of the CNC system, for example: the error due to rest friction; the error caused by the adjustment of the contour of the control system position, the error in approximating the

trajectory of movement of the actuating devices, and others. Taking the errors in the machine accuracy balance into consideration allows one not only to control trajectory testing by adjusting the parameters, but also to predict its accuracy. Therefore, to determine Δ_k , the following relationship is proposed:

$$\Delta_K = (\delta_{x, \text{pos}}^* - \varphi_{z3}(y - y_{k3}) + \varphi_{y3}(z - z_{k3})) \cos \chi + (\delta_{z, \text{pos}}^* - \varphi_{x2}(y - y_{k2}) + \varphi_{y2}(x - x_{k2})) \sin \chi \quad (3)$$

where $\delta_{(x,z)\text{pos}}^* = \delta_{(x,z)\text{syst}} + \delta_{(x,z)\text{s}}$; $\delta_{(x,z)\text{syst}}$ - systematic errors of the machine; $\delta_{(x,z)\text{rand}}$ - random errors.

Errors in the positioning of the transverse and longitudinal supports $\delta_{x, \text{noz}}^*$, $\delta_{z, \text{noz}}^*$ (noz = pos) in expression (3) take into account the static and dynamic errors of the machine, which can be compensated with the help of the CNC system. Accounting for these errors in the machine's accuracy balance allows one not only to control the accuracy of trajectory testing by setting parameters, but also to predict its accuracy.

The systematic errors are determined by the calculation-analytical method. Since all systematic errors of the CNC lathe are collinear vectors and are directed along the machine axis, it is possible to determine their influence on the positioning error of the feed drive by summation. Moreover, the summation of the errors takes place with the sign taken into account. The error is summed with a "+" sign if the direction of the error action coincides with the direction of the axis. In the case when the action of the error is opposite to the direction of the axis, the summation occurs with sign "-".

The expression for systematic errors affecting the positioning accuracy will have the form:

$$\delta_{(x,z)\text{syst}} = \delta_{(x,z)\text{other}} + \delta_{(x,z)\text{steady state}} + \delta_{(x,z)\text{frict}} + \delta_{(x,z)\text{appr}} + \delta_{(x,z)\text{dead zone}} \quad (4)$$

where, $\delta_{(x,z)\text{other}}$ - drive zero drift; $\delta_{(x,z)\text{steady state}}$ - steady-state command error; $\delta_{(x,z)\text{friction}}$ - error caused by static friction presence; $\delta_{(x,z)\text{approximation}}$ - approximation error; $\delta_{(x,z)\text{dead zone}}$ - drive dead zone.

To determine the total error of random components, the probabilistic calculation method is used. In accordance with this method, the random component of the error in positioning the drive can be represented in the form of expression:

$$\delta_{\text{ran}} = \frac{1}{K} \sqrt{\sum_{i=1}^n (K_i B_i \delta x_i)^2 + 2 \sum_{j \neq i}^m K_i K_j B_i B_j \delta x_i \delta x_j r_{ij}}, \quad (5)$$

where C_i , C_j coefficients of relative scattering; r_{ij} - correlation coefficient; C - coefficient of relative scattering of the output parameter; m - number of pairwise coupled stochastic parameters; δx_i , δx_j - errors affecting the positioning accuracy of the feed drive; I_i - coefficient of influence of the i -th error on positioning accuracy.

The relative scattering coefficient characterizes the ratio of the error scattering field under the normal distribution law to the actual scattering field. Then the coefficient of relative scattering is assumed to be 1.

In accordance with [6], I_i can be assumed equal to 1. Assuming that the components of the random error are independent, expression (5) can be written in the following form:

$$\Delta_{\text{rand}} = \frac{1}{K} \sqrt{\sum_{i=1}^n (\Delta x_i)^2}. \quad (6)$$

The coefficient of relative scattering of the output parameter [7] corrects the total error for the given guaranteed reliability $P_r=0,9973$. Then the coefficient of relative scattering of the output parameter C is equal to 1, and expression (6) takes the form:

$$\Delta_{\text{rand}} = \sqrt{\sum_{i=1}^n (\Delta x_i)^2}. \quad (7)$$

Substituting into the expression (7) the random errors affecting the accuracy of the positioning of the feed drive, let us obtain:

$$\delta_{(x,z)rand} = \sqrt{(\delta_{(x,z)sen})^2 + (\delta_{(x,z)spac})^2 + (\delta_{(x,z)geom})^2}, \quad (8)$$

where $\delta_{(x,z)sen}$ – position sensor error; $\delta_{(x,z)spac}$ – error caused by ball screw spacing; $\delta_{(x,z)geom}$ – cumulative error of the machine screw.

Based on the proposed dependence (3), an algorithm for diagnosing the accuracy of a CNC lathe consisting of several stages was developed.

At the first stage, the checks provided for [1, 4] for checking the geometrical accuracy of the machine are carried out. At the second stage, the trajectory is worked out in order to determine its actual state. If the actual machine state does not satisfy the required accuracy, the following steps are performed. The third stage determines the influence of the dynamic components of the contour error Δc , as well as their sorting out by the degree of influence on the contour error in order to determine the cause of its occurrence. At the fourth stage, machine parameters of the CNC are determined, with the help of which it is possible to eliminate the causes of the error and to determine the optimum values of these parameters.

In the event that the previous stage failed to achieve the required accuracy of the machine, in the fifth stage, the repair option for CNC lathe centers with a minimum cost is being determined. And, finally, in the sixth stage, they are being repaired in accordance with the chosen option.

The algorithm introduces correction factor c , which takes into account the kinematic inaccuracy of the machine in the overall processing accuracy:

$$c = \frac{c_{mach} * c_{fa}}{1 + (c_{geom} / c_{kin})} \quad (9)$$

where c_{fa} - coefficient taking into account the form accuracy; c_{mach} - coefficient of accuracy of the machine; c_{geom} - coefficient that takes into account the geometric inaccuracy of the machine ; c_{kin} - coefficient taking into account the kinematic inaccuracy of the machine.

The state of the CNC lathe meets the accuracy requirements if there is condition:

$$\Delta_c \leq \frac{c_{mach} \cdot c_{fa}}{1 + (c_{geom} / c_{kin})} \cdot T_d \quad (10)$$

In order to determine the cause of the contour error appearance, and also to reduce it, a technique has been developed that allows us to determine and compensate for static and dynamic errors affecting the accuracy of trajectory testing. The errors occurred due to the non-parallel axis of the spindle in the direction of displacement of the longitudinal support in the vertical and horizontal planes, the non-perpendicularity to the axis of the spindle of the transverse support movement direction, and the skew of the motion plane during longitudinal displacement are determined by performing a complex of checks of the geometrical accuracy of the machine in accordance with [1, 4]. The accumulated errors of the lead screw, the clearance in the mechanical gears, the drive dead zone, the error due to the presence of the feed drive zero drift and the friction of rest are determined using the developed diagnostic system.

Experimental studies to improve the accuracy of the CNC lathe were carried out using a CNC lathe of the 1B340F30 model. With the help of the developed diagnostic system, the need to improve the accuracy of the CNC lathe was determined. For this purpose, a circular trajectory was worked out (Figure. 2, a) by the machine actuating devices. In the process of working out the circular trajectory, the diagnostic trajectory was determined by the diagnostic system (Figure. 2, b). According to the actual trajectory, a contour error in the displacement of the machine's executive bodies was determined as the difference between the largest and the smallest deviation of the radius of the trajectory of displacement. The trajectory (ideal) of displacement of the machine actuating devices specified in the control program coincides with the abscissa axis (Figure. 4, b).

The radius of the circular trajectory of the machine actuating devices' movement was 20 mm; the contour feed rate was 200 mm / min. The contour error of the actual trajectory is $\Delta k = 0.085$ mm (Figure. 2).

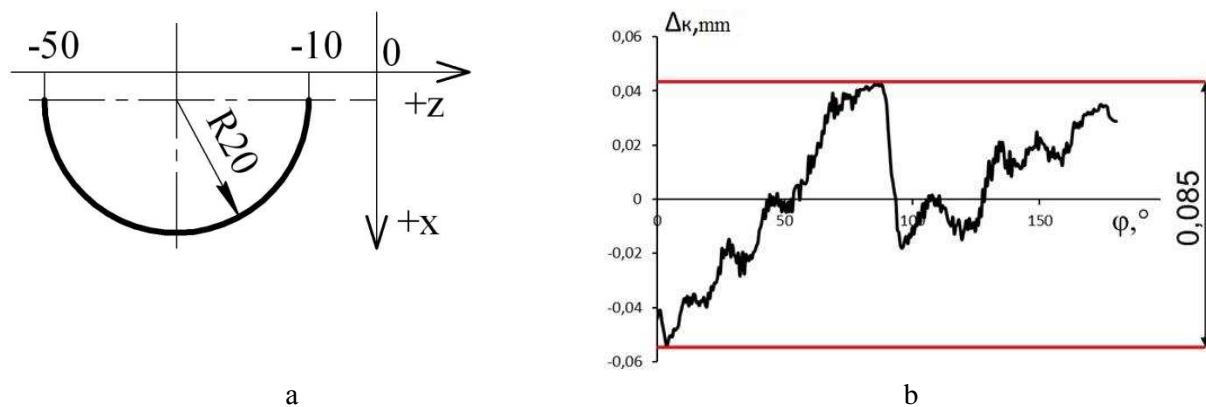


Figure 2. The trajectory of the movement of the machine's actuating devices: a - the trajectory in polar coordinates given in the control program (ideal); b - the actual trajectory obtained during the frame processing by the machine feeders

As a result of the measures to diagnose and improve the accuracy of the CNC lathe of the 1B340F30 model, it was possible to increase the accuracy of working out the trajectory of the displacement of the machine actuating devices by 30%, which in absolute values is expressed: initial contour error $\Delta c_{init} = 85 \mu\text{m}$; the final contour error is $\Delta c_{fin} = 60 \mu\text{m}$ (Figure 3).

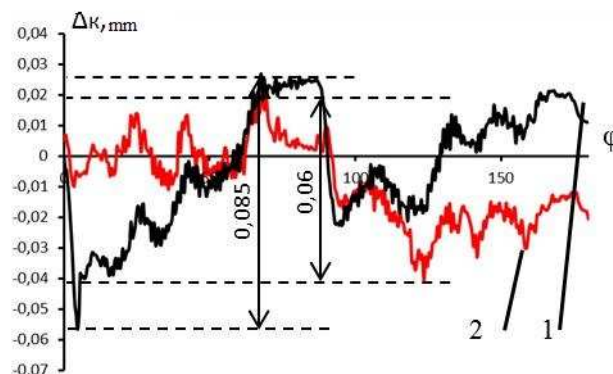


Figure 3. Result of setting the machine parameters: 1 - the original trajectory (before the adjustment); 2 - final trajectory (after the adjustment)

4. Conclusions

The described diagnostic procedure (machine diagnostics is performed after current, unplanned and major repairs) and compensation of machine errors is used in the modernization of the machine control system. In addition, it can be used in the operation of the machine, when there is a change in the state of the machine itself and, as a result, a partial loss of its accuracy takes place. In this case, there is a need to adjust the CNC settings. At the same time, as the example showed, only by adjusting the parameters of the CNC machine, without repairing its mechanical part, it is possible to increase the accuracy of working out the trajectory of the machine actuating devices' displacement by 30%.

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