INVESTIGATION OF THE POSSIBILITY OF CONTROLLING THE DEFORMATION OF THE CENTER AXIS OF A WORKPIECE PROCESSED BY TURNING DUE TO THE CUTTING FORCE WITH A DIGITAL PROGRAM

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Abstract

The article considers the issue of compensating the axial deformation caused by the cutting force during the cantilevered machining of rod-shaped and thin-walled parts processed by lathe operation with a digital program. The deformation of the axis of the part due to the cutting force causes a change in the cutting depth, as a result, the machining accuracy is not ensured, and after machining, shape errors appear in the cross section and also in the longitudinal section. This deformation takes a maximum value at the end of the cantilevered part, and as a result, the shape of the part is obtained according to the hyperbolic curve as it approaches the end. As a solution to this, the article proposes to use an equidistant to compensate for this deformation. The contour of this equidistant was taken into account in the digital program and the deformation of the center axis of the cantilevered parts due to the cutting force during the machining of experimental parts was minimized. The application of the equidistant in the numerical control program was performed in the turning operation of cantilever-mounted rod-shaped parts with a diameter of 10 mm and hollow parts with a diameter of 18 mm.

Keywords: turning operation, cutting force, cantilevered part, thin-walled part, center axis deformation, equidistant, numerical control, machining accuracy

I. Introduction

The introduction of CNC machines in agile manufacturing increases the need for machining accuracy control. The rigid control of accuracy by software gradually leads to the need to switch to software control of mechanical machining accuracy as a result of the improvement of modern numerical control devices [1].

In this regard, it is important to investigate the factors affecting the accuracy of mechanical processing, to study the causes of errors and the laws of variation. This is especially characteristic of cantilevered parts with low rigidity.

It is a very important and very urgent issue to study the law of variation of errors caused by the effect of cutting force during the turning of rod-shaped and thin-walled cantilevered parts, to determine the equidistant of the cutting tool's motion trajectory according to the law of variation of error, and to study the control of the resulting error with a numerical control program.

The main goal of the article is to investigate the possibilities of programmatically reducing the elastic deformation of the spindle axis caused by the radial component of the cutting force (P_y), as one of the factors affecting the machining accuracy of rod-shaped and thin-walled cylindrical parts on CNC lathes, and to determine ways to reduce errors caused by the influence of this factor.

II. Issues to be investigated

The study of the effect of deformations arising in the technological system under the influence of cutting force on the machining accuracy and its reduction is of great interest as a research object. Research in this area has been carried out mainly with the help of adaptive and rigid control systems [2]. The study of the possibility of program control of this problem in numerically controlled machine tools is of both theoretical and experimental importance, especially for parts with low rigidity.

In this regard, the article proposes to solve the following research questions in order to study the possibility of software control of errors arising in the technological system due to the effect of cutting force during the processing of hollow cylindrical parts with low hardness on numerically controlled lathes:

1.Investigation of errors caused by the effect of cutting force during the turning of cantilevered rod-shaped and thin-walled cylindrical parts;

2. Investigation of the possibility of controlling machining errors caused by the effect of cutting force in cantilevered rod-shaped and thin-walled parts using software on numerically controlled machine tools;

3. Designing variants of the compensating equidistant control program to compensate for the axial deformation of the part due to the effect of the cutting force;

4. Experimental study of software control of center axis deformation under shear force in cantilevered rod-shaped and thin-walled parts.

III. Errors caused by the effect of cutting force

One of the factors affecting the accuracy during the mechanical processing of thin-walled cylindrical parts is the displacements in the technological system caused by the action of cutting forces. The displacements caused by the cutting forces in the technological system cause errors in the longitudinal and transverse sections of the part and the violation of the shape accuracy [3]. Therefore, the investigation of the errors caused by the action of cutting forces in the longitudinal and transverse sections of the part is of great importance.

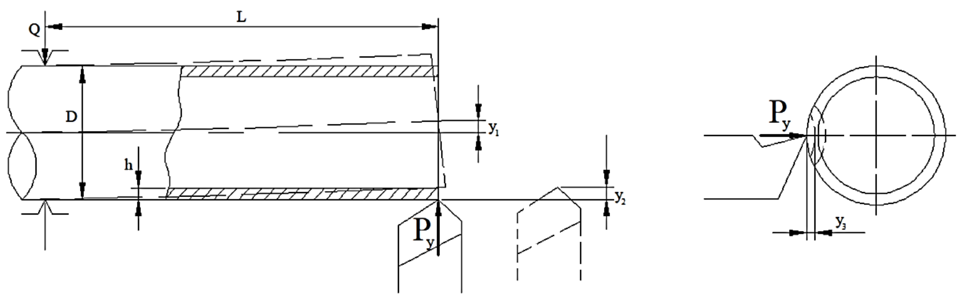

Figure 1: *Deformations caused by cutting force in the technological system*

As we know [3], in the simplest machining scheme, the deformations caused by the cutting force (P_y) in the technological system (figure 1) have the following designations: displacement of the axis of the workpiece - y_1, displacement of the cutting tool under the influence of the cutting force - y_2, and radial displacement in the cross section under the influence of the cutting force in thin-walled workpieces - y_3. All these deformations mentioned cause a change in the intended cutting depth, as a result of which the machining accuracy is not ensured, and after machining, shape errors appear in the cross section as well as in the longitudinal section [4].

İt is known that the deformation under the influence of the cutting force at the end of the cantilevered part takes on a maximum value and, as a result, the resulting part corresponds to a hyperbolic curve that increases towards the end [5]. In this regard, it is important to theoretically and experimentally study the law of change of the axial deformation of the workpiece. Studying the law of change of the deformation of the central axis of the cantilevered part will allow to design a program of the movement trajectory of the cutting tool in numerically controlled machines corresponding to the equidistant, which can take into account the value of this deformation.

Let us examine the displacements caused by the action of cutting force in cylindrical parts fixed to a thin-walled cantilever with low stiffness. The deformation y_1 that can occur under the action of the cutting force P_y, which is the sum of the shear forces, varies according to expression (1):

$$y_1 = \frac{P_y \cdot L^3}{3EJ} \tag{1}$$

where: P_y is the sum of the cutting force normal to the axis of the beam and is theoretically calculated using expression (2):

$$P_y = C_{P_y} \cdot t^x \cdot S^y \cdot V^n \cdot K_y \tag{2}$$

L- length of the cantilever part of the workpiece;

E- modulus of elasticity of the material, for steel $E=2{,}1 \cdot 10^6$ kq/sm^2;

J- is the moment of inertia.

For hollow workpieces:

$$J = \frac{\pi}{64}(D^4 - d^4)$$

For stick workpieces:

$$J = \frac{\pi}{64}D^4$$

where, D and d are the outer and inner diameters of the workpiece, respectively.

IV. Designing a control program for the required equidistant

One of the initial stages in designing an equidistant control program is the selection of a program control tool. A complex and fundamental solution to this problem can be achieved by developing an intelligent, adaptive, or logical control system [6].

Although intellectual control systems allow to solve the problem completely, their application in solving simple problems does not justify itself. That is, it is necessary to put the problem in a very fundamental form. Here it is necessary to create such control algorithms that after processing the information coming from the transmitters, the control system should be able to make a decision on which control algorithm to choose. Since modern digital software control devices are equipped with various transmitters, this will not create such a problem. However, various problems may arise in the means of obtaining the required information directly or indirectly based on electromechanical, etc. transformations. However, the control tool can also be solved through the control program of machines controlled by digital software. Two options are possible for this.

In the first variant, the direction of the solution is determined by the development of new types of interpolation algorithms. It is known that in modern digital program control systems, linear-circular interpolation algorithms are fully implemented. In order to construct an equidistant, theoretically any curve can be divided into elementary parts such as line-arc intersections. However, these elementary parts are not always equivalent to the exact line-arc intersection, they are replaced only within a certain error. On the other hand, sometimes the radius of curvature of the arc, even when it has very large values, does not correspond to the technical indicators of the existing linear-circular interpolation [7]. Therefore, the selection and development of new types of interpolation methods can be considered relevant in this sense. However, it should also be noted that in this case the software support system of the digital program control system must be changed.

The second option is a simpler, but relatively less accurate solution. The essence of this method is to replace the required equidistant with an equivalent equidistant that can reduce errors, using the technological and auxiliary commands provided by the existing control device and control program.

When building a logical control system, the main principle is to develop control algorithms for a specific situation based on the logical analysis of feedback signals received from the transmitters. The programmable controllers required for this control system are available in most CNC (Computer Numerical Control) machine tools. When building a logical control system, first of all, input-output programs are built, logic equations are compiled and minimized, and then converted into a programming language. The construction of mathematical equations is done with the help of "AND", "OR", "NEGATIVE" and other schemes.

For example:
IF L=50 mm; AND (X_1)
D=12 mm; AND (X_2)
t=1 mm if, THEN (X_3)
ON THE OTHER HAND S=0,3 mm/rev.

The text of the program is $\bar{y} = X_1 \cdot X_2 \cdot X_3$ or $y = \overline{X}_1 \cdot \overline{X}_2 \cdot \overline{X}_3$ will be in the form of.

During processing, the deformation due to the shear force at the end of the cantilevered part takes on a maximum value, and as a result, the shape of the part is taken to correspond to a hyperbolic curve as it approaches the end. Taking this into account, the scheme of the shape error resulting from processing and the compensating equidistant can be shown as follows:

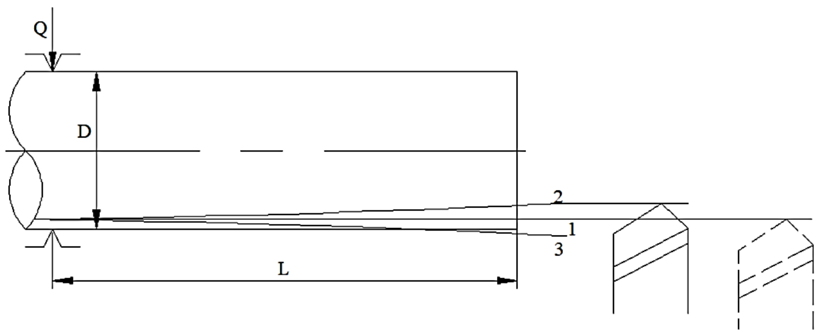

Figure 2: *Diagram of the error and the compensating equidistant during the processing of a cantilevered part*

In this figure, 1 is the desired surface, 2 is the real surface, and 3 is the compensating equidistant. This equidistant is obtained graphically by subtracting curves 2 and 1. As can be seen from figure 2, curves 2 and 3 are symmetrical with respect to surface 1 and will differ in the direction of the center.

As we know [7], three typical joining methods are used to join the support points of an equidistant: straight line-straight line, straight line-circle and circle-circle method. Since it is not possible to program an arbitrary curve directly as a hyperbolic curve in current numerically controlled machine tools, it is considered appropriate to program the equidistant as a line-circle junction [8].

To program the equidistant compensation for the error that occurs during the mechanical processing of the cantilevered part shown in figure 2, the part is first divided into five equal parts along the length. Then, a scheme for programming the equidistant is constructed. This scheme is shown in figure 3.

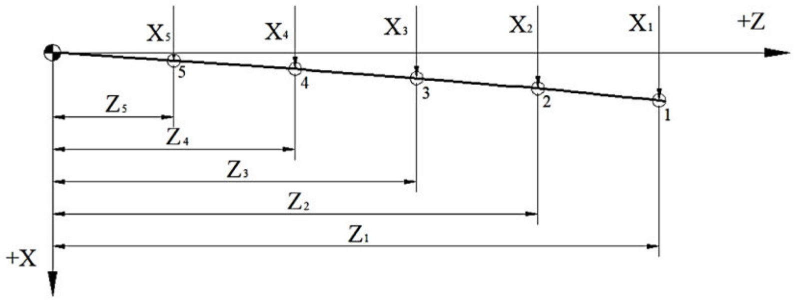

Figure 3: *Schematic of programming the compensating equidistant*

In this figure, the values of the coordinates on the Z axis are denoted by Z_1, Z_2, Z_3, Z_4, Z_5, and the values of the coordinates on the X axis are denoted by X_1, X_2, X_3, X_4, X_5. Three new methods can be proposed for programming this compensating equidistance. In order to conduct a comparative analysis of these three methods that we have proposed, it is necessary to refer to the text of the programs based on them.

In the first method, the most distorted part of the equidistant 0÷5 is approximated by chords that are broken line segments, and the processing share for each broken line is assigned in separate frames. Here, choosing the number of broken lines is an optimization issue. Thus, by increasing the number of these chords, the approximation accuracy of the equidistant will increase. On the other hand, increasing the number of chords will also lead to an increase in the number of intermediate support points arranged along the equidistant, which will reduce the cleanliness of the surface processed along the equidistant. The text of the program based on this method will be as follows:

N_i X0 Z0 E
N_{i+1} X1 Z1 F
N_{i+2} X2 Z2 F
N_{i+3} X3 Z3 F
N_{i+4} X4 Z4 F
N_{i+5} X5 Z5 F

This method is considered a relatively simple method, but the assignment of absolute coordinates of points limits its application, because in other details, it is enough to change the dimensions alone to make this program useless.

The second method is more universal than the first. Since, in the program text compiled by this method, displacements are assigned instead of coordinates. That is, regardless of the dimensions of the detail, such displacements can be programmed as many as the number of chords determined during the approximation. However, in this method, both the points on the X coordinate are still assigned with absolute coordinates, and the relatively large number of intermediate points at relatively large lengths will lead to an increase in the number of frames. The text of the program created based on this method will be as follows:

N_i X0 Z0 E

N_{i+1} W-A X1 U-a
N_{i+2} W-A X2 U-a
N_{i+3} W-A X3 U-a
N_{i+4} W-A X4 U-a
N_{i+5} W-A X5 U-a
where, W- axial displacement along the Z axis;
A- equal length of relative displacements along the Z axis;
a- the equal length of the relative displacements along the X-axis is.
The values of A and a are determined as follows:

$$A = \frac{Z_0 - Z_4}{n}$$
$$a = \frac{X_0 - X_4}{n}$$

It is known that in numerically controlled machines, the numerical time consists of processing and preparation-completion times. One of the processes that determines the preparation-completion time norm is the process of setting up the machine, which, together with other operations, includes the compilation of the control program. Therefore, minimizing the time spent on the compilation of the control program as much as possible is one of the main factors affecting the increase in processing productivity.

Herefore, in the third method, we use the commands for programming cycles. Here, both the program text is reduced many times, and relative coordinates or displacements are assigned to both coordinates, which makes the program text as universal as possible. The text of the program created based on this method will be as follows:

N_i X0 Z0 E
N_{i+1} W-A U-a
N_{i+2} M18
N_{i+3} L11 B N_{i+1} HK
N_{i+4} X0 Z0 E
where, L11- recycling cycle;
B- the frame at the beginning of the repeat;
K=n-1 is the number of repetitions.

The beginning of the repeated program part is the frame N_{i+1} specified at address B, and the end is the frame with M18.

Thus, the first proposed method is suitable for a specific part, the second method is suitable for all parts with the same diametrical dimensions, and the third method is suitable for typical parts with different diametrical and longitudinal dimensions. However, in any case, the optimization problem related to the number of intermediate support points remains unresolved.

V. Experimental study of software control of the deformation of the center axis due to the cutting force of a cantilevered part

To implement the problem, first the value of the radial component of the shear force (Py) was determined using expression (2), and the values of the displacements of the central axis for the rod and thin-walled rods in five equal sections along the length were calculated and recorded in table 1 (for rod parts) and table 2 (for thin-walled cylindrical parts). Then, according to these values, the dependence graphs y=f(L) were constructed for the rod parts (figure 4) and for the thin-walled cylindrical parts (figure 5).

Table 1: *Displacement of the axis of the rod-shaped workpieces*

Current cross-sections of the span of length L (x), mm	Axis displacement-y, mm J=0,05sm⁴ D=10mm Theoretical	Experimental	Without program	With the program	Cutting force Py, N	t, mm	S, mm/rev	n, rev/min
10	0,0063	0,0055	0,0032	0,0022	198	0,5	0,3	500
20	0,0051	0,0043	0,0021	0,0012				
30	0,017	0,014	0,008	0,004				
40	0,04	0,035	0,016	0,009				
50	0,078	0,067	0,03	0,02				

Then, the displacements of the axis in five equal sections of the beam were measured experimentally and the values of these displacements were added to table 1 (for rod parts) and table 2 (for thin-walled cylindrical parts).

Table 2: *Displacement of the axis of a thin-walled workpieces*

Current cross-sections of the span of length L (x), mm	Axis displacement-y, mm J=0,41sm⁴ D=18mm d=15mm Theoretical	Experimental	Without program	With the program	Cutting force Py, N	t, mm	S, mm/rev	n, rev/min
10	0,00007	0,00006	0,00003	0,00001	198	0,5	0,3	500
20	0,00061	0,00053	0,00027	0,00015				
30	0,0021	0,0017	0,0012	0,0007				
40	0,0049	0,0042	0,0028	0,0015				
50	0,0095	0,0083	0,006	0,003				

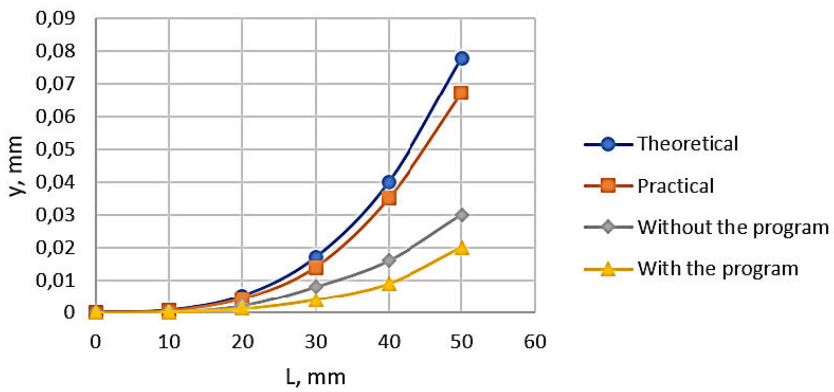

Figure 4: Displacement of the axes of rod workpieces (d=10 mm) depending on the length

Then, the workpieces were machined without a program in the machining modes t=0.5 mm, S=0.3 mm/cycle and n=500 cycles/min, the displacement values were measured and added to

Tables 1 and 2. The curve constructed based on these values was added to figures 4 and 5, respectively.

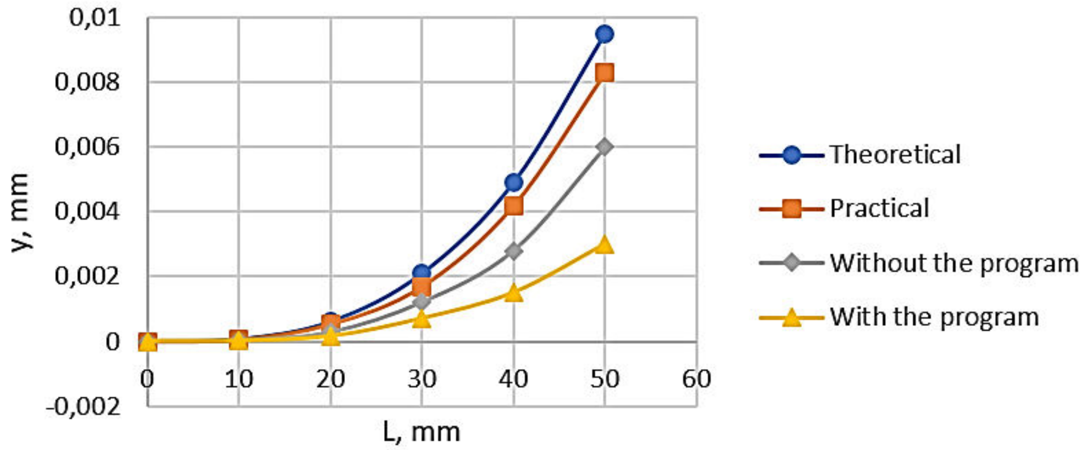

Figure 5: *Displacement of the axes of thin walled workpieces (D=18 mm, d=14 mm) depending on the length*

As a final result, the processing of rods and thin-walled plates was carried out using the developed control program in the same processing modes, and the results were added to the tables and figures. In all these experiments, the range of cutting force variation was 157...256 N.

VI. Results

1. Elastic displacements caused by the action of cutting force during the turning of cantilevered non-rigid parts have been studied theoretically and experimentally;
2. The possibility of software control of machining errors caused by the effect of cutting force in cantilevered rod-shaped and thin-walled parts on CNC machines has been investigated;
3. An equidistant was determined to compensate for the error caused by the bending of the axis due to the shear force of the cantilevered parts, a corresponding program was created and experimentally verified;
4. When comparing graphs constructed with known dependencies for determining the deflection of the center axis of cantilevered parts, it was found that the error during processing with and without programming the equidistant is reduced by 12-15%.

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