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Ensuring accuracy of contour milling on CNC machines

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Abstract. *Contour milling is characterized by quasi-stationary, which leads to the occurrence of a machining error caused by elastic deflections of the machining system. Moreover, such an error cannot be eliminated by sub-adjusting the control program "for size", since it not is constant and changes along the contour in a wide range. To ensure the accuracy of contour milling, a new method of combined control is proposed, which uses a posteriori information of machine verification measurements of the machined surface and a priori information of modeling the material removal process. In case of single manufacturing, the allowance on the last pass is divided into two parts, and after machining the first part, verifications are performed, then modeling and machining of the second half according to the corrected control program. In mass manufacturing, verifications are performed on the first part, and all subsequent ones are machined according to the adjusted control program. To obtain the necessary a posteriori information, the technology of machine verifications on CNC-machine with a three-coordinate probe according to standard control programs is proposed, and it is enough to perform two measurements or one, in the presence of surfaces inclined to the coordinate axes of the contour. A computer program was created, the core of which is a mathematical model of the process, which reproduces the structural diagram of the machining system closed behind two elastic deflections. The primary control file is loaded in G-codes with measurement data, and as a result of the process simulation, a new control file for the CNC-machine tool is formed, which eliminates the error from elastic deflections of machining system. Preliminary tests showed the possibility of increasing the accuracy of contour machining by more than 3 times.*

Keywords: *contour milling, correction of the control program, modeling of the contour milling.*

1. Introduction

Milling of complex surfaces of machine parts is always accompanied by a change in a wide range of cutting conditions along the forming trajectory, even with an absolutely equidistant allowance. Such changes provoke the emergence of a machining error caused by elastic deflections of the technological machining system (TMS) under the action of variable cutting force. The greatest influence of the cutting mode on the accuracy of processing is observed when milling non-rigid parts, which occurs mainly in the manufacturing technologies of aerospace parts [1].

Milling is carried out on CNC-machines using control programs designed in CAM-systems, the vast majority of which create shaping trajectories, based only on the geometric conditions of the interaction of the tool surface with the part. The same CAM systems that advertise "intelligent machining" [2] design a control program with feed control based on the analysis of the trajectory of the tool center recorded in G-codes, but the cutting that causes elastic deflections of the TMS occurs on the periphery during the Cutter Workpiece Engagement (CWE).

Therefore, such control cannot lead to the stabilization of the cutting process and equalization of the machining error along the entire contour [3]. In addition, even with the complete stabilization of the cutting according to its main characteristic MRR (Material Removal Rate), it is not possible to ensure a uniform error along the contour, since the vector of the cutting force changes its orientation, and the stiffness of the TOC is not the same along different coordinate axes. At the same time, the CNC-machine tool has the ability to permanently control both the forming trajectory and the cutting mode, which are not used in most cases.

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Thus, the problem of eliminating the forming error caused by the elastic deflections of TMS during milling of complex surfaces remains an urgent task, the solution of which will allow to significantly increase the accuracy of machining.

2. Problem status analysis

The contour surfaces of many parts, matrices and molds are machined in final milling operations on CNC machines. The accuracy of the contour of the milled surfaces is strongly influenced by the elastic deflections of the TMS, including the cutting tool, caused by the cutting force. Moreover, the error significantly changes along the forming trajectory due to the variable radial cutting depth and the change in the direction of the cutting force. Simulation of tool deviation to predict deviation errors in straight segments and corners for rough milling with slot cutting, as well as for finishing milling of contours of parts by determining the change in radial depth of cut provides prediction of machining accuracy [4]. To increase the accuracy of contour milling, it is suggested to reduce the radial depth during angular cutting. Such a trivial approach to solving the problem definitely leads to a loss of productivity and cannot be considered acceptable.

Milling of round corners when machining a pocket structure is widely used in the aerospace industry [5]. Reliable quantitative predictions of cutting force components in angle milling operations are essential for determining power requirements, geometric errors or deviations of machined components, vibration characteristics, and strength requirements of the cutting tool. The instantaneous angle of the CWE, when milling a circular angular structure is derived on the basis of a detailed analysis of the geometric ratios of the cutting tool and the corner radius of the part. And then the instantaneous undeformed chip thickness in the corner milling operation is derived from the presented iteration algorithm. Based on the two models given and the cutting coefficients selected through slot milling tests, the predicted cutting force can be used to control the cutting process. However, this approach does not lead to compensation of contour deviations during milling.

When milling parts with low stiffness, one should take into account not only the possibility of dynamic effects in the form of vibrations, but also the static deviation of the trajectory of the formation due to the cutting force [6]. The model takes into account the influence of the tool position and dynamic movements of the workpiece along the tool axis during peripheral milling of thin-walled workpieces with curved surfaces. A new dynamic model of the tool-workpiece system is proposed to take into account the dynamic behavior of the tool and workpiece, as well as the effect of the CWE and tool feed direction. The interaction between the tool and the thin-walled workpiece is simulated at individual nodes along the axial depth of cut. A method based on the scheme of structural dynamic modification has been developed to characterize the effect of material removal on the dynamics of the workpiece in the production process. A model and method for predicting the shape of the workpiece using the finite element method is proposed. Changes in cutting conditions are taken into account, in particular, the stiffness of thin-walled workpieces, but the cutting process is presented without taking into account its closedness, which can distort the forecasting results.

The study of the surface location error or part geometry errors that occur due to forced vibrations of the cutting tool during stable milling [7] present two analytical solutions. Analytical approaches are based on frequency domain analysis and harmonic balance. A comparison between analytical results, time-domain simulation, and experiment is included, and problems with numerical modeling and semi-analytical methods (eg, time-domain finite element analysis) are presented. This work provides two new analytical solutions to calculate surface location errors or part geometry errors that arise from forced vibrations of the cutting tool even during stable milling. However, there are no recommendations or practical process management actions to compensate for contour deviations in peripheral milling.

From the analysis of the presented studies on contour milling, it can be concluded that all of them use the cutting force models presented in [8] for analysis. Such models link the cutting mode and its components with the components of the cutting force and have been confirmed by experimental testing. The error of the shape of the surface machined by peripheral milling consists of static and dynamic parts. The static deflection caused by the normal force at the free end of the end mill is determined by the analytical dependences in which the proposed cutting force model is applied. The total static deflection at the axial contact point is calculated by the superposition of the deflections created by all elementary forces on the end mill. However, the closedness of the dynamic TMS is not taken into account in the proposed models, although such models are used in the analysis of the dynamic component.

In the case of rough 2.5D milling operations, the efficiency of processing can be significantly increased by ensuring a uniform load on the tool [9]. This is confirmed by the fact that a uniform load has a positive effect on both tool life and processing time. Unfortunately, conventional contour-parallel tool paths cannot guarantee a uniform load on the tool. Some advanced path generation techniques are presented that can provide a constant tool load by controlling the cutter engagement angle. However, it is argued that the spread of these methods of non-equidistant displacement is hindered by their dependence on complex calculations. As a solution to this problem, the Fast Offset Constant Entrainment Method is proposed, which takes a step toward reducing the computational requirements.

In the machining, the cutting force causes deformation of thin-walled parts and cutting tools due to their low rigidity [10]. Such deformation can lead to undercutting of the contour and damage to the parts. It is emphasized that since there are various unexpected factors that affect the cutting forces during the machining, the compensation of the deformation errors caused by the cutting force is considered to be a very difficult issue. To solve this problem, a new real-time deformation error compensation method based on dynamic features is proposed. A dynamic performance model is created to estimate the stiffness of the elements, as well as the relationship between the geometric information and the cutting force information in real time. Then the deformations are calculated based on the model of dynamic features. Finally, machining error compensation for elastic deformation is implemented based on function blocks. The algorithmic meaning of such blocks is not presented, although the results of the machining experiment show that the calculated deformation errors decrease with controlled deformation.

There are many machining situations where fine tools are used to machine thin-walled tubular workpieces [11]. Such cases are more common when machining details of the aircraft structure. In these cases, tool deflections caused by the cutting force as well as workpiece deflections are quite common, resulting in surface errors on machined components. The methodology of compensation of such surface errors, caused by elastic shifts of the tool and workpiece, during the machining of thin-walled forms by changing the trajectory of the tool is presented. The accuracy with which deflections can be predicted is highly dependent on the correctness of the cutting force model used. It is argued that traditionally used mechanical cutting force models overestimate tool and workpiece deviations in this case, as the change in process geometry due to deviations is not taken into account in the simulating. Thus, in this work, a model of the cutting force is adopted, which takes into account the change in the geometry of the process due to the static deviations of the tool and the workpiece. Such a force model is used to predict the surface errors of machined components caused by tool and workpiece deflection, and then compensates for them by changing the tool path.

The given overview of the works shows that everyone recognizes the quasi-stationary of the cutting mode during contour milling, as a result of which the cutting force changes and the elastic deflection distorts the desired shape of the part. Moreover, it is impossible to compensate for such an error by simply adjusting the size precisely because of its fluctuation along the trajectory of shape formation. The error due to elastic deflection takes up a significant part of the total machining error, especially when milling low-rigidity parts.

The task becomes more complicated when the stiffness of the machining system changes according to the shape formation coordinate. The methods of eliminating such errors are reduced to taking into account elastic deflections according to an a priori model, the accuracy of which significantly depends on the adequacy of the adopted model. The accuracy of the cutting force model during milling depends on empirical data obtained experimentally, which complicates the practical implementation of the proposed methods. In addition, the models of the machining system (TMS), according to which compensatory controls are calculated, do not take into account its closedness, which significantly reduces their adequacy.

Thus, the problem of ensuring the accuracy of contour milling and creating such a control technology that would combine the advantages of analytical forecasting with experimental results for a specific machining system of a CNC machine tool remains relevant.

3. The aim and objectives of the study

The purpose of this work is to create a technology for compensating the error from elastic deflections in the technological machining system by means of combined control, when the correcting transfer function is determined based on the results of on machine verification the machined surface, and the design of the corrected trajectory is determined based on the results of simulation the milling according to its main characteristic - an analogue of the Material Removal Rate.

To achieve the goal of the work, it is necessary to solve the following tasks:

– to develop a mathematical model of error formation from elastic deflections during contour milling;

– to develop a technology for verification the dimensions of the machined surface in some zones on a CNC-machine to determine the corrective transfer function of the control block-scheme based on a posteriori information;

– conduct a simulation of cutting the allowance, in the process of which obtain a posteriori information based on measurements and design a corrected trajectory for milling the contour of the part on a CNC machine tool;

– perform experimental testing of the developed technology.

4. The study materials and methods

The object of the study is the process of contour milling, which is performed on a CNC-machine tool. The process of error formation is subject to certain processes that occur during cutting in a closed machining system. In the process of milling, a cutting force occurs, which causes an elastic deflection of the TMS, which distorts the theoretical trajectory. The cutting force depends on the geometric engagement of the cutting tooth of the milling cutter and the workpiece. Such an interaction determines the main characteristic of the process – the Material Removal Rate, on which the cutting force depends.

Elastic deflections of the technological machining system cause a change in the geometric parameters of the CWE, which, in turn, provokes a change in the cutting force. This is the closedness of the TMS, where the forming process takes place, which is complicated by the change of the cutting arc during contour milling.

In the research process, it was decided to apply combined control methods that combine the advantages of control based on a posteriori information when determining system parameters based on the results of the first pass with control based on a priori information used in modeling. During the simulation, the task of adjusting the trajectory is solved, which will be implemented in the control program of the CHPK.

5. Results of devising contour milling programming technology

5. 1. Mathematical model of error formation from elastic deflections of the machining system

The process of contour milling takes place in an elastic machining system, which is under the influence of a force disturbance, its provokes the occurrence of elastic shifts along the δ_x and δ_y coordinate axes (Fig. 1). Therefore, under the action of the cutting force, the initial tool surface of the cutter moves by the amount of elastic displacement from position 1, which is specified by the control program, to position 2, which corresponds to its actual location. Such shifts are determined by the F_x and F_y components of the cutting force, which can be calculated from the geometric ratios of the cutting force distribution scheme in Fig. 1:

$$\begin{cases} F_x = F\,\mathrm{Cos}(\alpha - \varphi + \gamma) \\ F_y = F\,\mathrm{Sin}(\alpha - \varphi + \gamma) \end{cases}, \tag{1}$$

where *F* is the cutting force on the mill tooth, α is the angle of inclination of the contour of the part, φ is the angle of the cutting arc, γ is the angle between the tangential F_t and the radial F_r components of the cutting force. It is clear that the cutting force *F* is determined by its components:

$$F = \sqrt{F_t^2 + F_r^2}\,. \tag{2}$$

Such components also depend on the angle of the cutting arc and are determined according to empirical relationships [8]:

$$\begin{cases} F_t(\varphi) = k_{Ft} b h(\varphi) \\ F_r(\varphi) = k_{Fr} b h(\varphi) \end{cases}, \tag{3}$$

where k_{Ft}, k_{Fr} are empirical coefficients of linearized dependences, b is milling width, $h(\varphi)$ is the thickness of the allowance layer cut by the mill tooth. Empirical coefficients are assumed to be constant for the tool-workpiece material pair and can be estimated either mechanically from milling tests or from relevant reference books.

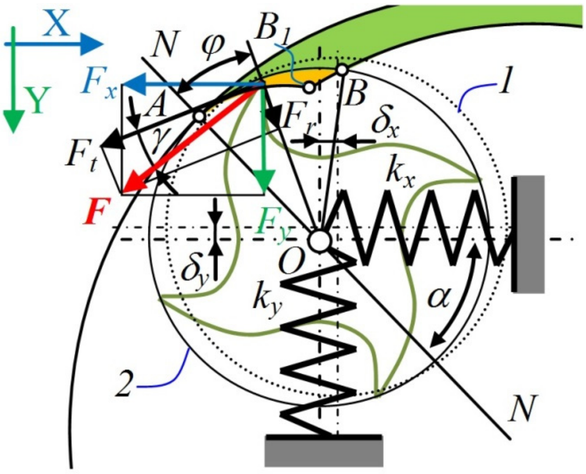


Fig. 1. Contour milling scheme

For the case of contour milling, where the cutting arc can vary over a wide range, it is advisable to determine the cross-sectional area of the undeformed chip, which is analogous to the material removal rate (MRR) as:

$$MRR = bh(\varphi) = b\int_0^{\varphi_{\max}} f_t\,\mathrm{Sin}(\varphi)\,d\varphi\,, \tag{4}$$

where f_t is the feed per tooth of the milling cutter. The integral presented in the program is calculated numerically at each step of the simulation. The maximum cutting angle is determined by the formula:

$$\varphi_{\max} = \arctan\left(\frac{O_x - x_A}{O_y - y_A}\right) + \arctan\left(\frac{x_B - O_x}{y_B - O_y}\right), \tag{5}$$

where x_A, y_A, x_B, y_B are the coordinates of the start and end point of the cutting arc at the current modeling step, O_x, O_y are the coordinates of the cutter center.

The procedure for determining the coordinates of point *A* of the beginning and point *B* of the end of the cutting arc is performed with arrays of data representing the contour of the workpiece and the initial tool surface of the mill. Therefore, the data arrays of workpiece coordinates will consist of three parts. The first part is an already machined surface that will represent the surface of the part. The second part is the cutting arc belonging to the initial surface of the mill and the third part is the unprocessed surface of the workpiece. When performing the next simulation step, such operations are repeated. Thus, at each simulation step, the contour of the workpiece is gradually transformed into the contour of the part being machined.

To determine the actual cutting thickness h(φ), it is necessary to take into account the closedness of the cutting process for each of the controlled coordinates (Fig. 2). According to this scheme, an algorithm for numerical modeling of the allowance removal process during contour milling was built [12].

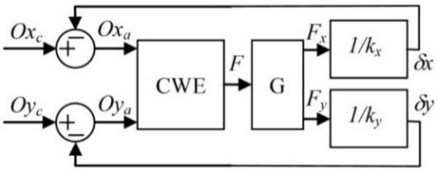


Fig. 2. Structural diagram of the processing system

Next, the determined value of the cutting thickness is used to calculate the components of the cutting force according to formulas (3) and to determine the cutting force according to formula (2). The cutting force is distributed in block G according to the scheme of Fig. 2 on the component, which will determine the elastic deflections of the machining system and which, due to the closedness of the system, will change the coordinates O_{xc} and O_{yc} of the shaping trajectory commanded by the control program. The elastic system in accordance with the scheme of fig. 1 is represented by two stiffness k_x and k_y along the coordinate axes without taking into account dynamic phenomena.

It should be noted that the cutting process is modeled in this way by representing the average cutting force, since with the presence of the angle of inclination of the cutting blade of the mill, the value of the cutting force will change according to the coordinate of the rotation angle of the mill. In addition, the model does not take into account dynamic phenomena that are necessarily present in the real process. Such an approach can be considered sufficient for the given task of correcting the forming trajectory, since dynamic phenomena will affect the surface roughness due to the occurrence of chatter of the dynamic elastic system and will not cause a change in the dimensions of the machined contour.

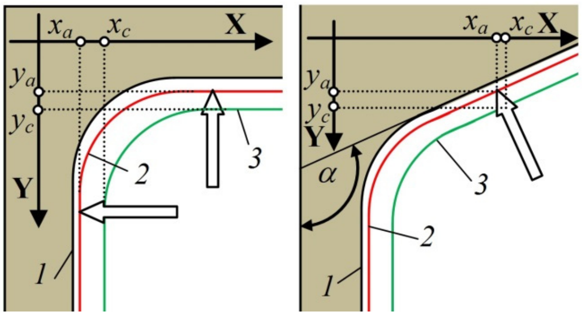
5. 2. The technology on machine verifications of the machined surface

To obtain data on the accuracy of the machined contour of the part, which will constitute a posteriori information in the algorithm for determining the corrected trajectory on the second pass, it is enough to perform several verifications according to the schemes of Fig. 3. In fig. 3 lines 1 denote the theoretical contour, lines 2 – the actually machined one, and lines 3 – the contour of the workpiece with an equidistant allowance *h* to the theoretical contour of the part.

If all rectilinear sections in the processed contour coincide with the directions of the machine tool coordinate axes (Fig. 3, a), it is necessary to measure in the direction of the arrows anywhere on the rectilinear sections to determine the errors:

$$\delta_x = h - (x_c - x_a), \quad \delta_y = h - (y_c - y_a), \tag{6}$$

where x_c, y_c are command coordinates according to the control program; x_a, y_a – actual coordinates of the machined contour.



a *b*

Fig. 3. Scheme of verification of the machined contour: *a*) – the sections coincide with the directions of the coordinate axes; *b*) – a site with a slope

If there is a section with a certain slope to the coordinate axis in the machining contour, then it is enough to perform one measurement in the direction of the arrow normal to the contour and use the angle α of the slope of the section determined from the control program:

$$\delta_x = h\,\mathrm{Cos}(\pi/2 - \alpha) - (x_c - x_a),$$
$$\delta_x = h\,\mathrm{Sin}(\pi/2 - \alpha) - (x_c - x_a). \tag{7}$$

Verifications must be performed directly on the machine, using the OMV (On Machine Verification) technology with a conventional three-coordinate probe Renishaw [14]. Before measuring, after installing the probe on the machine, it must be calibrated using the vector probe ball radius macro O9804. The probe is placed inside the calibrated ring at a certain height along the Z coordinate and a macro cycle is performed. After the cycle is completed, the defined radius of the probe ball is saved.

It is most difficult to measure the contour with an inclination to the coordinate axes of the machine. For this, it is recommended to use the cycle shown in fig. 4.

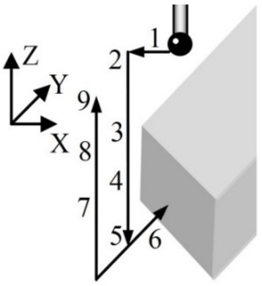


Fig. 4. Scheme of movements of verifications of an inclined surface

Below are the relevant loop commands.

1. T01M06 Probe selection.
2. G54X-40.Y20. Launching site.
3. G43H1Z100. Offset activation 1, transition to 100 mm (3.94 in).
4. G65P9832 Probe rotation (includes M19) or M19 for spindle orientation.

5. G65P9810Z-8.F3000 Protected positioning of the movement to the initial position.
6. G65P9821A45.D50.T10 Surface measurement.
7. G65P9810Z100. Protected positioning.
8. G65P9833 Probe return (if available).
9. G28Z100. Initial position.

The data on the contour errors determined in this way constitute a posteriori information of the machining system, which will be used in the design of the corrected trajectory.

5. 3. Simulation of cutting allowance and designing the corrected trajectory

A computer simulation program was created to determine a priori information about the forming process. As an example of the formation of a corrected trajectory, a fragment of a contour consisting of two straight lines and a conjugate arc of a circle was chosen. This contour is extremely common when machining parts with pockets in the aircraft industry.

Simulation is performed according to the created mathematical model using as input data the control program in G-codes for the CNC milling machine. During simulation, the movement of the milling cutter is animated along the forming trajectory and the main parameters of the process are synchronously displayed on the screen of the virtual oscilloscope. In fig. 5 presents the results of modeling the part contour milling with Steel 40 milling cutter P6M5 Ø20mm, number of teeth 6, equidistant allowance 3 mm, milling thickness 10 mm. The cutting mode is determined automatically from the control program that is loaded at the beginning of the simulation: the spindle speed of the cutter is 1500 rpm, the feed is 400 mm/min.

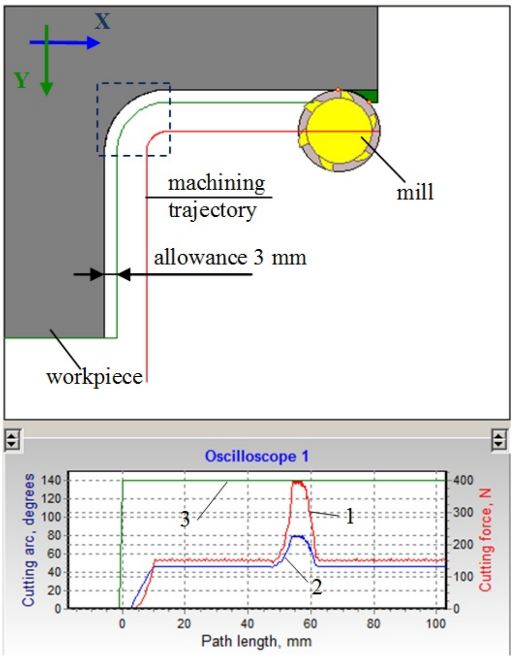


Fig. 5. State of the program interface at the end of the simulation

Synchronous with the movement of the milling cutter, the oscillograms of the average cutting force are displayed in the virtual oscilloscope window – line 1, cutting arcs – line 2 and feed – line 3. It can be seen that the milling process is characterized by a change in cutting conditions in a significant range in the section formed by the arc of a circle: the cutting arc increases to 80 degrees, and the average cutting force reaches 400 N, while in straight sections, the cutting arc is 45 degrees, and the average cutting force is 150 N. Therefore, such a process entails a corresponding response of the elastic machining system, which will determine the contour-variable forming errors.

The same changes are displayed in the window of the second virtual oscilloscope (Fig. 6). It is possible to observe changes in the components of the cutting force and the elastic shifts of the machining system caused by them along the corresponding coordinate axes. The F_y component (line 1) causes a shift along the Y coordinate (line 2), and the F_x component (line 3) causes a shift along the X coordinate (line 4). Regardless of the constant cutting conditions along the rectilinear sections of the contour (Fig. 5), the corresponding components and reactions of the elastic system change (Fig. 6).

The simulation takes place for the machining system with the coefficients of linearized dependencies introduced into the model for the components of the cutting force when machining the workpiece from Steel 40 and the stiffnesses of the machining system along the coordinate axes. It is clear that such data are a priori, used only to identify the modeled system and, in accordance with the accepted control paradigm of correction, are not used in further procedures.

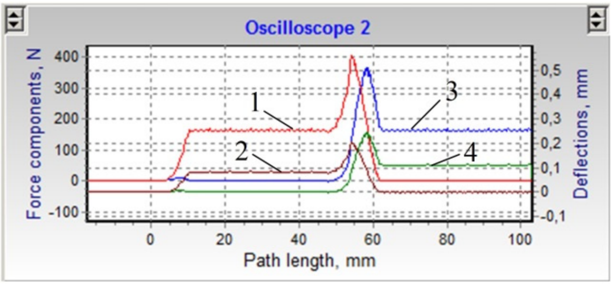


Fig. 6. Components of cutting forces and elastic shifts of the machining system

The determination of the corrected trajectory must be performed in accordance with the combined control with a combination of procedures using a posteriori information and with the identification of the machining system according to a priori information. The trajectory of the formation is determined by two coordinates. However, based on the principle of superposition, it is advisable to carry out further consideration only on one controlled coordinate. The obtained results will be valid for the second coordinate as well.

So, in order for the amount of displacement x_a along the X coordinate to be equal to the given x_c, you can use the principle of the control method based on a priori information, the structure of which is shown in Fig. 7. The magnitude of the transfer function of the MSx machining system in the verification place can be determined from the structural diagram as:

$$\frac{\delta x}{x_{cc}} = \frac{MSx}{1+MSx}. \tag{8}$$

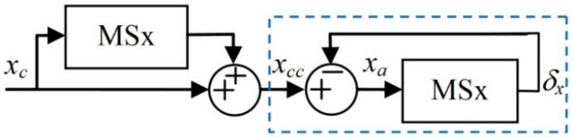


Fig. 7. Structural diagram of management based on a priori information

If take for the part of the scheme highlighted by a dashed line the given value of the coordinate $x_{cc} = x_c$ in accordance with the verification schemes (see Fig. 4), then:

$$MSx = \frac{\delta_x}{x_c - \delta_x}. \tag{9}$$

Since during machining movement is performed along the trajectory in accordance with the coordinates that determine the trajectory of the mill center (in the reverse scheme), during digital modeling, such a process is subordinated to the array of data according to the corresponding coordinates with a certain step. Therefore, transfer functions in general should be represented by appropriate arrays. In addition, taking into account the quasi-stationary of the cutting process and formula (3) for determining force disturbances, the array of the transfer function $MSx_c[i]$ for trajectory correction takes the form:

$$MSx_c[i] = MSxk[i], \tag{10}$$

where $k[i]$ is an array of the correction coefficient.

Such an array can be determined based on the results of simulation, because at each step, the maximum cutting angle φ and the area, which is an analogue of the Material Removal Rate – the volume of the removed material, are determined by a numerical method based on the cutter workpiece engagement. So:

$$k[i] = sq[i]/sq^*, \tag{11}$$

where sq^* is the area of the undeformed chips by the cutter tooth in the place that corresponds to the verification coordinates, $sq[i]$ is the array of areas determined during simulation along the entire trajectory.

Similar calculations will be valid for the y coordinate. Thus, the design of the corrected trajectory on the second pass is performed numerically in accordance with the scheme of fig. 7 according to the formulas:

$$\begin{cases} x_{cc}[i] = \left(MSx_c[i]+1\right)x_c[i] \\ y_{cc}[i] = \left(MSy_c[i]+1\right)y_c[i] \end{cases}. \tag{12}$$

The calculation step is determined by the required accuracy of the machined contour and taking into account the step of the output arrays formed in the machine rack during machining. In the future, to implement the corrected program, it is desirable to design the control program of the corrected trajectory in G-codes. For this purpose, it can use the developed algorithms for representing the array of data in the form of geometric primitives – a straight line, an arc of a circle or in the form of splines.

Data for performing trajectory correction operations in graphic form are obtained in the simulation program at the end of the cycle. To perform such procedures, verifications of the machined surface are performed in advance in places that meet the requirements formulated in section 5.2. Of course, the measurements are performed virtually, and the values calculated during simulation are used as the measured errors.

In fig. 8 presents a fragment of trajectories highlighted by a dotted square in fig. 5. The machined contour is represented by line 1, and the theoretical contour is represented by line 2. The maximum error that can be measured along the normal to the surface is 0.3 mm. The geometric equidistant corresponding to the movement specified in the control program is marked by line 3, and the actual trajectory of movement, which is distorted due to elastic deflections of the machining system, is marked by line 4.

As a result of the functioning of the developed procedures, in accordance with algorithm (9)–(12), arrays of the corrected trajectory are determined, which are presented in Fig. 8 by line 5. It is assumed that when milling the contour along the corrected trajectory, the error caused by elastic shifts will be compensated.

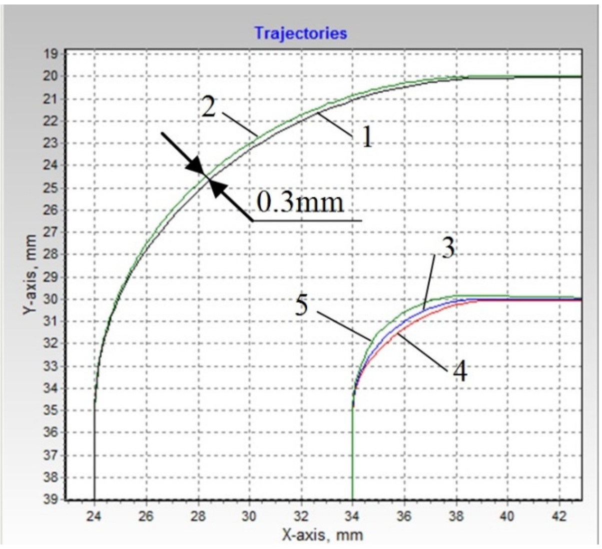


Fig. 8. Fragments of the trajectories of forming and the contour of the part when simulation machining according to the original control program

Therefore, when designing the corrected trajectory, the program did not use data that are difficult to measure on a real machine (stiffness along the coordinate axes) and data that determine the power characteristics of the cutting process.

5. 4. Approbation of the results

To confirm the obtained results, a similar program was used to simulate the milling process of the same contour, but with the control of the corrected trajectory, which was obtained digitally at the previous stage. All raw data of the machining system, workpiece material and tool parameters were saved as for the simulation stage when designing the corrected trajectory. The program also provides the possibility of presenting the results in the form of trajectories with the possibility of enlarging the image (Fig. 9).

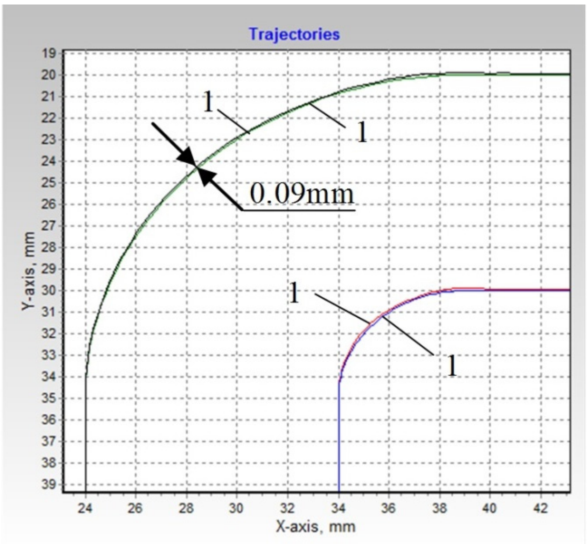


Fig. 9. Fragments of shaping trajectories and part contour when simulation machining according to the adjusted control program

The test results indicate the effectiveness of the developed method: the processed contour (line 1) almost coincides with the theoretical contour (line 2). The maximum error measured by the normal is 0.09 mm. The actual trajectory of the cutter center (line 3), controlled by the adjusted program, also almost coincides with the theoretical equidistant (line 4). In this way, the accuracy of machining by the error from elastic deflections is increased by more than 3 times.

6. Discussion of the proposed method of ensuring accuracy of contour milling

A new method of designing a corrected trajectory during contour milling has been developed, which eliminates errors from elastic deflections of the machining system. The greatest effect from the application of the work results is expected in the machining of contour surfaces, where the cutting process is characterized by significant non-stationary, which provokes the occurrence of errors from elastic deflections of the machining system, which cannot be compensated for by simple adjustment “to size”.

The method is based on combined control, which involves the use of a posteriori and a priori information at the same time. Since elastic deflections occur in a closed elastic machining system and depend on both the cutting force and the stiffness, it is necessary to have an adequate mathematical model for their compensation due to trajectory correction. The model should provide a priori information about the cutting process, which consists in determining the main characteristic of the cutting process – an analogue of the allowance removal rate – volume of Material Removal Rate.

This characteristic is calculated by a numerical method based on the value of the cutting arc (4), which is determined by a special procedure for the cutter workpiece engagement at each step of the simulation. The procedure requires the presentation of the contour of the workpiece and the trajectory of the forming in the form of two-dimensional digital arrays, which are formed in the developed simulation program according to the G-codes of the control program.

Determination of a posteriori information about the process takes place on the basis of two or one measurement, as shown in Fig. 3, which significantly reduces time, but provides the necessary information about the corrective transfer function of the structure in accordance with the control scheme based on a posteriori information (8) (9). The simulation program performs all the necessary calculations for designing the corrected trajectory and provides the possibility of synchronous presentation of results in the windows of virtual oscilloscopes and graphical representation of the projected trajectories (Fig. 8 and Fig. 9)

The practical application of the method in the machining of responsible parts in single production is somewhat different from the machining of a batch of parts. In the first case, the allowance on the last pass is divided in half and after machining the first half, appropriate verifications are performed, then simulation with automatic design of a new control program on the last pass and finish milling are carried out. When processing a batch of parts, such verifications are performed on the first machined part, and the corrected program, which was designed according to the developed method, is applied to subsequent ones.

For the approbation of the developed method, the second program for simulating the contour milling process according to the corrected trajectory, which was projected in the first program, was used. The results confirmed the reduction of the error from the elastic shifts of the machining system with all the same initial data by more than 3 times. Of course, the most adequate result of the effectiveness of the developed method can be obtained only experimentally, which is planned to be performed during milling of the contour of the part. However, the currently obtained results allow us to hope for achieving the planned effect, since all the numerical procedures of the created computer programs correctly reflect the real process of contour milling.

7. Conclusions

1. A new method of ensuring accuracy of contour milling on a CNC machine tool has been developed, which consists in the application of combined control using a posteriori information of on machine verifications of the machined surface and a priori information of simulation the material removal process. In case of single production, the allowance on the last pass is divided into two parts, and after machining the first part, verifications are performed, then simulating and machining of the second half according to the adjusted control program. In mass production, verifications are performed on the first part, and all subsequent ones are machined according to the adjusted control program.

2. The proposed technology for measuring the machined contour on a machine tool with a CNC three-coordinate probe according to standard control programs. Moreover, to obtain the a posteriori information necessary for the method, it is enough to perform two measurements or one, if there are contour surfaces inclined to the coordinate axes.

3. A mathematical model of the contour milling process was developed, which reproduces the structural diagram of the machining system, which is closed by elastic deflections along two coordinates. The mathematical model is the core of the created computer program, which provides for the loading of the primary control file in G-codes and measurement data, and as a result of the process simulation, a new control file for the CNC machine tool is formed, which eliminates the error from elastic deflections. Preliminary tests showed the possibility of increasing the accuracy of machining by more than 3 times.

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Забезпечення точності фрезерування контурів на верстатах з ЧПК

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Анотація. *Процеси контурного фрезерування характеризуються квазістаціонарністю, що приводить до виникнення похибки оброблення яка викликана пружними зсувами обробної системи. Причому таку похибку не можна усунути підналагодженням управляючої програми "на розмір", оскільки вона змінюється за контуром в широкому діапазоні. Для забезпечення точності контурного фрезерування запропонований новий спосіб комбінованого управління, що використовує апостеріорну інформацію вимірювань обробленої поверхні і апріорну інформацію моделювання процесу видалення матеріалу. При одиничному виробництві припуск на останньому проході ділиться на дві частини і після оброблення першої виконуються вимірювання потім моделювання і оброблення другої половини за скоригованою управляючою програмою. При серійному виробництві вимірювання виконуються на першій деталі, а всі подальші обробляються за скоригованою управляючою програмою. Для отримання необхідної апостеріорної запропонована технологія вимірювань на верстаті з ЧПК трикоординатним щупом за стандартними управляючими програмами, причому достатньо виконати два вимірювання або одне, при наявності похилих до осей координат поверхонь контуру. Створена комп'ютерна програма, ядром якої є математична модель процесу, що відтворює структурну схему замкненої за двома пружними зсувами обробної системи. Передбачене завантаження первинного управляючого файлу в G-кодах і даних вимірювань, а в результаті моделювання процесу формується новий управляючий файл для верстату з ЧПК, що усуває похибку від пружних зсувів. Попередні випробування показали можливість підвищення точності оброблення більш ніж в 3 рази.*

Ключові слова: *контурне фрезерування, корекція управляючої програми, моделювання процесу фрезерування.*