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Increasing the Accuracy of Machining by Means of Complex Process Management Through Active and Adaptive Control

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***Abstract*— One of the main indicators of the manufactured parts quality and the efficiency of the technological processes in mechanical engineering is machining accuracy. During the machining process, errors of various nature occur, which can lead to deviations from the specified dimensions and geometric parameters. This requires the implementation of modern approaches to controlling and managing the machining process.**

***Keywords*— *Active control, adaptive control, CNC machine tools, intelligent computer control mechanical engineering*.**

I. INTRODUCTION

The development of scientific knowledge about the machining process, computer technology and machine tools has created prerequisites for finding new approaches to managing the machining process. The integration of the accumulated knowledge about the process, presented in the form of a database, the use of adaptive control during machining and the application of active control after completing it in order to populate the database, provide a possibility to implement intelligent computer control.

The work of the various subsystems in machining is aimed at achieving effective management of the technological process to achieve higher accuracy of the machined parts.

The process is managed based on the input information about the size of the workpieces and the dimensions of the parts after their machining. [1] - [2].

II. MATERIALS AND METHODS

The growing use of CNC machine tools in serial production imposes the search for new opportunities to increase machining accuracy and productivity. Such an opportunity is offered by complex computer-controlled process management, integrating adaptive and active control without complicating the machine's sensory system. The block diagram of such a system is presented in Fig. 1 [3] - [4].

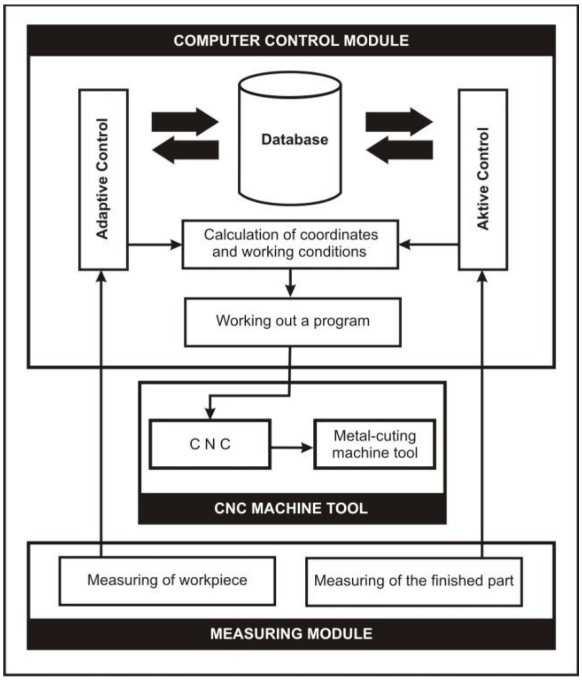

Fig. 1. Block diagram of an intelligent computer control system based on adaptive and active control.

The system comprises the following modules:

- Control module, through which the dimensions of the workpieces before machining and the dimensions of the machined parts are controlled. The results, concerning the workpieces, are fed into

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an adaptive control system (block), and those, related to the finished parts go into an active control system (block);

- Process implementation module, containing the machine tool and the CNC system;
- Module for computer control, which generates the management program and performs the machining of the parts in communication with the machine's CNC system. This module combines algorithms for controlling the accuracy of the results from the machined parts control (active post-processing control APPC) with algorithms for adaptive accuracy control (AAC), performed on the basis of the results from the inspection of the workpieces;

The computer control module is the core of the system. It is a computer system, containing the database, the specialized software for adaptive and active control, for generating management programs and communication with the machine's CNC system.

A. APPC algorithm with real-time processing of statistical information about the process

The characteristics of the technological process are known when using the classical APPC algorithm. It is applied in large-scale and mass production, where there is sufficient statistical information, concerning both the instantaneous dispersion field and the trend in the average value of dimensions, caused by systematic factors. The control limits for the process can be determined in advance in this case, as well as the magnitude of the dimensional adjustment pulse, depending on whether the control method is based on samples or on single parts.

A different algorithm can be applied nowadays thanks to modern computer technologies. The algorithms must be adequate to modern requirements for production flexibility and high degree of automation with frequent product changes and relatively small batch sizes [5] - [6]. Under these conditions, the statistical characteristics of the process and the decisions for the timing and magnitude of dimensional adjustment must be determined dynamically (in real time) during the technological process. Research in this direction shows [7] that if the results of the dimensional control of each of the sequentially machined parts are used to sequentially generate regression equations for the average value of the dimension, this can be used to determine with sufficient accuracy the moment of dimensional sub-adjustment and the magnitude of the sub-adjustment pulse. Graphical representation of the idea can be seen in Fig. 2.

The change in the average dimensional value can be determined after having each part machined from the regression equation, derived based on all machined parts to the moment:

$$\Delta\bar{A} = \bar{A}_n - \bar{A}_0 = \tilde{b}n \qquad (1)$$

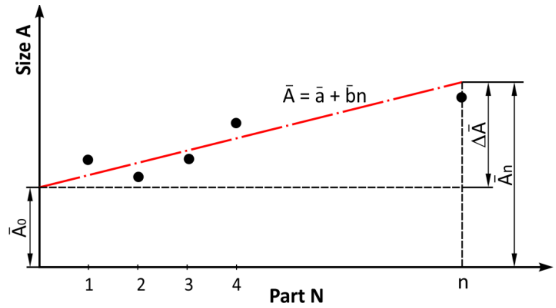

Fig. 2. Linear regression equation of the average dimensional value.

If the determined change in the average value is statistically significant, then dimensional sub-adjustment should be performed with the same magnitude of the adjustment pulse.

Due to the small volume of statistical data, a significant fluctuation of the regression equation slope (precession) is observed at the beginning of the process. As the number of processed parts increases, the precession decays exponentially [8].

The decision for dimensional sub-adjustment is made if the following conditions are simultaneously met:

- sufficient precession damping;
- adequate regression equation;
- statistical significance of the increase in the average dimensional value $\Delta\bar{A}$.

The smallest value of the total dispersion field with this algorithm is:

$$\omega_{\Sigma\min} = \omega\sqrt{1+\frac{1}{n}+\frac{t_{\alpha,K}{}^2}{6n}}, \qquad (2)$$

where $t_{\alpha,K}$ is a critical value of the Student's t-test at a significance level α and degrees of freedom $K = 2(n - 1)$.

Formula (2) is presented graphically in Fig. 3. It shows that the total dipersion field with this algorithm approaches in magnitude to the instantaneous one, when the number of machined parts increases. In practice, $\omega_{\Sigma\min}$ is greaterp since formula (2) does not take into account the sub-adjustment error.

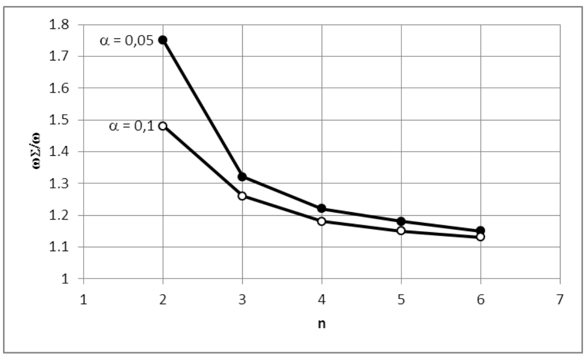

Fig.3. Dependence of the total dispersion field on the instantaneous one and the number of machined parts.

B. Possibility to reduce the instantaneous dispersion field through adaptive control

Dimensional dispersion, caused by random factors, can be reduced by incorporating force deformation control devices into the technological system [9]. These devices can be used to adjust the operating modes and/or dimensional adjustment. However, their disadvantage is that they are not universal, which means that the method is only suitable for large-scale production.

At present there are various options to obtain data about errors, resulting from force deformations. As a result of the development of CNC machine tools and computer and information technologies, adaptive control can be implemented based on mathematical models of the technological system deformation behavior [10] – [12].

The force deformation at a certain point M of the workspace can be represented as a function of the forces, acting in the system, and the coordinates of the point. Since the application of forces to a given point is represented by the dynamo of the resultant force and the torque, the mathematical model of the force deformations will have the form:

$$y = \varphi\left[\vec{F}_{tot}, \vec{M}_{tot}, M(x_M, y_M, z_M)\right]. \quad (3)$$

The model (3) provides a possibility to implement adaptive control in order to stabilize and/or compensate for force deformation errors through direct computer control, using the machine's working elements and the CNC system [13] – [15].

III. Results and discusion

The developed algorithms for adaptive control in rough machining and APPC in fine machining make it possible to implement a computer system for complex accuracy control. The system contains the described three modules, together with the software for their functioning and data exchange between them, so that the modules work as a single unit.

Adaptive control, as a separate algorithm, is performed in accordance with the obtained results from the workpiece control. Active control, as a separate algorithm, is carried out in accordance with the results from controlling already machined parts.

The system has been tested when boring cylindrical sleeves made of steel 35 with a cantilever boring bar on a CNC lathe LT580.

A suitable solution for rough machining is adaptive accuracy control. As a result of the increase in dimensional accuracy, the dispersion of the cutting depth for clean machining reduces, and so does the dispersion of the force deformations. The influence of technological heredity on the accuracy of clean machining decreases in this case.

It is accepted to carry out adaptive accuracy control without the use of special devices for controlling force deformations in real time. Experimentally obtained for specific operating conditions mathematical models of the force deformations in the technological system are used in this case. The regression equations are of the following type:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 . \quad (4)$$

The cutting depth a, the feed f and the coordinate z of the cutting area are considered as variable factors, determining the magnitude of the force deformation Y. Two-factor and three-factor models are used.

The two-factor model is typical for cases where the magnitude of the force deformation does not significantly depend on the z coordinate of the cutting area, for example, when boring cylindrical sleeves with a cantilever boring bar. In this case, the deformation can be considered as a function only of the depth of cut and the feed, while the other conditions under which the operation occurs, are assumed to be constant. In the three-factor model, in addition to the cutting depth and feed, the z coordinate of the cutting area also has a significant influence on the deformation, for example, when scraping long cylindrical surfaces, mounted cantilevered or between centers.

In the two-factor model, the regression equation for the force deformation has the form:

$$y = b_0 + b_1 a + b_2 f + b_3 af + b_4 a^2 + b_5 f^2 , \quad (5)$$

From equation (5) the feed f_i is determined, given the magnitude of the deformation y and the cutting depth, determined by the size of the workpiece. The workpiece will be machined with this feed. Then, using standard control commands, a program sentence is compiled, and passed by the CNC system to the machine tool for execution.

The three-factor model is assumed to be implemented by sequentially applying the two-factor model in sections of the machined surface with a length L_k, within which the influence of the coordinate z is insignificant (the increase in y does not exceed a predetermined value). Under these assumptions, the length of the surface under machining is divided into k number of sections of equal length L_k. Each of them is characterized by a position coordinate in axial direction z_k and a regression equation of the type (5), obtained from the three-factor model at $z = z_k$. For each of the sections, the feed f_k is determined and a corresponding group of sentences for the CNC system is written. This procedure is repeated for all sections of the surface. Finally, the program sentences for machining the entire surface are compiled from these groups and submitted to the CNC system for execution.

A computer system for complex accuracy management has been built based on the created algorithms for adaptive accuracy control in rough machining and for APPC in clean machining. The CNC system is controlled directly by the computer system on which the adaptive accuracy control software and APPC software are installed.

For experimentation of the model and the adaptive control algorithm, it is accepted that the research should be carried out under conditions where the technological system has a relatively high sensitivity to force loads and is characterized by significant dispersion of force deformations. The capabilities of the adaptive control can be more fully demonstrated in this case. The specified conditions are met when boring cylindrical holes with a cantilever-mounted tool. The force deformations of the technological system are mainly determined by the sagging of the tool.

The scheme of the experiment for determining the function (5) is presented in Fig. 4.

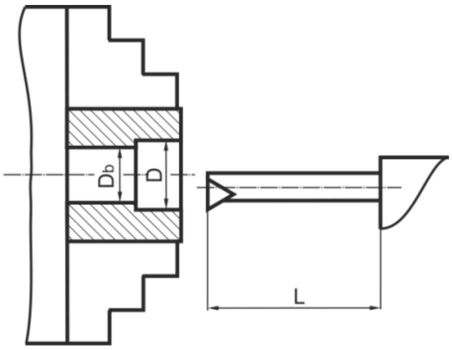

Fig.4. Experimental scheme (Db – diameter of the workpiece; D – diameter of the machine part).

The length of the boring tool L is a constant for the duration of the machining and is not included as a factor in the model. For a tool with a different length, a different model will be present in the database.

The cutting depth is ensured according to the experimental design plan by using step workpieces. The difference between the step radii for a given workpiece is the required depth of cut. The first step is equal in diameter to the dimension of static adjustment. Both steps are machined with the same feed rate, consistent with the experimental design. The difference between the radii of the two steps after completing the process of boring is taken as the magnitude of force deformation of the system.

The software product EXPLAN V 1.0 is used to process the data. It performs a model adequacy check, defines the regression equation in normalized and natural coordinates, and plots a diagram of the response.

The conditions for conducting the experiment are: machine - CNC lathe LT580; machined material - steel BDS EN 10083-2 C35, hot-rolled pipe ∅40/7; diameter of the machined hole D = 28,5 mm; diameter of the cutting tool – 20 mm; length of the cantilever part of the tool L = 100 mm; hard-alloy plate made of P15, type TPUN 110302; main tool setting angle $\chi_r = 90°$; cutting speed V_c = 85 m/min; measuring instrument – digital caliper 150/0,01.

The matrix of the experiment and the obtained deformation results are presented in Table 1.

TABLE 1 MATRIX OF THE EXPERIMENT AND DEFORMATION RESULTS

№	Experimental design plan				Result
	*X*1	*X*2	*a*, [mm]	*f*, [mm/об]	*y*[µm]
1	-1	-1	0,25	0,10	35
2	+1	-1	0,75	0,10	65
3	-1	+1	0,25	0,50	90
4	+1	+1	0,75	0,50	305
5	-1,414	0	0,15	0,30	40
6	+1,414	0	0,85	0,30	190
7	0	-1,414	0,50	0,02	25
8	0	+1,414	0,50	0,58	200
9	0	0	0,50	0,30	125
10	0	0	0,50	0,30	135
11	0	0	0,50	0,30	135
12	0	0	0,50	0,30	140
13	0	0	0,50	0,30	140

The regression equation in natural coordinates is:

$$y(a, f) = 8 + 71{,}4a + 8{,}1f + 925af - 120{,}4a^2 - 219{,}3f^2. \quad (6)$$

Fig. 5 shows the graphical interpretation of the obtained model.

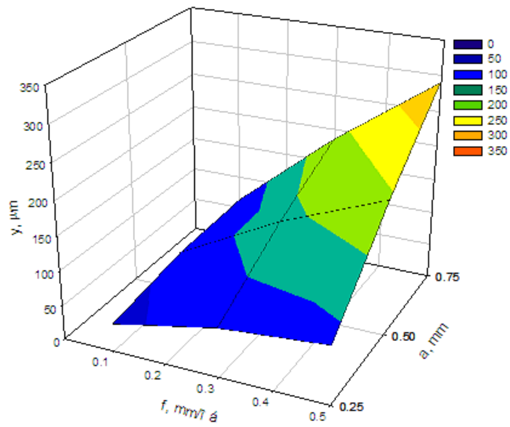

Fig.5. Graphical interpretation of the force-deformation model.

Rough boring is performed under similar conditions to those, under which the force deformation model has been taken. A batch of 50 workpieces is bored, varying the cutting depths from 0,25 to 0,75 mm. For each workpiece, the feed is determined by the computer system in accordance with the algorithm, discussed in [9].

The effect of applying the adaptive accuracy control can be visually assessed from the scatter diagram in Fig.6.

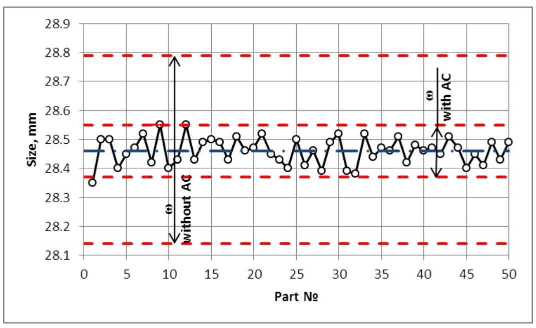

Fig.6. Scatter diagram of rough boring with adaptive accuracy control.

The dispersion of dimensions without applying adaptive accuracy control can be determined from the mathematical model of force deformations (6):

$$\omega_{\Sigma y} = \Delta y + \omega_y \,, \qquad (8)$$

where Δy is the increase in the deformation when varying the variable factors within the model limits from their minimum to their maximum level; ω_y - dispersion field around the regression equation.

In this particular case: $\omega_{\Sigma y}$ = 250 + 62 = 312 μm

The dispersion of the diametric dimensions $\omega_{\Sigma D}$ will be: $\omega_{\Sigma D} = 2\omega_{\Sigma y}$ = 624 μm.

The dispersion of the dimensions with applying adaptive accuracy control can be determined from the obtained results:

$\omega = 2k_{50;\,0,9;\,0,9}$; S = 2 . 1,916 . 0,047 = 0,18 mm.

The result from the experimental study shows that the dimensional dispersion reduces 3,5 times as a result of implementing adaptive control. The achieved specification is:

$K_{y1} = \omega_r / \omega_{p1}$ = 1 / 0,624 = 1,6;
$K_{y2} = \omega_r / \omega_{p2}$ = 1 / 0,18 = 5,

where ω_r is the dispersion field of the workpiece dimensions for rough boring; $\omega_{p1} = \omega_{\Sigma D}$ - dispersion of the dimensions of the parts after rough boring without adaptive accuracy control; $\omega_{p2} = \omega$ - dispersion of the dimensions of the parts after rough boring with adaptive accuracy control.

A boring bar cantilevered in the turret of a CNC lathe is used to perform clean boring under the following conditions: machine - CNC lathe LT580; machined material - steel BDS EN 10083-2 C35, hot-rolled pipe ∅40/7; diameter of the machined hole D = 29,0 mm; size tolerance T = 50 μm; diameter of the cutting tool – 20 mm; length of the cantilever part of the tool L = 100 mm; hard-alloy plate made of P15, type TPUN 110302; main tool setting angle $\chi_r = 90°$; cutting speed V_c = 120 m/min; feed f = 0,05 mm/rev; average cutting depth a_p = 0,3 mm; measuring instrument – internal gauge with a measuring clock with a division value of 0,001 mm.

The effect of implementing APPC can be visually assessed from the scatter diagram in Fig. 7.

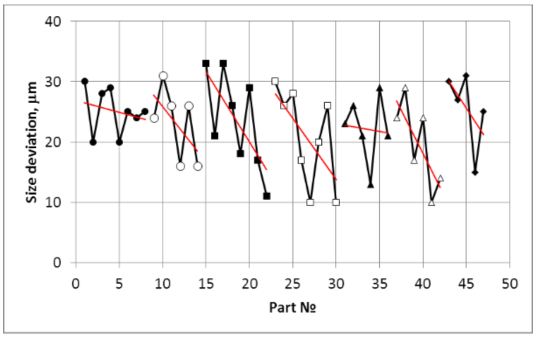

Fig.7. Scatter diagram of clean boring with APPC.

In accordance with the input data, with a given tolerance of the machined surface T = 50 μm and instantaneous dispersion field ω = 24 μm, the computer system selects an operating algorithm with a limited accuracy resource. From the experimental data it can be seen that the entire batch of 50 parts is machined with seven sub-adjustment pulses, with eight groups of parts distinguished.

The first group contains 3 parts and serves to check the dimensional adjustment. For this purpose, the system compares the average dimensional value for the group with the working size of the adjustment and determines a sub-adjustment pulse with a magnitude of ΔA_1 = 73,3 μm. The desired dimensional adjustment for getting the work started is achieved when the CNC system implements the sub-adjustment pulse.

The next groups of parts are machined with a sequential check of the criteria for adequacy of the regression equation, precession damping, and significance of the difference between the average dimension from the regression equation and the working dimension of the adjustment. When all three criteria are satisfied simultaneously, the magnitude of the sub-adjustment pulse is determined and the pulse is fed into the CNC system for execution. The algorithm is demonstrated as a result in Fig.7, with the exception of the first group of parts.

The software provides information about the variance around the regression equation for each group of parts. The Fisher test shows that the dispersions of the seven groups are homogeneous, which gives reason to work with the averaged dispersion to determine the instantaneous dispersion field after clean boring:

$\omega_{cb} = 2k_{47;0,9;0,9}$;

S = 2 . 1,927 . 0,00674 = 0,026 mm.

The total dispersion field within the experiment can be determined by the range of the experimental data:

$\omega_\Sigma = R = D_{\max} - D_{\min}$ = 29,033 – 29,01 = 0,23 mm.

The estimated value $\omega_{\Sigma ev1}$ of the total field for this computer system and this process can be determined from the sum:

$$\omega_{\Sigma ev1} = \sqrt{\omega_{cb}^2 + 3.\Delta A_{aver}^2 + \omega_{pe}^2}\,;$$

$$\omega_{\Sigma ev1} = \sqrt{0,026^2 + 3.0,0103^2 + 0,0097^2} = 0,032 \text{ mm.}$$

In the expression ΔA_{aver} = 0,0103 mm is the average magnitude of the sub-adjustment pulse for the six sub-adjustments in Fig. 7; ω_{pe} = 0,0097 mm is the positioning error for the specific machine, in case of unidirectional dimensional sub-adjustment.

The achieved specification is:

$K_y = \omega_{p2} / \omega_{cb}$ = 0,18 / 0,026 = 6,92,

where ω_{p2} = 0,18 mm is the field of dispersion of dimensions after rough machining with adaptive accuracy control; ω_{cb} = 0,026 mm - instantaneous field of dispersion during clean boring with APPC.

The effect of combining APPC with adaptive accuracy control can be estimated by determining the expected instantaneous dispersion field ω_{cb2} under the assumption that rough boring is performed without adaptive accuracy control and the technological system has the same specification:

$$\omega_{cb2} = \omega_{p1} / K_y = 0,624 / 6,92 = 0,09 \text{ mm.}$$

In this case, the estimated value of the total dispersion field will be:

$$\omega_{\Sigma ev2} = \sqrt{\omega_{cb2}^2 + 3.\Delta A_{aver}^2 + \omega_{pe}^2}\ ;$$

$$\omega_{\Sigma ev2} = \sqrt{0,09^2 + 3.0,0103^2 + 0,0097^2} = 0,092 \text{ mm.}$$

In other words, as a result of applying adaptive control, the reduction in the dimensional error will be:

$$\omega_{\Sigma ev2} / \omega_{\Sigma ev1} = 1,88 \text{ times.}$$

The effect of APPC as an increase in machining accuracy can be assessed by determining the total dispersion field $\omega_{\Sigma ev3}$ under the assumption that no dimensional sub-adjustment has been performed, i.e.:

$$\omega_{\Sigma ev3} = \omega_{cb} + \sum_{i=1}^{6} \Delta A_i = 0,026 + 0,062 = 0,088 \text{ mm.}$$

Consequently, the reduction in dimensional dispersion with APPC will be:

$$\omega_{\Sigma ev3} / \omega_{\Sigma ev1} = 2,75 \text{ times.}$$

IV. Conclusions

Using a designed experiment, regression equations have been obtained and used to model the force deformations, resulting from boring cylindrical holes with a cantilever tool on a CNC lathe LT580.

The algorithms and the programs for implementing APPC with adaptive accuracy control have been experimentally verified when boring cylindrical sleeves with a cantilever tool at a low accuracy resource. The conducted studies prove the working capacity of the proposed algorithm and software.

With the help of adaptive accuracy control, the dispersion of the allowance for clean boring has been reduced 3,5 times. As a result, the instantaneous dispersion field for clean boring also decreases 3,5 times and the total dispersion field for APPC goes down 1,88 times.

Reduction in the dimensional dispersion of 2,75 times has been achieved by applying APPC together with adaptive accuracy control in this particular case.

Acknowledgments

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