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Possibilities for Increasing the Accuracy of Active Control in Turning on CNC Machine Tools Through Adaptive Accuracy Control

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***Abstract*— In clean and fine turning on CNC machine tools, it is advisable to carry out active control by measuring the parts after their processing. With this type of active control, accuracy is highly dependent on dimensional dispersion caused by random factors. A solution for reducing these errors and increasing the accuracy of active control is the use of adaptive control of roughing accuracy.**

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

I. Introduction

Studies on the accuracy capabilities of Active Post-Processing Control (APPC) [1]-[3] show that the instantaneous dimensional dispersion field, which is caused by random factors, occurring during the machining process, has a significant impact on the total field of dimensional dispersion of the machined parts.

In classical APPC algorithms, after assuming that the magnitude of the sub-adjustment pulse ΔA cannot be smaller than the instantaneous dispersion field ω, the dependencies are obtained fo r the smallest possible total dispersion field $\omega_{\Sigma\min}$ [4]:

- for APPC, applied according to the individual values of the processed parts:

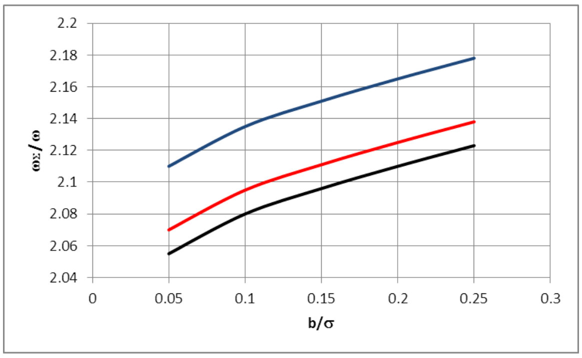
$$\omega_{\Sigma\min} = \omega\sqrt{4+\left(\frac{\Delta_p}{\omega}\right)^2+\left(\frac{b}{\sigma}\right)^{0,5}}, \qquad (1)$$

- for APPC, based on the group average values of the dimensions of the machined parts:

$$\omega_{\Sigma\min} = \omega\sqrt{4+\left(\frac{\Delta_p}{\omega}\right)^2+\left(\frac{b}{\sigma}\right)^{0,5} n^{2\frac{b}{\sigma}-0,5}}, \qquad (2)$$

where Δ_p is the positioning error of the sub-adjustment system; σ - mean square deviation, characterizing the instantaneous field of dispersion; b - trend of the average dimensional value; n - number of parts in the current sample (sample volume).

Fig. 1 presents the graphical interpretation of formulas (1) and (2), and shows that $\omega_{\Sigma\min}$ is greater than 2ω for both methods. This proves the significant influence of the random factors on the accuracy of APPC.



(a) APPC according to individual values

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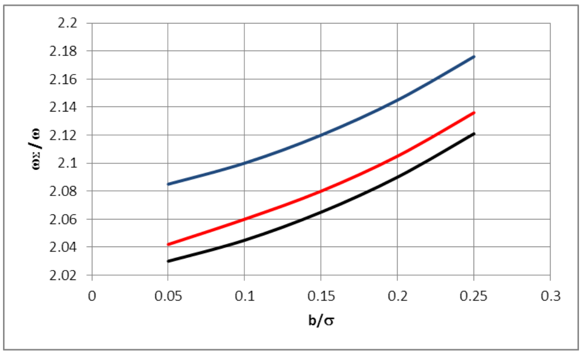

(b) APPC according to group average values, at n = 5

Fig. 1. Graphical dependences for the smallest possible total dispersion field $\omega_{\Sigma\min}$

II. Materials and Methods

The possibilities for increasing the accuracy of the APPC need to be analyzed and the search should go in two directions:

- finding an algorithm, in which the magnitude of the sub-adjustment pulse is possible to be smaller than the instantaneous field of dimensional dispersion;
- reduction of the instantaneous field of dimensional dispersion.

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

The classical APPC algorithm is based on known characteristics of the technological process. It is applied in large-scale and mass production, where the process has been sufficiently studied and both the instantaneous dispersion field and the trend of the average dimension value are known. Control limits are set in this case, and the size of each processed part, or the average size of a periodically taken current sample, is monitored. The magnitude of the pulse for dimensional sub-adjustment is also determined in advance. When the part size (average dimension value) is outside the control limits, a signal for dimensional sub-adjustment is given.

Modern computer technologies make it possible to apply a different algorithm than the described above. It must meet the present-day requirements for production flexibility with frequent changes in the product range and a high degree of process automation with small batch volumes [5], [6]. Under these conditions, the statistical characteristics of the technological process must be established dynamically during its course, and therefore the decisions for dimensional sub-adjustment and the magnitude of the sub-adjustment pulse must be made in real time.

Research in this direction has shown [7] that if the regression equation for the average value is determined after machining each part, by the results from the dimension control over the processed parts, then it is possible to determine with sufficient accuracy both the moment for dimensional sub-adjustment and the magnitude of the sub-adjustment pulse. The idea is presented graphically in Fig. 2.

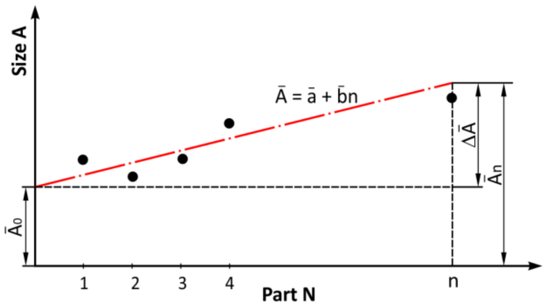

Fig.2. Linear regression of the sizes

After each processed part, from the regression equation for all parts processed so far, the change in the average dimension value from the beginning of work to the present can be determined:

$$\Delta\bar{A} = \bar{A}_n - \bar{A}_0 = \bar{b}n\,. \tag{3}$$

If the resulting difference $\Delta\bar{A}$ is statistically significant, there is reason to perform a dimensional sub-adjustment with a pulse, equal to $\Delta\bar{A}$.

Due to the small volume of statistical data at the beginning of the process, the regression equation has a wide confidence interval, and a significant fluctuation in its slope is observed. This can be considered as a "precession" of the regression equation. With increasing the number of processed parts, the precession decays and this process can be described by an equation of an exponentially decaying cosine function [8].

The decision to make a dimensional sub-adjustment is made when the following three conditions are simultaneously met:

- adequate regression equation;
- sufficiently damped precession;
- statistical significance of the difference $\Delta\bar{A}$.

With this algorithm, for the smallest value of the total dispersion field it is obtained:

$$\omega_{\Sigma\min} = \omega\sqrt{1+\frac{1}{n}+\frac{t_{\alpha,k}{}^{2}}{6n}}\,, \tag{4}$$

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

Dependence (4) is presented graphically in Fig. 3. It can be seen that, together with the increase in the number of the processed parts, the total dispersion field with this algorithm approaches the instantaneous one. In practice, the value of $\omega_{\Sigma\min}$ is higher, because formula (4) does not take into account the error with which the sub-adjustment is performed.

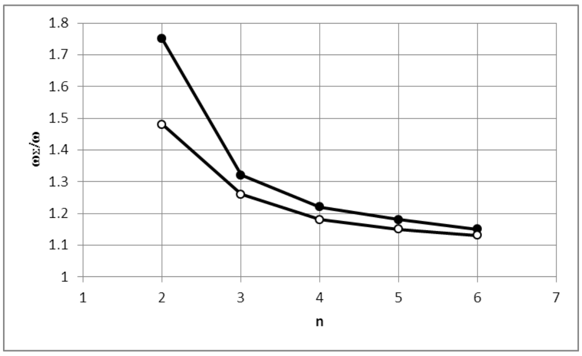

Fig.3. Dependence of the total dispersion field on the instantaneous one at APPC, applied according to the regression equation

The results obtained from the analysis of the accuracy of APPC prove that the main direction for increasing accuracy is to reduce the instantaneous dispersion field.

B. Opportunities for reducing the instantaneous dispersion field with adaptive control

It is known that the force deformations of the technological system are the main factor, which determines dimensional dispersion in machining. Therefore, options to increase the accuracy of the APPC should be sought through the methods for reducing the influence of the force deformations, using adaptive accuracy control (AAC). In this case, accuracy and productivity increase simultaneously [9] – [14].

The idea of reducing the dimensional dispersion caused by random factors through adaptive control was proposed and developed as early as the 1960s and 1970s [15]. In all implementations of this idea, the technological system includes a special device for real-time control of force deformations and an automatic adjustment device. Since these devices are not universal, the application of the method is economically justified in large-scale production.

Other options for obtaining data about force deformations are being sought under the modern conditions. As a result of the development and achievements of the CNC machine tools, of computer equipment and technologies, as well as of information technologies, it has become possible to implement control over the dimensional process and, more specifically, on the deformation behavior of the technological system, based on mathematical models [16].

In general, force deformation at a certain point M of the workspace can be represented as a function of the forces, acting in the technological system, and the coordinates of this point [11]. When brought to point M, the action of the system of forces is represented by the dynamo of the system – a vector of the resultant force $\vec{F}_{tot}$ and the torque $\vec{M}_{tot}$. Thence, the mathematical model for the force deformations at a certain point in the machine's workspace has the form:

$$y = \varphi\left[\vec{F}_{tot}, \vec{M}_{tot}, M(x_M, y_M, z_M)\right]. \qquad (5)$$

Under specific operating conditions, if the influence of only the cutting depth a and the feed f on the magnitude of the force deformation is studied, the mathematical model will have the form:

$$y = b_0 + b_1 a + b_2 f + b_{12} af + b_{11} a^2 + b_{22} f^2 . \qquad (6)$$

If the coordinate of the cutting area has a significant influence on the magnitude of the force deformation, it is included in the model as a third variable.

The model (6) provides the possibility to implement adaptive control for stabilizing or for compensating the force deformation, using both the working parts of the CNC machine tool and direct computer control [16]-[20].

- *Adaptive control for stabilizing the force deformations*

In the two-factor model of the force-deformation errors, the influence of the cutting depth a and the feed f is represented by the polynomial (6) [16], [18].

Fig. 4 presents the graphical interpretation of this polynomial. A two-dimensional diagram is used, representing the cutting depth a by a family of curves, which reflect its different values in the range from $a_{\min}$ to $a_{\max}$.

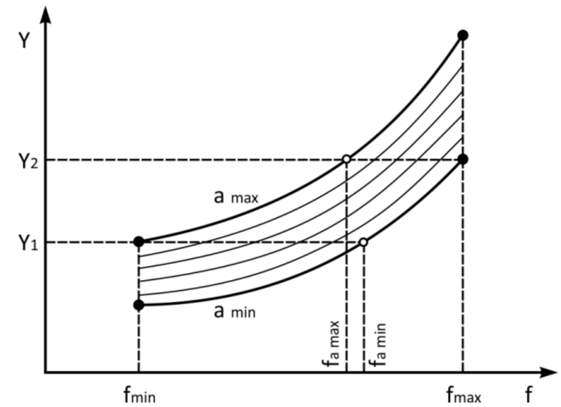

Fig. 4. Graphical interpretation of the force-deformation error model and the characteristic levels of stabilization

The solution to the problem of stabilizing the force deformations at a given level Y = const at a measured cutting depth a_i by finding the feed rate with which to perform the machining, is the cross-section of the regression surface with a plane Y = const.

Equation (6), expressed to the feed f, has the following form:

$$b_{22}f^2 + \left(b_2 + b_{12}a\right)f + \left(b_0 + b_1a + b_{11}a^2 - Y\right) = 0\,. \quad (7)$$

The root of this quadratic equation, satisfying the condition $f_{\min} \leq f_i \leq f_{\max}$, is a solution for the chosen value of Y at a cutting depth a_i.

The described method stabilizes the errors, resulting from force deformations, by selecting a feed rate f depending on the specific depth of cutting.

The choice of a level of stabilization is determined by the machining efficiency indicators – productivity, cost, dimensional accuracy, micro-geometric shape accuracy, etc. It is, therefore, necessary to evaluate the different stabilization levels from the perspective these indicators.

The levels can be compared by the accuracy of the obtained dimensions, based on known data about the dimensional dispersion, resulting from the force deformations. The existence of a correlation between the magnitude of the deformations and the dispersion field of the dimensions ω is well known. Then, as Y increases, ω also increases. For the force-deformation error model, used to implement the control, this increase will be within the dispersion around the regression surface.

An analysis of the process efficiency indicators shows their inconsistency. Thence, when implementing adaptive control by using the algorithm for stabilizing the errors from force deformations, an opportunity should be created to choose the level from the perspective of prioritizing one or another of them.

Based on the model for stabilizing the force deformations, an algorithm for programmatic adaptive control has been developed.

Initially, input data about the machined part, the workpiece, and the mathematical model are introduced. The way of determining the stabilization level depends on the performance and surface quality conditions. High productivity and high surface quality variants are possible, as well as variants in the possible solutions area between $Y1$ and $Y2$.

The limit levels до deformation $Y1$ and $Y2$ are calculated.

The value of the deformation Y_c, at which stabilization will take place, is determined.

The algorithm is completed after calculating the feed for performing the machining.

- *Adaptive control for compensating the force deformations*

The method is described and illustrated by the two-factor model (6) and its graphical interpretation in Fig. 4 [16], [19].

Adaptive control, aiming at compensating for the force deformations, is reduced to determining the value of the deformation Y_i at a cutting depth a_i in the range $a_{\min}$ - $a_{\max}$ at a feed f = const, selected in the range $f_{\min}$ - $f_{\max}$. Under these conditions, the solution to equation (6) for Y_i gives us the required compensation value.

The determined value of the force deformation error Y_i is used as a correction of the set-up dimension, which defines the tool path for the specific machining operation.

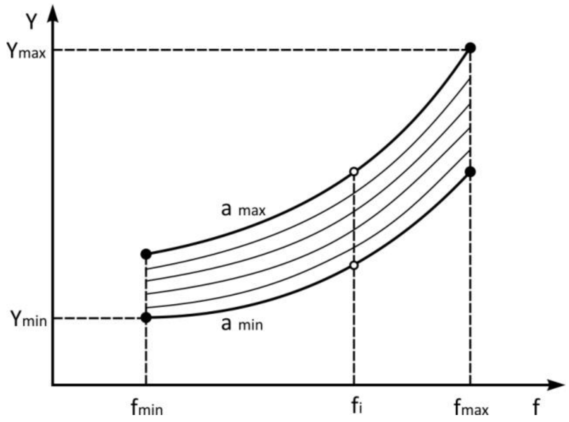

Fig. 5. Graphical interpretation of the model of errors, resulting from of force deformations in case of applying adaptive control for their compensation

The compensation level is determined for each machined surface and depends on the cutting depth a and the selected feed. It can be seen from the diagram in Fig. 5 that at higher feed values the compensation level value will be higher.

The choice of the feed f is determined by the machining efficiency indicators: productivity, cost, dimensional accuracy, micro-geometric shape accuracy, etc.

There are certain limitations to applying the method. When the deformations change within a machined section due to a variable value of the cutting depth or the influence of the coordinates of the cutting area, then dimensional sub-adjustment is required within the boundaries of a machined surface. This will generate a step-shape appearance on the treated surface. Therefore, the method is suitable for cases, in which within the boundaries of the workpiece surface under machining the allowance and system stability are relatively constant.

An algorithm for applying programmatic adaptive control has been developed based on the model, which aims at compensating for the force deformations [19].

Input data about the machined part, the workpiece, and the mathematical model are entered first. The feed rate f is selected depending on the process requirements. The error due to force deformations Y is calculated. The algorithm completes with calculating a correction to the set dimension.

- *Complex adaptive control, aiming at stabilizing and compensating for the force deformations*

The method for complex adaptive accuracy control combines the two methods for force deformations stabilization and compensation for their joint operation.

The combination of the two algorithms is imperative in cases, in which the task of stabilizing the force deformations does not have a solution for the entire range of the cutting depth dispersion. Such a case is presented in Fig. 6 [16], [20].

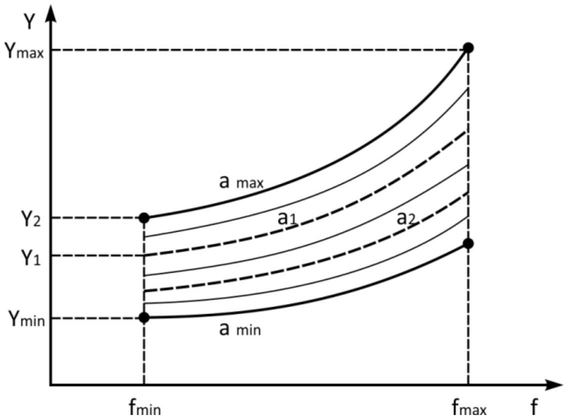

Fig. 6. Graphical interpretation of the force-deformation error model in complex adaptive control

In the general case, presented in Fig. 6, it is not possible to achieve complete stabilization of the force deformations for all values of the cutting depth of the considered model (there is no deformation level Y at which all curves for a intersect in the feed range from f_{min} to f_{max}). For some of the possible cutting depth values, it is necessary to compensate for the residual deformation after force deformations stabilization. The compensation value is determined by the expression:

$$Y_c = Y_s - Y_{cal}, \quad (8)$$

where: Y_c is the compensation value (residual deformation); Y_s – deformation, at which stabilization is performed; Y_{cal} – deformation, calculated from (6) for the feed value f_i and allowance a_i.

The sign of the obtained Y_c determines the direction of compensation. With a "–" sign, the tool moves towards the workpiece, with a "+" sign, the direction of its motion is away from the workpiece.

The system of adaptive control is adjusted to operate at a selected level of stabilizing the force deformations Y_c. The choice of this level is determined by the machining efficiency indicators: productivity, cost, dimensional accuracy, micro-geometric shape accuracy, etc.

Three characteristic cases can be considered in the case of applying complex adaptive control, depending on the selected level of deformation.

1) *The selected deformation level is in the range from Y_2 to Y_{max} ($Y_2 < Y_s \le Y_{max}$).*

The stabilization of the force deformations is carried out at a feed $f_i > f_{min}$. The increase in the value of the selected deformation leads to limitation of the range in which the feed changes. As Y_c increases, the minimum value for f increases.

The compensation Y_c, determined by (8) in the considered section, takes positive values. The compensation is performed when working with feed $f = f_{max}$.

In the borderline case $Y_c = Y_{max}$, the system will operate as an adaptive control system for compensating the force deformations with a feed $f = f_{max}$.

In the considered case ($Y_s > Y_2$), and the productivity of the system is higher since it operates with higher feed values.

The accuracy of the obtained dimensions depends on the dispersion of the force deformations ωY, meaning that higher deformation levels will lead to greater dispersion of the dimensions.

2) The selected deformation level is in the range from Y_1 to Y_2 ($Y_1 \le Y_s \le Y_2$).

In this case, the entire feed range is used to control the force deformations for stabilization purposes.

The compensation value can take both positive and negative values.

In the borderline case $Y_c = Y_1$ at cutting depths $a_i > a_1$, compensation of the force deformations is needed, working with a feed f_{min} and compensation value Y_c, determined for the corresponding cutting depth a_i.

In the borderline case $Y_c = Y_2$ at cutting depths $a_i < a_2$, compensation of the force deformations is needed, using a feed f_{max} and compensation value Y_c, determined for the corresponding cutting depth a_i.

When working with deformations in the considered range, the adaptive system operates according to one of the two options considered for the borderline cases. The value of the allowance a_i is decisive.

The productivity of the system in the considered case is lower, compared to its operation at larger deformations. If we assume that the allowance is distributed according to a normal law, it follows from the principle of the system operation, that we will mainly work with average feed values.

The dispersion of the obtained dimensions is expected to be less than it is in case 1, due to working with smaller deformation values.

3) The selected deformation level is in the range from Y_{min} to Y_1 ($Y_{min} \le Y_s < Y_1$).

In this case, the stabilization of the force deformations occurs at a feed rate $f_i < f_{max}$. Decreasing the value of the selected deformation results in limiting the range in which the feed changes. As Y_c decreases, the maximum value of the stabilization feed decreases.

The compensation Y_c, determined by (8) in the considered section, takes negative values. The compensation is performed when working with a feed rate $f = f_{min}$.

In the borderline case $Y_c = Y_{min}$, the system works as an adaptive control system, aiming to compensate for the force deformations with a feed $f = f_{min}$.

The productivity of the system in the considered range of Y_c is lowest due to its operation with feeds close to f_{min}.

The dispersion of the obtained dimensions should be lower than it is in the other two cases due to the low deformation values.

In the first two variants, the limiting value of the cutting depth a_1 or a_2, respectively, is determined by substituting Y_s and the feed for the considered variant in formula (6). A check is made to see if compensation is necessary. If it is needed, the feed f is determined as $f = f_{min}$ or $f = f_{max}$, correspondingly, and then the compensation Y_c is calculated.

Based on the model of applying complex control over the force deformations, an algorithm for programmatic adaptive control has been developed.

After entering the input data, the corresponding levels Y_1 and Y_2 are calculated. A check is performed to see if the model is of a type, requiring stabilization and compensation.

If it is not of this type, stabilization of the force deformations is performed according to the corresponding algorithm. If the model satisfies the condition $Y_1 < Y_2$, then a deformation level Y_s is determined according to the conditions of the introduced input data.

Next, a check follows, for affiliation to one of the three characteristic cases according to the selected deformation level Y_s($Y_c < Y_2$; $Y_s < Y_1$; $Y_1 \leq Y_s < Y_2$).

III. RESULTS AND DISCUSION

A. *Research on the adaptive control algorithm with stabilization of the force deformation errors during scraping*

Conditions of the experimental study: machine tool – CNC lathe LT580; workpieces – cylindrical sleeves mounted on a mandrel; fixture – mandrel mounted in a chuck and rear center; machined material – steel BDS EN 10083-2 C45; diameter of the machined workpieces – ∅100 mm; width of the machined workpieces – 25 mm; cutting tool – cutter with mechanically fixed carbide insert with designation PSBNR 25 25 L 12; main tool mounting angle χ_r =75°; cutting speed V_c = 80m/min.

A total of fifteen trials is performed at five cutting depths. For each cutting depth, using the force-deformation error model, presented in Table 1, the problem of calculating the feed f at cutting depth a and deformation level Y = 14,7µm, is solved.

The regression equations in normalized and natural coordinates, describing the force deformation errors for the studied area of the workspace and at the given technological parameters, are written in Table 1.

The data on the conducted experiments and the obtained results are presented in Table 2 and Fig. 7.

TABLE 1 REGRESSION EQUATIONS FOR ERRORS FROM FORCE DEFORMATIONS DURING SCRAPING

Normalized coordinates
$Y(X_1,X_2)=16,6+4,8X_1+12,4X_2+0,75X_1X_2+3X_1^2+3,5X_2^2$
Natural coordinates
$Y=11,3-17,5a_p-21f+10a_pf+12a_p^2+156f^2$

TABLE 2 RESULTS FROM STUDYING AN ALGORITHM FOR ADAPTIVE CONTROL WITH FORCE DEFORMATIONS STABILIZATION DURING SCRAPING

a_p, mm	0,6	0,8	0,9	1,2	1,4
f, mm/об	0,3	0,29	0,28	0,24	0,19
Y,µm	20	25	17	15	17
Y,µm	15	19	17	17	21
Y,µm	17	16	21	16	20

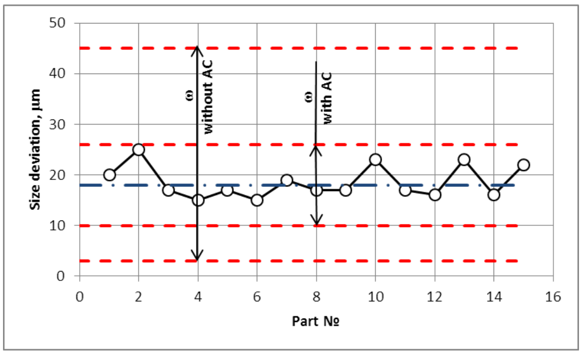

Fig.7. Scatter diagram of adaptive control, aiming to stabilize errors from force deformations during scraping

Figure 7 illustrates the probable dispersion fields, ω, obtained without adaptive control (AC) and with adaptive control applied to stabilize errors caused by force deformations.

The data from the process of machining are subjected to statistical analysis. The following results are obtained:

- arithmetic mean value: $\bar{X} = 18,2$ µm;
- dispersion: $s^2 = 7,6$ µm^2;.
- probable dispersion field at n = 15; confidence level γ = 0,95; coverage probability P = 0,95; k = 2,945; ω = 16,23 µm.

Both the probable dispersion field around the regression surface for the model ω_1 = 7,22 µm and the total dispersion field for the force-deformation error model ω_M = 41,6 µm are known. Thence, a reduction of the order of three times in the probable dispersion field of the errors, resulting from force deformations, is achieved.

B. Research on the adaptive control algorithm with compensation of errors from force deformations during scraping

The experimental conditions are the same as in the previous case and the same force-deformation model is used (Table 1).

A total of fifteen trials is performed at five cutting depths. For each cutting depth, using the force-deformation error model, the problem of calculating the force-deformation error level Y is solved. The feed is constant for all trials $f = 0{,}3$ mm/rev.

The machining is performed by compensating the calculated error from force deformations through the controlled elements of the machine. The resulting error is measured after machining.

The data on conducting the experiments and the obtained results are presented in Table 3 and Fig. 8.

TABLE 3 RESULTS FROM STUDYING AN ADAPTIVE CONTROL ALGORITHM WITH COMPENSATION FOR FORCE DEFORMATIONS DURING SCRAPING

a_p, mm	0,6	0,8	0,9	1,2	1,4
Y, µm	15	15	16	19	22
Y_{res}, µm	6	8	7	7	11
Y_{res}, µm	5	12	7	14	8
Y_{res}, µm	7	5	10	8	7

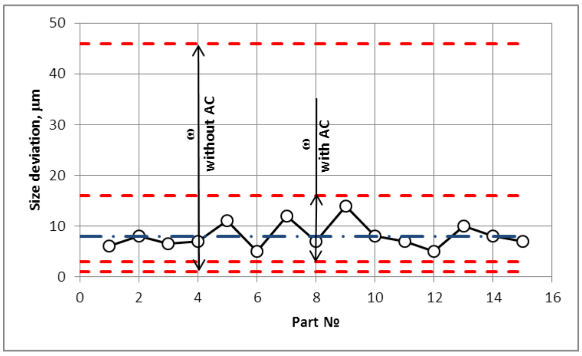

Fig.8. Scatter diagram, illustrating the application of adaptive control to compensate for errors from force deformations during scraping

Figure 8 illustrates the probable dispersion fields, ω, obtained without adaptive control and with adaptive control applied to compensate errors caused by force deformations.

In Table 3, Y denotes the calculated values for the force-deformation error, and Y_{res} denotes the measured error after conducting the experiment.

The following results are obtained from the statistical analysis:

- arithmetic mean value: $\bar{X} = 8{,}0667$ µm;
- dispersion: $s^2 = 6{,}780952$ µm^2;
- probable dispersion field at $n = 15$; confidence level $\gamma = 0{,}95$; coverage probability $P = 0{,}95$; $k = 2{,}945$: $\omega = 15{,}34$ µm.

The probable dispersion field around the regression surface for the model $\omega_I = 7{,}22$ µm and the total scattering field for the force-deformation error model $\omega_M = 41{,}6$ µm are known.

The application of the adaptive control algorithm with compensation of force deformation errors leads to a reduction by about three times in the field of dimensional dispersion during machining.

C. Research on an adaptive control algorithm with stabilization of errors from force deformations during boring

Conditions of the experimental study: machine tool - CNC lathe LT580; machined material - steel BDS EN 10083-2 C35, outer diameter of the sleeves ∅40 mm; diameter of the machined hole - ∅30 mm; length of the workpiece - $L = 30$ mm; cutting tool - boring bar with mechanically fixed carbide plate; diameter of the cutting tool - 20 mm; length of the cantilever part of the cutting tool - $L_u = 100$ mm; main tool setting angle $\chi_r = 90°$; cutting speed $V_c = 100$ m/min;

Variable factors: depth of cut a_p. The research uses the methodology, presented in [7].

A total of twenty-five trials were conducted at five cutting depths, with five trials for each depth.

For each cutting depth, the feed f at the deformation level $Y = 83$µm is determined from the force deformation error model, presented in Table 4.

The regression equations in normalized and natural coordinates, describing the force deformation errors for the studied area of the workspace, and at the given technological parameters, are given in Table 4.

TABLE 4 REGRESSION EQUATIONS FOR ERRORS FROM FORCE DEFORMATIONS DURING BORING

Normalized coordinates
$Y(X_1, X_2) = 135 + 57{,}1X_1 + 67{,}8X_2 + 46{,}3X_1X_2 - 7{,}5X_1^2 - 8{,}8X_2^2$
Natural coordinates
$Y = 8 + 71{,}4a_p + 8f + 925a_pf - 120{,}4a_p^2 - 219f^2$

The preliminary preparation for conducting the study involves machining the hole in the sleeves and a 5mm-long step at one of their ends. The resulting step shape of the workpiece ensures the required cutting depth a_p for the experiment.

The results of the study are presented graphically by means of a scatter diagram in Fig. 9.

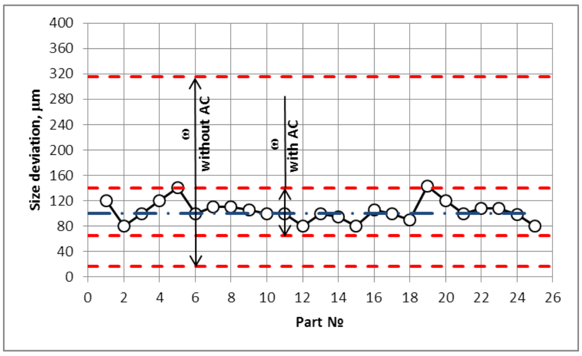

Fig.9. Scatter diagram, illustrating the application of adaptive control, aiming to stabilize errors from force deformations during boring

Figure 9 illustrates the probable dispersion fields, ω, obtained without adaptive control and with adaptive control applied to stabilize errors caused by force deformations.

From the statistical processing of the data, after eliminating a gross error, the following results are obtained:

- arithmetic mean value: $\bar{X} = 101,456$ µm;
- dispersion: $s^2 = 161,9112$ µm^2;
- probable dispersion field at $n = 26$; confidence level $\gamma = 0,95$; coverage probability $P = 0,95$; $k = 2,945$: $\omega = 68,879$ µm

The probable dispersion field around the regression surface for the model $\omega_1 = 51,45$ µm and the total scattering field for the force-deformation error model $\omega_M = 301$ µm are known.

The diagram shows the probable dispersion fields both without applying adaptive control and in case of implementing adaptive control. The probable field of dispersion of errors from force deformations when applying the adaptive control algorithm is more than 4 times smaller than the total one, obtained during modeling in the studied area.

IV. Conclusions

One of the possibilities for increasing the accuracy of APPC is to reduce the instantaneous field of dimensional dispersion. This can be achieved through adaptive control to reduce the influence of force deformation errors.

The control of force deformations can be implemented based on mathematical models for the deformation behavior of the technological system. Adaptive control can compensate for or stabilize the force deformation errors.

The experimental study conducted during CNC machining, has proven the feasibility and possibility of increasing the accuracy of APPC by applying adaptive control to reduce the influence of errors from force deformations.

Acknowledgments

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References

[1] S. S. Volosov, M. L. Shleyfer, V. Ya. Ryumkin, et al., Active Control of Dimensions. Moscow, Russia: Mashinostroenie, 1984.

[2] G. Gatev, V. Georgiev, and G. Nenov, Special Course in Manufacturing Technology. Ruse, Bulgaria: VIMMESS, 1981.

[3] S. Salapateva, “Technological Investigations for Active Control in CNC Turning”, Ph.D. dissertation, Plovdiv, Bulgaria, 2005.

[4] V. Georgiev and S. Salapateva, “Influence of process accuracy and tool dimensional stability on the efficiency of active control with adjustment,” in Proc. Int. Conf. Machine Building Technologies and Technics (AMTECH), Varna, Bulgaria, pp. 87–91, 2003.

[5] S. Koleva, “Ensuring accuracy in turning,” Engineering Proceedings, vol. 100, no. 1, 2025, https://doi.org/10.3390/engproc2025100014.

[6] S. Koleva and M. Enchev, “Modern problems and tendencies of effective accuracy control of turning operations,” AIP Conf. Proc., vol. 2449, 2022, doi: https://doi.org/10.1063/5.0090675

[7] V. Georgiev and S. Salapateva, “Investigation of the turning process for implementation of active control with adjustment on lathe ST161,” in Proc. Scientific Session of Ruse University, Ruse, Bulgaria, pp. 8–12, 2003.

[8] V. Georgiev and S. Salapateva, “Investigation of active control in CNC turning as part of an intelligent computer control system,” J. Tech. Univ. Plovdiv, Technical Sciences, vol. 11, pp. 51–56, 2005.

[9] J. Sun, Z. Liu, C. Qiu, J. Luo, L. He, H. Liu, G. Sa, Z. Jiang, and J. Tan, “Machining accuracy prediction and adaptive compensation method of CNC machine tool under absence of machining process sensing,” *Journal of Intelligent Manufacturing*, vol. 36, no. 6, pp. 3923–3940, 2025, doi: https://doi.org/10.1007/s10845-024-02403-5.

[10] L. Gan, L. Wang, and F. Huang, “Adaptive Backlash Compensation for CNC Machining Applications,” *Machines*, vol. 11, no. 2, Art. no. 193, 2023, doi: https://doi.org/10.3390/machines11020193.

[11] J. Švéda, Š. Chládek, T. Hornych, T. Kozlok, and J. Smolík, “Increasing Machining Accuracy Based on CNC Machine Tool Correction Data by Using Ad Hoc Modification,” Machines, vol. 10, no. 5, Art. no. 288, 2022, doi: https://doi.org/10.3390/machines10050288.

[12] S. N. Bhat, S. B. Sharma, and R. Singh, “Development of In-Situ Adaptive Controller for End Milling Based on Vibration Feedback,” SN Applied Sciences, vol. 3, Art. no. 97, 2021.

[13] T. A. Davis, Y. C. Shin, and B. Yao, “Adaptive robust control of machining force and contour error with tool deflection using global task coordinate frame,”Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, vol. 232, no. 1, pp. 40–50, Jan. 2018, https://doi.org/10.1177/0954405416654100.

[14] H. Wu, H. J. Chen, P. Meng, and J. G. Yang, “Modelling and real-time compensation of cutting-force-induced error on a numerical control twin-spindle lathe,” Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, vol. 224, no. 4, pp. 679–690, Apr. 2010, https://doi.org/10.1243/09544054JEM1641.

[15] B. S. Balakshin, Adaptive Control of Machine Tools. Moscow, Russia: Mashinostroenie, 1973.

[16] I. Chetrokov, “Adaptive Control of Accuracy in Machining on CNC Machine Tools”, Ph.D. dissertation, Plovdiv, Bulgaria, 2005.

[17] V. Georgiev and I. Chetrokov, “Investigation of force deformations in the working space of CNC machine tools,” J. Tech. Univ. Plovdiv, Technical Sciences, vol. 10, pp. 17–25, 2003.

[18] V. Georgiev and I. Chetrokov, “Adaptive control for stabilization of force deformations in CNC lathes,” J. Tech. Univ. Plovdiv, Technical Sciences, vol. 10, pp. 27–33, 2003.

[19] V. Georgiev and I. Chetrokov, “Adaptive control for compensation of force deformations in CNC lathes,” in Proc. Int. Conf. Machine Building Technologies and Technics (AMTECH), Varna, Bulgaria, pp. 91–93, 2003.

[20] V. Georgiev and I. Chetrokov, “Complex adaptive control for stabilization and compensation of force deformations in CNC machine tools,” in Proc. Int. Conf. Machine Building Technologies and Technics (AMTECH), Varna, Bulgaria, pp. 81–86, 2003.