Model of monitoring precision of technological processes based on principal component analysis

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Abstract. The article presents the results of theoretical and experimental research to improve the accuracy of machining of complex shapes on CNC machines. The proposed monitoring system improves the quality of operation of technological systems as a whole. A new analytical method for assessing the quality of products obtained on CNC machines is given. Monitoring consists of: evaluation of the accuracy and rigidity of the technological system of the machine; monitoring the state of the machine based on the analysis of technological accuracy of processing; control of accuracy of processing by adjusting the program for the CNC system and changing the processing modes.

1. Introduction
One of the preferred methods of adjusting CNC machines to size is the processing of a workpiece followed by dimensional analysis. In this case, the workpiece is processed according to the control program. Next, the resulting part is measured and corrected control program.

2. Theoretical research
Precision machining of complex contour parts on CNC machines has always deserved special attention. It is known that the error of machining on CNC machines consists of a large variable number of variables. According to the basic provisions of mechanical engineering technology, these factors can be both constructive, depending on the design of the machine and its control system, and technological, determined by the selected tool, cutting conditions, the design of the device and other factors. Design factors determine the error of the mechanical system of the machine and CNC system errors. And if the latter can be adjusted by the control program, the errors of the mechanical system of the machine tool can not be eliminated, since they consist not only of the actual geometric errors, but also are a reflection of the physical processes occurring in the machine tool system.

Analysis of the production of parts on CNC machines allows to distinguish the following main types of errors inherent to this type of equipment: programming error; the error of settings of the machine, the positioning error; error automatic tool changers; the geometric error arising from misalignment, not parallel and not perpendicular of the vectors of displacement of the parts of the machine tool; error from elastic displacements; error from fast processes; processes with average speed; the error from the slow processes. It should be taken into account that the bulk of the errors are random variables, they changes in time and has the property of vectors.
Thus, the total error of processing parts of a complex circuit on CNC machines forms a hypervector \( GV \), given in the coordinate system of the controlled surface. The components of this vector are determined by the formula

\[
GV_N = \Theta_N \cdot ZD_N + \Sigma \text{Var}
\]

\( \Theta_N \) – operator of transferring the value of \( ZD_N \) to the coordinate system of the controlled surface; \( ZD_N \) – vector of deviation of the "zero" of the machine; \( \Sigma \text{Var} \) – a complex of deviations of the surface geometry, which are of probabilistic nature.

Analysis of the process of forming the error of the \( GV \) made it possible to develop a model of precision machining on CNC machines with an error of type \( ZD \). With the help of the obtained model, the mathematical dependences linking the indicators of technological accuracy with the parameters of the machine and processed products are determined. Consider the basic component of the model.

2.1. Mathematical model of accuracy, taking into account the dynamic processes occurring in the machine system

The basis of the model is the algorithm given in [1]. The error of the vector of movement of the machine unit, caused by dynamic processes, can be calculated by the formula

\[
\Delta_n = [\Omega \sum_{n=1}^{N} \left\{ \frac{F_p}{\sigma_{pq}} \right\} S_p] \Delta x^q,
\]

\( \Delta_n \) is the deviation of the end point displacement \( S \) or the positioning node, measured along the \( n \)-th coordinates of the coordinate system associated with the part of machine tool; \( S_p \) – component \( S \), directed along the \( p \)-th coordinate; \( \Omega \) – the operator, correcting the amplitude values and frequency coefficients of linkage \( \left\{ \frac{F_p}{\sigma_{pq}} \right\} \) of the coordinate systems of the nodes, if the oscillations occur with a significant deviation from the harmonic law; \( \Delta x^q \) – spatio-temporal accuracy of the location of the start point of the displacement vector \( S \) (\( \Delta x^q \) find as the sum of errors and result in the part of machine tool in the form of delay, i.e. "time errors"); \( N \) – the number of coordinates along which the movement occurs, including the coordinate "time" (provided that the coefficients connecting \( \left\{ \frac{F_p}{\sigma_{pq}} \right\} \) these coordinates are not zero).

2.2. The component of the model that takes into account the rigidity of the machine

According to the theoretical provisions on the rigidity of machines [2], the unit of the technological system can be represented as an elastic-friction module consisting of two main elements – stiffness and friction. The values of these elements are determined depending on the action of external forces. The displacement vector can be determined using an integral sum

\[
L_q = \sum_{i=1}^{m} \left[ \sum_{j=1}^{n} F_j \right] \frac{1}{j}
\]

\( L_q \) – displacement of the technological system units in the direction of the \( q \)-th axis of the working space of the machine tool (X; Y or Z); \( F_i \) – friction forces acting in the guides of the \( i \)-th part of machine tool in the direction X; Y or Z; \( j \) – the stiffness of the \( i \)-th node in the direction X; Y or Z; \( n \) – the number of part of machine tool; \( m \) – the serial number of the summand.

The displacement determines the relative position of the tool and workpiece at the end of the cutting process, that is, the machining accuracy and positioning accuracy after the feed is stopped. The values of residual displacements and processing errors are so significant that they can reach the tolerance value for the size to be processed. In backlash-free, elastic-friction modules, you must consider the component of error caused by the processes of the rheology of materials. Rheological
processes must be considered when finding the parts at the same point in the working space of the machine for a period of time from 1 to 15 minutes. For example, at the operating pause of the program or zero displacement of the node of the CNC, the components of the vector $LF$ residual power offsets will be of the form

$$LF_{q} = L_{q} \pm \sum^{n}_{i} R[L_{q}]$$

(3)

$\Sigma R[L_{q}]$ is the total rheological displacement of the critical and basic parts of the technological system in the direction of the $q$–th axis.

2.3. The order of inclusion of the equations of surfaces of complex shape in the balance of the accuracy of the machine

The solution of problems on the analysis of error of forming of surfaces of a complex contour is based on the vector-matrix device of transformation of coordinates of object. For the surface of a complex shape, the object is the point of its forming line, given by the vector $\rho$. The method of formation, constants and functions describing the generator, its kinematic changes (errors) are reflected in the relative movements of the Executive units of the machine. These changes $\Delta \rho_{n}$ are determined in the coordinate system of the element of the technological system that determines the movement of the Executive unit of the machine and in the coordinates of the product is determined as:

$$\Delta P_{n} = J^{m} e_{n} K_{n} e_{n},$$

(4)

$J^{m}$ – the Jacobian of transformation between coordinate systems of the nodes of the machine; $e_{n}$ – vectors characterizing the baseline (reference point) at each point in the coordinate system of the host item (if they are given as functions of a basis of the coordinate system of the Executive host of the machine, the Jacobian matrix $J^{m}$ of formula (4) exclude); $K_{n}$ – coefficient of the decomposition of the vector $\rho$ for a given time-space basis $e_{n}$. Summation in equation (4) is produced by repeated indices.

The calculation is carried out in the form of a sequential transition from the fixed parts of the bearing system of the machine to the nodes that make the movement of shaping, consistent with the equation describing the generator and its kinematic changes.

The greatest difficulty is the compilation of the functional dependence of the surface in the coordinate system of the product with the displacement of the beginning of the curve profiling the surface by the value of $ZD$. In General, the function changes. For example, in the case of processing involute can change the very basis – involute.

2.4. The dependence of the technological accuracy of the geometric

The geometric accuracy of the technological system is the expected error of the finished product. Its relationship with technological accuracy is probabilistic. To reveal this connection, it is necessary to separate the systematic and random errors characterizing the technological process. The method of separation of systematic and random errors is developed.

The objects of the studies were selected multipurpose lathe machining center ST–10Y and milling boring and milling machine TM–1P manufactured by Haas Automation and machine 400V Sterlitamak plant of NPO "Stankostroenie" company "STAN". Evaluation of $ZD$ produced in the following order. In the device installed on the table of the machine, a spiral disk was fixed, with a spiral profiled along the involute with a variable value of the involute. The accuracy of the spiral profile was evaluated on the coordinate measuring machine. In the machine spindle, and the mandrel is fastened to two of the tripod with the indicators MIG 2 (graduation 0.002 mm) who have undergone annual appraisal. The indicators were installed at an angle of $90^\circ \pm 30$ between the measuring tips. Adjustment of the machine was made so that the measuring tips periodically touch the side face of the spiral disk. The profile of the spiral was tested to an accuracy of 0.001 mm on the coordinate measuring machine model XO 55 TM 1 manufactured by Wenzel.
The study was performed on idling of the machine without the processing spiral. In determining ZD the machine is worked automatically by the program developed for surface treatment evaluating circuit. The machine was carried out the whole cycle of programmed work movements. The processing time of the program cycle was 5 minutes and 32 seconds. After completion of the cycle, the relative position of the spindle and the machine table was measured along the x and Y axes after their return to the initial position. To register measurements, a zero-displacement cycle was included at the beginning of the program.

The formula (1) was tested experimentally. Verification of formulas (2) and (3) was carried out with the help of a certified dynamometer in the directions of movement of the working bodies of the machine X; Y and Z. Registration of the rheological displacement of the critical and basic parts of the technological system of the machine was made in 1 second after reaching the maximum loading force. The loading force was taken equal to the maximum possible cutting force acting in the system of the machine under study. The fall in the rigidity of the machine due to the processes of the aftereffect of the elastic system was noted in the period of time up to 15 minutes.

At the same time, experimental studies were carried out to verify the compliance of the theoretically obtained dependences of the technological accuracy of the machine on the geometric one. During the processing of test parts, ZD measurements were carried out. The obtained ZD values caused by the machine workloads were compared with the theoretical ones.

3. Experimental Works and Discussion
Empirical testing of machines showed that ZD can reach values exceeding the tolerance for the manufacture of the spiral from 1.5 to 2 times. A significant difference between the distribution of ZD and the exponential law is revealed. The distribution pattern ZD has a pronounced stochastic nature. The distribution law of ZD is close to normal. Deviations of the ZD distribution from the Gauss law have their own specifics and are associated with the design features of the technological system and processing modes.

The most important result is the study of the effect of the elastic system of the machine. In the course of the experiments, it was noted that the aftereffect of the machine system is manifested in one second after loading, and not in one minute, as noted in the known books.

4. Conclusions
1. This paper presents a method for developing an error model which expresses the observed error in a multy-axis machine tool as function of its elemental errors.
2. For the first time the calculation of ZD was carried out throughout the working space and in the directions of movement of parts of the machine tool.
3. The theoretical basis for the calculation of ZD with the processes dynamics, friction, stiffness, and effectiveness of the system of the machine tool.

References
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