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Synergetic approach to improve the efficiency of machining process control on metal-cutting machines

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ABSTRACT

Introduction. The efficiency of processing on metal-cutting machines is evaluated by the reduced cost of producing a batch of parts while ensuring the required quality. In modern production, parts are usually made on CNC machines. Today the CNC program and the trajectories of the machine tool actuators match each other with high accuracy, which, however, does not yet guarantee quality and efficiency of production. The definition of the CNC program is based on the knowledge base of rational modes, tools, coolant and etc. during processing. This base reflects some averaging over the set of machines, tools and processing conditions, and does not take into account changes in the properties of the dynamic system in the process of cutting. **Subject.** The paper deals with the synergistic matching of external control (CNC programs) and cutting dynamics (internal control). The internal control factors can be set a priori, as well as determined as a result of the influence of irreversible energy transformations in the cutting zone. **The purpose of the work** is to determine the law of controlling the trajectories of the machine's executive elements in such a way that, with changing properties of the dynamic cutting system, the required surface quality of the part and minimizing the intensity of tool wear are ensured during the processing of the part. **Method and methodology.** Mathematical simulation of the controlled dynamic system, which properties change due to the a priori set laws of variation of subsystem parameters, as well as changes in the cutting properties conditioned by the power of irreversible energy transformation is presented. Consideration of the power of irreversible energy transformations is necessary for predicting back-edge wear, changes in dynamic coupling parameters, and evolutionary restructuring of cutting dynamics. **Results and Discussion.** The regularity of matching the CNC program with the changing properties of the cutting process, which allows increasing the processing efficiency while ensuring the required quality of parts, is disclosed. A number of properties of the dynamic cutting system caused by changing trajectory of the longitudinal feed rate of the tool during processing of the shaft, the stiffness change of which is given, are revealed and analyzed.

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Introduction

Currently, the system-synergetic paradigm of analysis and synthesis of complex systems has been formed [1–4]. It is used in controlling technical systems [5–8], including machining processes on machine tools [9–13], and in studying the dynamics of systems interacting with different environments [14–16]. When determining CNC programs that specify trajectories of executive elements (TEE), the knowledge base, based on various ideas about the influence of technological parameters on machining, is used [16–24]. It is shown that the wear intensity is influenced by the power released in the cutting zone. It is estimated, as a rule, by temperature [25–32]. Various techniques have been developed for correcting control programs that depend on information exchanges in subsystems [33–38]. One effective method for ensuring part quality is to control the elastic deformations of the tool relative to the workpiece [39]. This method has gained recognition especially in cases where the workpiece stiffness varies along the machine's TEE [40–44]. It has also been shown that the machining output characteristics depend on the state of the dynamic system (DS) [45–54]. Machining modes, as a rule, remain unchanged. Changes in DS properties, such as power path-dependent irreversible energy transformations by performed work, are not taken into account [55–58]. The next step, aimed at increasing the machining efficiency, is the synergistic coordination of the CNC program with the cutting DS. Firstly, it is necessary to coordinate the technological modes and the corresponding CNC programs with the cutting system. Secondly, it is necessary to ensure this coordination with the changing properties of the system in the course of evolution. The aim of the research is to develop algorithms, mathematical tools and methods of matching the CNC program with the changing properties of the cutting DS along the tool trajectory.

Research methodology

State space

Let's consider the space in which we will place the workpiece and consider the tool tip movement trajectories consisting of the machine tool tip $\mathbf{L}=\{L_1,L_2,L_3\}^T\in\Re^{(3)}$ and deformation displacement trajectories $\mathbf{X}=\{X_1,X_2,X_3,Y\}^T\in\Re_X^{(4)}$, in which we will distinguish the deformation displacements of the tool tip $\mathbf{X(t)}=\{X_1(t),X_2(t),X_3(t)\}^T\in\Re_X^{(3)}$ relative to the machine carrier system and the deformation displacements of the workpiece $Y(t)$ in the direction normal to its axis. The origin of the space coordinates is placed in the right rotation center of the workpiece (Fig. 1). In addition, we will set the trajectory of its rotation ($\Omega=d\alpha/dt,\alpha=L_4$). Space $\Re_X^{(3)}$ is movable. Its motion is constrained to trajectories $\mathbf{L}$. The orientation of space coordinates $\Re_X^{(3)}$ is shown in Fig. 1. Vectors $\mathbf{L}$ and $\mathbf{X}$ correspond to its velocities $\mathbf{V(t)}=\{V_1,V_2,V_3,V_4\}^T\in\Re^{(4)}$ and $\mathbf{v_X}=\{v_{X,1},v_{X,2},v_{X,3},v_{X,4}\}^T\in\Re^{(4)}$. At that, $V_4=\pi D\Omega$. The set of $\mathbf{L(t)}$ and $\mathbf{V(t)}$ is defined by the CNC program. Let us also consider the trajectories of the form-forming motions $\mathbf{l(t)}=\{l_1,l_2,l_3,l_4\}^T$

$$\mathbf{l(t)}=\mathbf{L(t)}-\mathbf{X(t)}, \tag{1}$$

as well as its velocities $\mathbf{v(t)}=\{v_1(t),v_2(t),v_3(t),v_4(t)\}^T\in\Re^{(4)}$, that is $\mathbf{l(t)}=\int_0^{\mathbf{t}}\mathbf{v(\xi)d\xi}$. If $\mathbf{l(t)}$ is set, then the skeletal geometrical topology $\mathbf{\Psi^{(l)}}\subset\mathbf{\Psi^{(0)}}$ of the surface formed by cutting [10–12] is also defined, from which it is possible to determine the geometry estimates used in engineering practice without taking into account the influence of independent physical processes accompanying processing on the surface. Condition

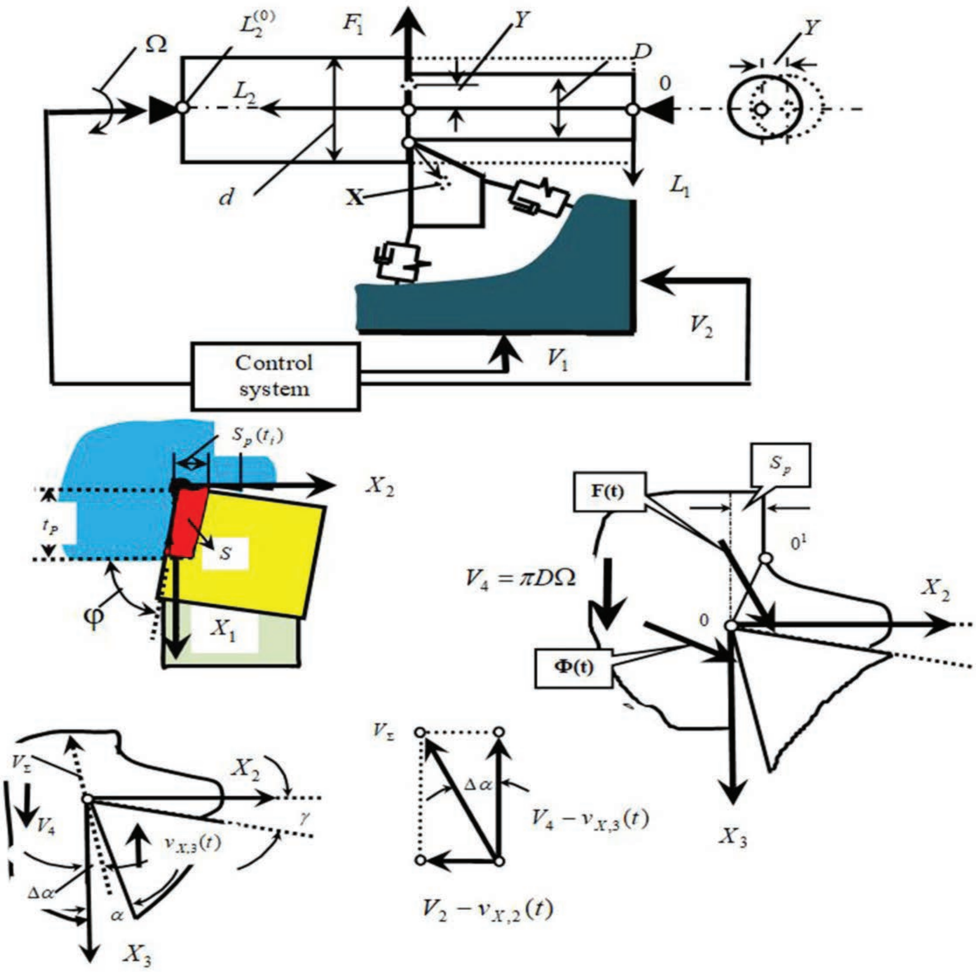

Fig. 1. Scheme of interaction between the spindle rotation and feed drives of the slide, as well as the formation of a dynamic connection of the cutting process

$$\mathbf{I(t)} \in \mathbf{\Psi^{(I)}} \subset \mathbf{\Psi^{(0)}} \tag{2}$$

defines the requirement for the quality of the surface formed by cutting. This condition is considered to be achievable on a machine tool if the TEEs $\mathbf{L(t)}$ are controlled. However, in the case of evolution, the condition $\mathbf{\Psi^{(I)}} \subset \mathbf{\Psi^{(0)}}$ may become unattainable.

We will rely on the synergetic principle of "expansion-compression" of the state space dimension [6–8]. As applied to machining, it reveals the interaction between the tool and the workpiece through the medium formed by the cutting process.

Let us limit ourselves to the mechanical interactions of the three tool faces

$$\mathbf{F_\Sigma(t)} = \mathbf{F(t)} + \mathbf{\Phi(t)} + \mathbf{\Phi^{(B)}(t)}, \tag{3}$$

where $\mathbf{F(t)} = \{F_1(t), F_2(t), F_3(t)\}^T \in \Re^{(3)}$ – forces formed in the interface area of the front face of the tool, $\mathbf{\Phi(t)} = \{\Phi_1(t), \Phi_2(t), \Phi_3(t)\}^T \in \Re^{(3)}$ – forces formed in the interface area of the main back face of the tool and its auxiliary face $\mathbf{\Phi^{(B)}(t)} = \left\{\Phi_1^{(B)}(t),\ \Phi_2^{(B)}(t),\ \Phi_3^{(B)}(t)\right\}^T$. It is necessary to represent it in coordinates of state and control. In the areas of interface of faces, the work $\mathbf{A(t)} = \{A_1, A_2, A_3\}^T$ and power of irreversible energy transformations $\mathbf{N(t)} = \{N_1, N_2, N_3\}^T$ are considered. The phase trajectory $(\mathbf{A(t)} - \mathbf{N(t)})$ is the generator of all evolutionary changes in the cutting process [55–58].

Model of interactions

A system is defined if the interactions between the subsystems are disclosed. The interactions between the tool and the workpiece through the medium formed by the cutting process are formed by the intersection of the tool body and the workpiece. Parameters, characterizing the intersection, are modes (feed, depth and cutting speed): $\mathbf{T(t)} = \{S_P(t), t_P(t), V_P(t)\}^T$. It is related to $\mathbf{V(t)}$ and $\mathbf{v_X(t)}$ by the relations

$$S_P(t) = \int_{t-T}^{t} \left[V_2(\xi) - v_{X,2}(\xi)\right] d\xi;$$
$$V_P(t) = V_3(t) - v_{X,3}(t); \quad t_P(t) = d/2 - \int_0^t \left[V_1(\xi) - v_{X,1}(\xi) - v_{X,4}(\xi)\right] d\xi, \tag{4}$$

where $T = (\Omega)^{-1} = \text{const}$ – time of a turn in $[S]$. We suppose that there is no torsional deformation of the workpiece and the workpiece of constant diameter is being processed, and the system is undisturbed. It follows from (4) that interactions only exist when the tool moves relative to the workpiece. For example, the feed rate $S_P(t)$ is determined by an integration operator of the total feed rate in the time window determined by the frequency of Ω. If in (4) there are no deformations and all velocities are constant, we will use the values for the modes: $S_P^{(0)}$, $t_P^{(0)}$, $V_P^{(0)}$.

We will rely on the studies [55, 56] to determine the deformations,

$$\mathbf{m}\frac{\mathbf{d^2X}}{\mathbf{dt^2}} + \mathbf{h}\frac{\mathbf{dX}}{\mathbf{dt}} + \mathbf{cX} = \mathbf{F}_\Sigma(S_P, t_P, V_P), \tag{5}$$

where $m = [m_{s,k}]$, $m_{s,k} = m$, при : $s = k$, $m_{s,k} = 0$, при : $s \neq k, s, k = 1,2,3$, $m_{4,4} = m_0(L)$ в kgs^2/mm, $h = [h_{s,k}]$, $h_{s,4} = h_{4,s} = 0, s = 1,2,3$ в kgs/mm, $c = [c_{s,k}], s,k = 1,2,3,4$, $c_{s,4} = c_{4,s} = 0, s = 1,2,3$ in kg/mm are symmetric, positively determined matrices of inertial, velocity, and elastic coefficients. The parameters of the workpiece subsystem ($m_{4,4} = m_0(L)$, $h_{4,4}(L)$, $c_{4,4}(L)$) depend on L. The force projections in space $\Re^{(3)}$ are determined by the coefficients χ_i satisfying the conditions of $\sum_{i=1}^{i=3}(\chi_i)^2 = 1$. In this case $F_4 = -F_1$. When machining a part of complex geometry, the coefficients χ_i and matrices c change depending on the trajectory. The possibility of considering the deformation displacements of the workpiece as a scalar model is justified by the fact that its cross section is circular. Then any orthogonal system of coordinates, normal to the axis of rotation, is the main one. We will take into account the dependence $\mathbf{F}$ on the area *S*, the cutting speed $V_P(t)$ and take into account the delay of forces in relation to variations of *S*. Then

$$\mathbf{F(t)} = F^{(0)}(t)\{\chi_1, \chi_2, \chi_3, \chi_1\}^T, \tag{6}$$

where $T^{(0)} dF^{(0)}/dt + F^{(0)} = \rho\left\{1 + \mu \exp\left[-\zeta\left(V_3 - v_{X,3}(t)\right)\right]\right\}\left[t_P^{(0)} - X_1 - Y\right] \int_{t-T}^{t} \left\{V_2(\xi) - v_{X,2}(\xi)\right\} d\xi$; ρ – pressure in $[\text{kg/mm}^2]$; ζ – steepness parameter of forces in [s/mm]; μ – dimensionless coefficient; $T^{(0)}$ – parameter that determines the delay of forces.

The model of forces $\mathbf{\Phi(t)}$ is presented in state coordinates. The modulus of these forces depends on the convergence of the back faces to the workpiece, that is, on the back angle $\alpha_\Sigma(t)$ (Fig. 1). This angle is defined by the sum of

$$\alpha_\Sigma(t) = \alpha + \Delta\alpha(t), \tag{7}$$

where α is the value of the back angle; its increment $\Delta\alpha = \text{arctg}\left[\frac{V_2 - v_{X,2}(t)}{V_3 - v_{X,3}(t)}\right]$. Similarly, the angle between the trailing edge and the workpiece $\alpha_\Sigma^{(1)}(t) = \alpha^{(1)} + \Delta\alpha^{(1)}(t)$ changes. Since $\alpha_\Sigma(t)$ and $\alpha_\Sigma^{(1)}(t)$ are small values, it is true for the forces $\mathbf{\Phi(t)}$.

$$\begin{cases} \Phi_1 = \rho_0 \left\{ \int\limits_{t-T}^{t} \left[V_2 - v_{X,2}(t)\right] dt \right\} \exp\left[\alpha_1 \alpha_\Sigma^{(1)}(t)\right]; \\ \Phi_2 = \rho_0 \left[t_p^{(0)} - X_1(t) - Y(t)\right] \exp \alpha_2 \alpha_\Sigma(t); \\ \Phi_3 = k_T[\Phi_1 + \Phi_2], \end{cases} \tag{8}$$

where α_1, α_2 is a slope coefficient; ρ_0 is a parameter, which has the sense of stiffness; k_T – coefficient of friction in the contact of the tool face with the workpiece.

System (8) augmented by (2–6) allow to study $\mathbf{X}$, $\mathbf{F}$, $\mathbf{\Phi}$ and the power of irreversible energy transformations. It changes if the parameters of the dynamic coupling and $\mathbf{V(t)}$ vary. The dependences also make it possible to calculate the power $N_2(t)$ and work of the forces

$$N(t) = \Phi_1(t) v_{X,1}(t) + \Phi_2(t)\left[V_2 - v_{X,2}\right] + k_T\left[\Phi_1(t) + \Phi_2(t)\right]\left[V_4 - v_{X,3}(t)\right]. \tag{9}$$

Consideration of power $N_2(t)$ is necessary for predicting back-edge wear, changes in dynamic coupling parameters and evolutionary restructuring of cutting dynamics. In this paper, we limited ourselves to considering the power of irreversible transformations in the interface area of the back face of the tool and the workpiece, because when cutting with carbide tools, the prevailing wear is observed exactly at its back face.

Alignment of trajectories with varying stiffness

In the paper, the problem of synergistic matching of machine TEEs with an a priori specified law of variation $m_0(L)$, $h_{4,4}(L)$, $c_{4,4}(L)$ is considered. The problem is solved in three stages.

At the first stage, a set of phase trajectories $V_2(L_2)$ is defined at which the diameter deviation $\Delta D = 2(X_1 + Y) = \text{const}$. The function $c_{4,4}[L_2(t)]$ is assumed constant within the impulse response of the system. Then to determine the relation ΔD and V_2 we can use the system

$$X_1 + Y = \frac{\Delta_{\mathbf{X_1}} + \Delta_{\mathbf{Y}}}{\Delta} = \Delta_\Sigma = \text{const}, \tag{10}$$

where

$$\Delta = \begin{bmatrix} c_{1,1} + \chi_1\rho_0 V_2 T & c_{2,1} & c_{3,1} & \chi_1\rho_0 V_2 T \\ c_{1,2} + \chi_2\rho_0 V_2 T & c_{2,2} & c_{3,2} & \chi_2\rho_0 V_2 T \\ c_{1,3} + \chi_3\rho_0 V_2 T & c_{2,3} & c_{3,3} & \chi_3\rho_0 V_2 T \\ \chi_1\rho_0 V_2 T & 0 & 0 & c_{4,4}(L_2) + \chi_1\rho_0 V_2 T \end{bmatrix}; \quad \rho_0 = \rho\{1 + \mu\exp[-\zeta(V_3)]\};$$

$$\Delta_{\mathbf{X_1}} = \rho_0 t_P^{(0)} V_2 T \begin{bmatrix} \chi_1 & c_{2,1} & c_{3,1} & \chi_1 \rho_0 V_2 T \\ \chi_2 & c_{2,2} & c_{3,2} & \chi_2 \rho_0 V_2 T \\ \chi_3 & c_{2,3} & c_{3,3} & \chi_3 \rho_0 V_2 T \\ \chi_1 & 0 & 0 & c_{4,4}(l_2) + \chi_1 \rho_0 V_2 T \end{bmatrix};$$

$$\Delta_{\mathbf{Y}} = \rho_0 t_P^{(0)} V_2 T \begin{bmatrix} c_{1,1} + \chi_1 \rho_0 V_2 T & c_{2,1} & c_{3,1} & \chi_1 \\ c_{1,2} + \chi_2 \rho_0 V_2 T & c_{2,2} & c_{3,2} & \chi_2 \\ c_{1,3} + \chi_3 \rho_0 V_2 T & c_{2,3} & c_{3,3} & \chi_3 \\ \chi_1 \rho_0 V_2 T & 0 & 0 & \chi_1 \end{bmatrix}.$$

The speed V_2 is considered averaged over the periods of rotation of the workpiece in determining $V_2(L_2)$, and its variation of V_2 should not exceed the allowable values based on the requirements for surface roughness.

At the second stage, asymptotically stable trajectories are selected from this set $V_2(L_2)$. For this purpose it is necessary to calculate the equilibrium points $\mathbf{X}^* = \{X_1^*, X_2^*, X_1^*, Y_1^*\}^T$ and F_0^*, and after substitution of variables $\mathbf{X(t)} = \mathbf{X}^* + \mathbf{x(t)}$ and $F_0(t) = F_0^* + f(t)$ determine the equation in variations, linearize it and investigate by known methods [55–58]. The linearized equation in variations corresponding to (5) and (6) in the neighborhood of equilibrium is given in (11)

$$\mathbf{M d^2 z(t) / dt^2 + H dz(t) / dt + C z(t) = 0}, \tag{11}$$

where

$$\mathbf{z(t)} = \{x_1(t), x_2(t), x_3(t), y(t), f(t)\}^T; \quad \mathbf{M} = \begin{bmatrix} m & 0 & 0 & 0 & 0 \\ 0 & m & 0 & 0 & 0 \\ 0 & 0 & m & 0 & 0 \\ 0 & 0 & 0 & m_0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix};$$

$$\mathbf{H} = \begin{bmatrix} h_{1,1} & h_{2,1} & h_{3,1} & 0 & 0 \\ h_{1,2} & h_{2,2} & h_{3,2} & 0 & 0 \\ h_{1,3} & h_{2,3} & h_{3,3} & 0 & 0 \\ 0 & 0 & 0 & h_0 & 0 \\ 0 & 0 & -\rho\left(t_P^{(0)} - X_1^*\right) S_P^{(0)} \varsigma \mu \exp(-\varsigma V_3) & 0 & \dfrac{k S_P^{(0)} \left(t_P^{(0)} - X_1^*\right)}{V_3} \end{bmatrix};$$

$$\mathbf{C} = \begin{bmatrix} c_{1,1} & c_{2,1} & c_{3,1} & 0 & -\chi_1 \\ c_{1,2} & c_{2,2} & c_{3,2} & 0 & -\chi_2 \\ c_{1,3} & c_{2,3} & c_{3,3} & 0 & -\chi_3 \\ 0 & 0 & 0 & c_{4,4}(L_2) & -\chi_1 \\ \rho\{1 + \mu \exp(-\varsigma V_3)\} S_P^{(0)} & \rho\{1 + \mu \exp(-\varsigma V_3)\}\left[t_P^{(0)} - X_1^*\right] & 0 & \rho\{1 + \mu \exp(-\varsigma V_3)\} S_P^{(0)} & 1 \end{bmatrix}.$$

The synthesis procedure is illustrated by the example of turning a fuel system nozzle shaft made of steel 45. Length $L_2^{(0)} = 120$ mm, diameter 20 mm, modes: $t_p^{(0)} \le 2.0$ mm, $V_3 = 2.0$ mm/s. The parameters of the matrix of velocity coefficients and the dynamic coupling are given in Table 1 and Table 2, respectively. The generalized masses: $m = 0.5 \cdot 10^{-3}$ kg·s^2/mm, generalized mass m_0 and coefficient $h_{4,4}$ change when varying $c_{4,4}$ so that the natural frequency and damping coefficient of the workpiece subsystem remain constant.

The trajectories of stiffness $c_{4,4}(L_2)$, deformation displacements $\Delta_\Sigma(L_2)$, and velocity $V_2(L_2)$ providing $\Delta_\Sigma(L_2) = \text{const}$ are given as example in Fig. 2.

Depending on the parameters, the image point in Fig. 2 may intersect the figurative line. Then the trajectory $V_2(L_2)$ becomes unstable.

The loss of stability also depends on V_2 changing along L_2, that is tool wear. It is necessary to change the parameters of subsystems by design methods or to correct the cutting speed $V_P^{(0)} = V_3$ and the corresponding feed rate V_2 to ensure condition (10). Fig. 3 shows that with increasing speed, the stability

Table 1

Parameters of the matrix of velocity coefficients and elasticity

$h_{1,1}$	$h_{2,2}$	$h_{3,3}$	$h_{1,2} = h_{2,1}$	$h_{1,3} = h_{3,1}$	$h_{2,3} = h_{3,2}$	$h_{4,4}$
0.25	0.15	0.15	0.1	0.08	0.08	0.18
$c_{1,1}$	$c_{2,2}$	$c_{3,3}$	$c_{1,2} = c_{2,1}$	$c_{1,3} = c_{3,1}$	$c_{2,3} = c_{3,2}$	$c_{4,4}$
1000	800	800	200	100	100	200...300

Table 2

Parameters of the dynamic link

ρ, [kg/mm^2]	ς, m/s	T_0, c	μ
500	0.1	0.001...0.005	0.5

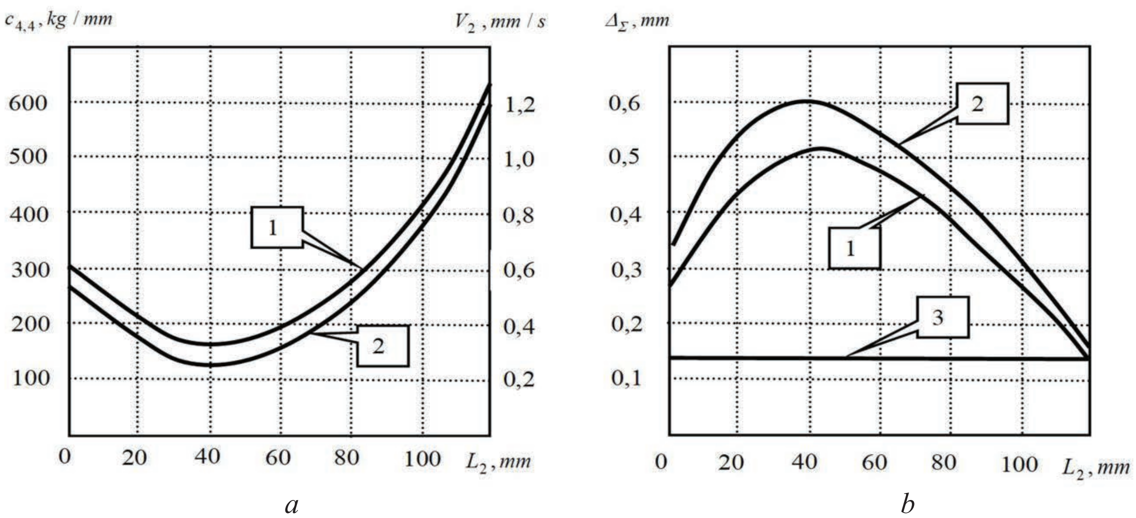

Fig. 2. Changing the properties of the system along the axis L_2:
a – trajectory of radial stiffness change $c_{4,4}$ (*1*) and rational feed rate trajectory V_2 (*2*); *b* – error caused by elastic deformations Δ_Σ at (1) – constant feed, at (*2*) – constant force, at (*3*) – feed rate control

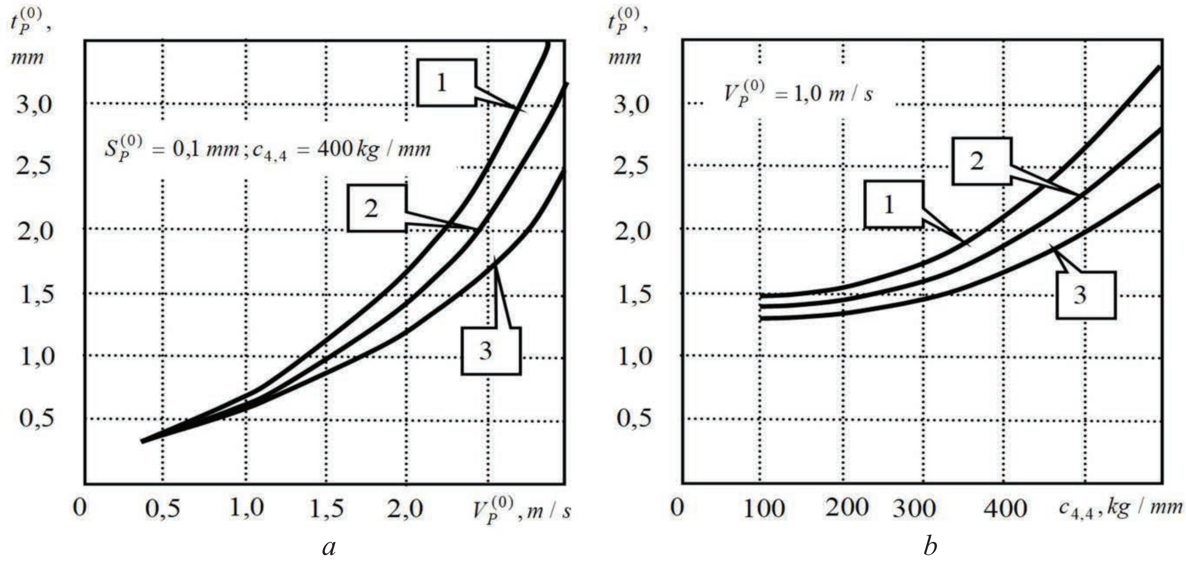

Fig. 3. Areas of stability of the "frozen" system at different values of wear w_0:
1 – $w_0 = 0.05$; *2* – $w_0 = 0.1$; *3* – $w_0 = 0.15$

area always expands. It was previously shown that, as the speed increases, parametric self-excitation is also observed in the system [11–13]. Therefore, when the velocity increases, there is its range, in which the stability margin is maximum.

At the third stage, the trajectories that provide a minimum tool wear intensity are selected from the set $\mathbf{\Psi}^{(L)}$. It is taken into account [29–32] that as the work is done, there is an evolutionary restructuring of the properties of the cutting process, including the intensity of tool wear. Moreover, each evolutionary diagram is unique. It depends on the initial parameters, modes and perturbations. Therefore, even its small variations correspond to excellent diagrams of wear and changes in the geometric characteristics of the workpiece surface formed by cutting.

Results and discussion

During cutting, there are changes in the properties of the dynamic system, determined by two reasons. Firstly, changes in the parameters of interacting subsystems: its stiffness, variations of the allowance, etc. These factors are a priori given. Secondly, the change in the properties of the dynamic coupling formed by cutting, which combines the subsystems, as well as the development of tool wear. These factors are determined by the capacity of irreversible transformations of the energy supplied to the cutting. It is important to emphasize that the properties of the dynamic cutting system during processing change even when the parameters of the subsystems (matrix of $\mathbf{m}$, $\mathbf{h}$ and $\mathbf{c}$) remain unchanged. Therefore, it is necessary to coordinate the TEE of the machine (the CNC program) with the changing cutting properties.

Depending on a priori set laws of variation of the system parameters, it is possible to determine the set of desired TEEs of the machine, at which the output requirements to the cutting process are provided and to select from this set asymptotically stable, i.e. attractors. The given example of selecting the trajectory of the longitudinal feed rate when processing a shaft, the change in the stiffness of which is set, allowed us to identify a number of properties.

1. If the dynamic cutting system is unperturbed and stiffness variations are the only parameter varying in space, the elastic strain displacements can be stabilized by software methods with high accuracy. In this case, stabilization of cutting forces leads to even larger diameter errors than uncontrolled machining at constant modes (Fig. 3). This is due to the self-regulating properties of the cutting process, in which the generated forces, represented in the state coordinates, play the role of an internal regulator of the machining diameter with negative feedback formed by the cutting process itself. If the main variable parameter is

allowance variation, then force stabilization by feed variation can fully compensate the effect of allowance variation on diameter accuracy. In all cases, it is necessary not to stabilize cutting forces, but to ensure the constancy of elastic deformations on the basis of its coordination with the law of cutting properties change and a priori specified disturbances.

2. The possibilities of controlling the accuracy of parts by varying the feed rate are limited. It follows from (4) that variations in the feed rate $S_P(t)$, which affects the cutting forces, depend both on the time window T in which the feed rate is integrated and on the velocities of $v_{X,2}(t)$. Usually, the natural frequencies of oscillatory loops, which are formed in the subsystems on the tool and workpiece side, are at least an order of magnitude greater than the rotation frequency of the workpiece. Then, when considering deformation displacements, we can limit ourselves to elastic reactions, and with this in mind, analyze the transformation of the feed rate into its value in the frequency domain. It is not difficult to obtain the amplitude-phase frequency response of $V_2(t)$ the transformation in $S_P(t)$ view of (10). First, let us give an expression for the transfer function

$$W_{V,S}(p)=\frac{S_P(p)}{V_2(p)}=\frac{1-\exp(-pT)}{p}\left\{1-\frac{A[1-\exp(-pT)]}{1+A[1-\exp(-pT)]}\right\}, \quad (12)$$

where $A=\frac{\rho_0 t_P^{(0)}}{c_0}$ is the dimensionless parameter of the influence of the cutting system on the transformation $V_2 \to S_P$; $c_0=\frac{\Delta_{X_2}}{\Delta}$;

$$\Delta_{X_2}=\begin{bmatrix} c_{1,1}+\chi_1\rho_0 V_2 T & \chi_1 & c_{3,1} & \chi_1\rho_0 V_2 T \\ c_{1,2}+\chi_2\rho_0 V_2 T & \chi_2 & c_{3,2} & \chi_2\rho_0 V_2 T \\ c_{1,3}+\chi_3\rho_0 V_2 T & \chi_3 & c_{3,3} & \chi_3\rho_0 V_2 T \\ \chi_1\rho_0 V_2 T & \chi_1 & 0 & c_{4,4}(L_2)+\chi_1\rho_0 V_2 T \end{bmatrix}.$$

Or after the obvious transformations we have

$$W_{V,S}(j\omega)=\left\{\frac{\sin(\omega T)}{\omega}-j\frac{1-\cos(\omega T)}{\omega}\right\}\{R(\omega)+jI(\omega)\}, \quad (13)$$

where

$$R(\omega)=1-\frac{A[1+2A][1-\cos(\omega T)]}{[1+A-A\cos(\omega T)]^2+A^2\sin^2(\omega T)}=\frac{1+A-A\cos(\omega T)}{[1+2A(1+A)(1-\cos(\omega T)]};$$

$$I(\omega)=\frac{A\sin(\omega T)}{[1+A-A\cos(\omega T)]^2+A^2\sin^2(\omega T)}=\frac{A\sin(\omega T)}{[1+2A(1+A)(1-\cos(\omega T)]}.$$

Examples of changes $W_{V,S}(j\omega)$ in the dimensionless frequency function $\Omega=\omega T$ are given at Fig. 4. The analysis of (13), as well as Fig. 4. allow to draw the following important conclusions. First, at variations in velocity $V_2(t)$ with the frequency of rotation of the workpiece, the deformation displacements of the tool relative to the workpiece are uncontrollable. Second, in the low-frequency region (up to a frequency of 0,1Ω), the feed variations $S_P(t)$ differ from the velocity $V_2(t)$ by a constant "T" factor. Then, there is rapid phase rotation and periodic, with monotonic decay of the maximum amplitude, variation of $S_P(t)$. The phase rotates between "0-π", which affects the dynamic properties, including stability. Third, the dynamic properties of the conversion $V_2(t)$ to forces depend not only on the properties of the drives, but also on the stiffness parameters of the tool and workpiece subsystems, as well as on the parameters of the dy-

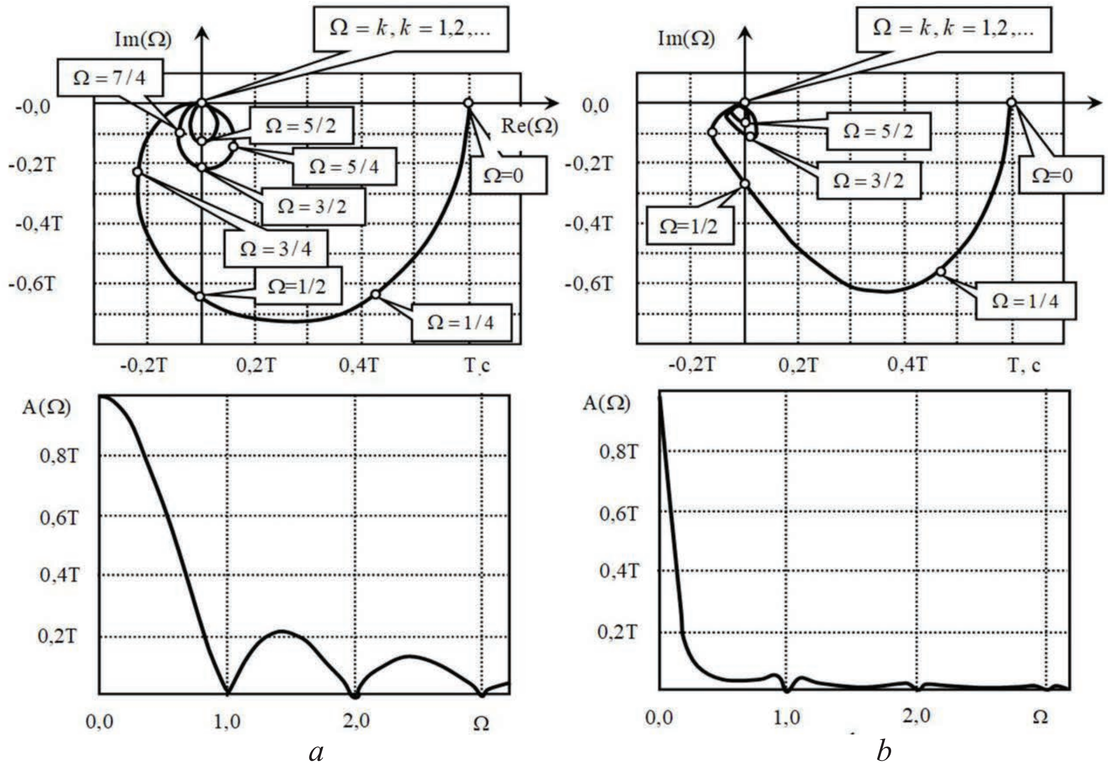

Fig. 4. Frequency conversion characteristics $V_2 \rightarrow S_P$:
$a - A = 0$; $b - A = 0.5$

namic coupling formed by the cutting process. For example, a decrease in the reduced stiffness causes an increase in the transient time. In Fig. 4 this is reflected in a decrease in the bandwidth of the system. Thus, when designing the desired feed path, its values should be averaged over several periods of rotation of the workpiece using sliding average algorithms.

Finally, the transformation $V_2 \rightarrow S_P$ that affects the cutting forces also depends on the rotational speed of the workpiece that sets the cutting speed, which is chosen on the basis of minimizing the intensity of tool wear.

Conclusions

When machining parts of complex geometry and having a priori set law of changing the stiffness of the workpiece, when determining the CNC program, it is necessary to perform its coordination with the changing properties of the system. An effective way of such coordination can be based on the synergistic paradigm of ensuring the coherence of external control with the changing internal dynamics of the cutting system. The proposed algorithm for such coherent control includes determining the desired trajectory and ensuring its asymptotic stability while minimizing the tool wear intensity. At the same time, the conditions of control feasibility, disclosed in the paper, which depend on the features of the dynamic cutting system, are taken into account.

References

1. Haken H. *Information and self-organization: a macroscopic approach to complex systems.* Amsterdam, Elsevier, 2006. 258 p. ISBN 978-3-540-33021-9. DOI: 10.1007/3-540-33023-2.

2. Prigogine I., George C. The second law as a selection principle: the microscopic theory of dissipative processes in quantum systems. *Proceedings of the National Academy of Sciences of the United States of America*, 1983, vol. 80, pp. 4590–4594.

3. Ebeling W. von, Engel A., Feistel R. *Fizika protsessov evolyutsii* [Physics of evolution processes]. Moscow, URSS Publ., 2001. 328 p.

4. Nikolis Dzh. *Dinamika ierarkhicheskikh sistem* [Dynamics of Hierarchical Systems]. Moscow, Mir Publ., 1989. 488 p.

5. Kolesnikov A.A. *Prikladnaya sinergetika: osnovy sistemnogo sinteza* [Applied synergetics: fundamentals of system synthesis]. Taganrog, SFU Publ., 2007. 384 p.

6. Kolesnikov A.A. *Sinergeticheskaya teoriya upravleniya* [Synergetic theory of control]. Moscow, Energoatomizdat Publ., 1994. 344 p. ISBN 5-230-24678-2.

7. Kolesnikov A.A., Kuzmenko A.A. Metod AKAR i teoriya adaptivnogo upravleniya v zadachakh sinteza nelineinykh sistem upravleniya [The ACAR method and the theory of adaptive control in problems of synthesis of nonlinear control systems]. *Mekhatronika, avtomatizatsiya, upravlenie = Mechatronics, Automation, Control*, 2017, vol. 18, no. 9, pp. 579–589. DOI: 10.17587/mau.18.579-589.

8. Kolesnikov A.A., Kolesnikov Al.A., Kuz'menko A.A. Metody AKAR i AKOR v zadachakh sinteza nelineinykh sistem upravleniya [Methods of ACAR and ACOR in problems of synthesis of nonlinear control systems]. *Mekhatronika, avtomatizaciya, upravlenie = Mechatronics, automation, control*, 2016, vol. 17, no. 10, pp. 657–669. DOI: 10.17587/mau.17.657-669.

9. Zakovorotniy V.L., Flek M.B., Pham D.T. Sinergeticheskaya kontseptsiya pri postroenii sistem upravleniya tochnost'yu izgotovleniya detalei slozhnoi geometricheskoi formy [Synergetic concept in the construction of precision control systems for manufacturing parts of complex geometric shapes]. *Vestnik Donskogo gosudarstvennogo tekhnicheskogo universiteta = Vestnik of Don State Technical University*, 2011, vol. 11, no. 10 (61), pp. 1785–1797.

10. Zakovorotny V.L., Gubanova A.A., Lukyanov A.D. Stability of shaping trajectories in milling: Synergetic concepts. *Russian Engineering Research*, 2016, vol. 36 (11), pp. 956–964. DOI: 10.3103/S1068798X16110216.

11. Zakovorotny V.L., Gubanova A.A., Lukyanov A.D. Parametric self-excitation of a dynamic end-milling machine. *Russian Engineering Research*, 2016, vol. 36 (12), pp. 1033–1039. DOI: 10.3103/S1068798X16120194.

12. Zakovorotny V.L., Gvindjiliya V.E. Influence of spindle wobble in a lathe on the tool's deformational-displacement trajectory. *Russian Engineering Research*, 2018, vol. 38 (8), pp. 623–631. DOI: 10.3103/S1068798X1808018X.

13. Zakovorotny V.L., Bykador V.S. Cutting-system dynamics. *Russian Engineering Research*, 2016, vol. 36 (7), pp. 591–598. DOI: 10.3103/S1068798X16070182.

14. Zakovorotny V.L., Flek M.B., Ugnich E.A. Synergetic approach to the modeling of industrial enterprise's economic activity. *International Journal of Economic Perspectives*, 2016, vol. 10 (4), pp. 371–375.

15. Zakovorotny V.L., Shapovalov V.V. Dinamika transportnykh tribosistem [Dynamics of transport tribosystems]. *Sborka v mashinostroenii, priborostroenii = Assembling in Mechanical Engineering, Instrument-Making*, 2005, no. 12, pp. 19–24.

16. Ryzhkin A.A. *Sinergetika iznashivaniya instrumental'nykh materialov pri lezviinoi obrabotke* [Synergetics of tool wear in cutting edge treatment]. Rostov-on-Don, Don State Technical University Publ., 2019. 289 p. ISBN 9785789016695.

17. Starkov V.K. *Fizika i optimizatsiya rezaniya materialov* [Physics and optimization of cutting materials]. Moscow, Mashinostroenie Publ., 2009. 639 p.

18. Migranov M.Sh. Issledovaniya iznashivaniya instrumental'nykh materialov i pokrytii s pozitsii termodinamiki i samoorganizatsii [Research of wear of tool materials and coatings from the positions of thermodynamics and self-organization]. *Izvestiya vysshikh uchebnykh zavedenii. Mashinostroenie = Proceedings of Higher Educational Institutions. Machine Building*, 2006, no. 11, pp. 65–71.

19. Karimov I.G. Vliyanie temperatury rezaniya na energeticheskie parametry kontakta instrumenta s detal'yu [Influence of the cutting temperature on the energy parameters of the tool contact with the part]. *Vestnik Ufimskogo gosudarstvennogo aviatsionnogo tekhnicheskogo universiteta = Vestnik USATU*, 2012, vol. 16, no. 44 (49), pp. 85–89.

20. Gomez-Solano J.R., July C., Mehl J., Bechinger C. Non-equilibrium work distribution for interacting colloidal particles under friction. *New Journal of Physics*, 2015, vol. 17, p. 045026. DOI: 10.1088/1367-2630/17/4/045026.

21. Banjac M. Friction and wear processes-thermodynamic approach. *Tribology in Industry*, 2014, vol. 36, no. 4, pp. 341–347.

22. Abdel-Aal H.A. Thermodynamic modeling of wear. *Encyclopedia of Tribology*. Boston, MA, Springer, 2013, pp. 3622–3636. DOI: 10.1007/978-0-387-92897-5_1313.

23. Duyun T.A., Grinek A.V., Rybak L.A. Methodology of manufacturing process design, providing quality parameters and minimal costs. *World Applied Sciences Journal*, 2014, vol. 30 (8), pp. 958–963. DOI: 10.5829/idosi.wasj.2014.30.08.14120.

24. Mukherjee I., Ray P.K. A review of optimization techniques in metal cutting processes. *Computers and Industrial Engineering*, 2006, vol. 50, no. 1–2, pp. 15–34. DOI: 10.1016/j.cie.2005.10.001.

25. Kozochkin M.P., Fedorov S.V., Tereshin M.V. *Sposob opredeleniya optimal'noi skorosti rezaniya v protsesse metalloobrabotki* [Method for determining the optimal cutting speed in the process of metalworking]. Patent RF, no. 2538750, 2015.

26. Zariktuev V.Ts. Avtomatizatsiya protsessov na osnove polozheniya ob optimal'noi temperature rezaniya [Automatization of process based on concept of optimal cutting temperature]. *Vestnik Ufimskogo gosudarstvennogo aviatsionnogo tekhnicheskogo universiteta = Vestnik USATU*, 2009, vol. 12, no. 4, pp. 14–19.

27. *Lapshin V.P., Khristoforova V.V., Nosachev S.V.* Vzaimosvyaz' temperatury i sily rezaniya s iznosom i vibratsiyami instrumenta pri tokarnoi obrabotke metallov [Relationship of temperature and cutting force with tool wear and vibrations in metal turning]. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2020, vol. 22, no. 3, pp. 44–58. DOI: 10.17212/1994-6309-2020-22.3-44-58.

28. Lapshin V., Moiseev D., Minakov V. Diagnosing cutting tool wear after change of cutting forces during turning. *AIP Conference Proceedings*, 2019, vol. 2188, p. 030001. DOI: 10.1063/1.5138394.

29. Begic-Hajdarevic D., Cekic A., Kulenovic M. Experimental study on the high speed machining of hardened steel. *Procedia Engineering*, 2014, vol. 69, pp. 291–295. DOI: 10.1016/j.proeng.2014.02.234.

30. Blau P., Busch K., Dix M., Hochmuth C., Stoll A., Wertheim R. Flushing strategies for high performance, efficient and environmentally friendly cutting. *Procedia CIRP*, 2015, vol. 26, pp. 361–366. DOI: 10.1016/j.procir.2014.07.058.

31. Chin C.-H., Wang Y.-C., Lee B.-Y. The effect of surface roughness of end-mills on optimal cutting performance for high-speed machining. *Strojniski Vestnik = Journal of Mechanical Engineering*, 2013, vol. 52 (2), pp. 124–134. DOI: 10.5545/sv-jme.2012.677.

32. Kant G., Sangwan K.S. Prediction and optimization of machining parameters for minimization power consumption and surface roughness in machining. *Journal of Cleaner Production*, 2014, vol. 83, pp. 151–164. DOI: 10.1016/j.jclepro.2014.07.073.

33. Martinov G., Martinova L., Ljubimov A. From classic CNC systems to cloud-based technology and back. *Robotics and Computer-Integrated Manufacturing*, 2020, vol. 63. DOI: 10.1016 / j. rcim.2019.101927.

34. Martinov G.M., Kovalev I.A., Grigoriev A.S. Approach to building an autonomous cross-platform automation controller based on the synthesis of separate modules. *Advances in Automation. RusAutoCon 2019*. Cham, Springer, 2020, pp. 128–136. DOI: 10.1007/978-3-030-39225-3_15.

35. Sosonkin V.L., Martinov G.M. Noveishie tendentsii v oblasti arkhitekturnykh reshenii sistem ChPU [Latest trends in the architecture of CNC systems]. *Avtomatizatsiya v promyshlennosti = Automation in Industry*, 2005, no. 4, pp. 3–9.

36. Martinov G.M., Sokolov S.V., Martinova L.I., Grigoryev A.S., Nikishechkin P.A. Approach to the diagnosis and configuration of servo drives in heterogeneous machine control systems. *Advances in Swarm Intelligence. ICSI 2017. Lecture Notes in Computer Science*. Ed. by Y. Tan, H. Takagi, Y. Shi, B. Niu. Cham, Springer, 2017, vol. 10386, pp. 586–594. DOI: 10.1007/978-3-319-61833-3_62.

37. Sang Z., Xu X. The framework of a cloud-based CNC system. *Procedia CIRP*, 2017, vol. 63, pp. 82–88. DOI: 10.1016/j.procir.2017.03.152.

38. Martinov G.M., Kozak N.V., Nikishechkin P.A. Reshenie zadachi rezervirovaniya v stankakh s chislovym programmnym upravleniem [Solution of the redundancy problem in numerical control machines]. *STIN = Russian Engineering Research*, 2018, no. 7, pp. 2–7. (In Russian).

39. Bazrov B.M., Balakshin B.S. *Adaptivnoe upravlenie stankami* [Adaptive control of machine tools]. Moscow, Mashinostroenie Publ., 1973. 688 p.

40. Zhdanov A.A., Plotnikov A.L., Tchigirinsky Ju.L., Firsov I.V. Matematicheskaya model' utochneniya rezhimov rezaniya dlya obespecheniya tochnosti tokarnoi obrabotki nezhestkikh valov na stankakh s ChPU [The mathematical model of corrections the cutting conditions to providing the precision of nonrigid shafts turning on CNC machines]. *Nauchnye trudy SWorld = Scientific papers SWorld*, 2015, vol. 3, no. 4 (41), pp. 41–47.

41. Nikishechkin P.A., Grigoriev A.S. Prakticheskie aspekty razrabotki modulya diagnostiki i kontrolya rezhushchego instrumenta v sisteme CHPU [Practical aspects of the development of the module diagnosis and monitoring of cutting tools in the CNC]. *Vestnik MGTU STANKIN = Vestnik MSTU STANKIN*, 2013, no. 4 (27), pp. 65–70.

42. Bobrovsky A.V., Drachev O.I. Tekhnologiya mekhanicheskoi obrabotki malozhestkikh osesimmetrichnykh detalei [Technology of processing of low-rigid axisymmetric details]. *Izvestiya Volgogradskogo gosudarstvennogo tekhnicheskogo universiteta = Izvestia of Volgograd State Technical University*, 2019, no. 9 (232), pp. 15–17.

43. Drachev O.I. Sistema avtomaticheskogo upravleniya ekspluatatsionnoi tochnost'yu dlinnomernykh valov [System of automatic control of operational accuracy of long-length shafts]. *Izvestiya Volgogradskogo gosudarstvennogo tekhnicheskogo universiteta = Izvestia of Volgograd State Technical University*, 2017, no. 5 (200), pp. 18–20.

44. Kazakov A.V., Zholobov A.A. Prognozirovanie i obespechenie tochnosti tokarnoi obrabotki stupenchatykh valov [Forecasting and ensuring the accuracy of stepped shafts turning]. *Vestnik Belorussko-Rossiiskogo universiteta = Bulletin of the Belarusian-Russian University*, 2014, no. 1 (42), pp. 6–14.

45. Kudinov V.A. *Dinamika stankov* [Dynamics of machine tools]. Moscow, Mashinostroenie Publ., 1967. 359 p.

46. Voronov S.A., Kiselev I.A. Nelineinye zadachi dinamiki protsessov rezaniya [Nonlinear problems of cutting process dynamics]. *Mashinostroenie i inzhenernoe obrazovanie = Mechanical engineering and engineering education*, 2017, no. 2 (51), pp. 9–23.

47. Gouskov A.M., Voronov S.A., Paris H., Batzer S.A. Nonlinear dynamics of a machining system with two interdependent delays. *Communications in Nonlinear Science and Numerical Simulation*, 2002, vol. 7, pp. 207–221. DOI: 10.1016/s1007-5704(02)00014-x.

48. Kao Y.-C., Nguyen N.-T., Chen M.-S., Su S.T. A prediction method of cutting force coefficients with helix angle of flat-end cutter and its application in a virtual three-axis milling simulation system. *The International Journal of Advanced Manufacturing Technology*, 2015, vol. 77, no. 9–12, pp. 1793–1809. DOI: 10.1007/s00170-014-6550-8.

49. Stepan G., Insperge T., Szalai R. Delay, parametric excitation, and the nonlinear dynamics of cutting processes. *International Journal of Bifurcation and Chaos*, 2005, vol. 15, no. 9, pp. 2783–2798. DOI: 10.1142/S0218127405013642.

50. Corpus W.T., Endres W.J. Added stability lobes in machining processes that exhibit periodic time variation – Part 1: An analytical solution. *Journal of Manufacturing Science and Engineering*, 2004, vol. 126, pp. 467–474. DOI: 10.1115/1.1765137.

51. Peigne G., Paris H., Brissaud D., Gouskov A. Impact of the cutting dynamics of small radial immersion milling operations on machined surface roughness. *International Journal of Machine Tools and Manufacture*, 2004, vol. 44, pp. 1133–1142. DOI: 10.1016/j.ijmachtools.2004.04.012.

52. Hasnul H., Tajul L., Zailani Z.A., Hamzas M.F.M.A., Hussin M.S. The parametric effect and optimization on JIS S45C steel turning. *International Journal of Engineering Science and Technology*, 2011, vol. 3, no. 5, pp. 4479–4487.

53. Rusinek R., Wiercigroch M., Wahi P. Influence of tool flank forces on complex dynamics of a cutting process *International Journal of Bifurcation and Chaos*, 2014, 24 (9), pp. 189– 201. DOI: 10.1142/S0218127414501156.

54. Rusinek R., Wiercigroch M., Wahi P. Modeling of frictional chatter in metal cutting. *International Journal of Mechanical Sciences*, 2014, vol. 89, pp. 167–176. DOI: /10.1016/j.ijmecsci.2014.08.020.

55. Zakovorotny V.L., Gvindjiliya V.E. Svyaz' samoorganizatsii dinamicheskoi sistemy rezaniya s iznashivaniem instrumenta [Link between the self-organization of dynamic cutting system and tool wear]. *Izvestiya vysshikh uchebnykh zavedenii. Prikladnaya nelineinaya dinamika = Izvestiya VUZ. Applied Nonlinear Dynamics*, 2020, vol. 28, no. 1, pp. 46–61. DOI: 10.18500/0869-6632-2020-28-1-46-61.

56. Zakovorotny V.L., Gvindjiliya V.E. Bifurkatsii prityagivayushchikh mnozhestv deformatsionnykh smeshchenii rezhushchego instrumenta v khode evolyutsii svoistv protsessa obrabotki [Bifurcations of attracting sets of cutting tool deformation displacements at the evolution of treatment process properties]. *Izvestiya vysshikh uchebnykh zavedenii. Prikladnaya nelineinaya dinamika = Izvestiya VUZ. Applied Nonlinear Dynamics*, 2018, vol. 26, no. 5, pp. 20–38. DOI: 10.18500/0869-6632-2018-26-5-20-38.

57. Lapshin V.P., Turkin I.A., Khristoforova V.V. Assessment of metal wear in turning on the basis of components of the cutting force. *Russian Engineering Research*, 2020, vol. 40, no. 9, pp. 797–800.

58. Zakovorotny V.L., Gvindjiliya V.E. Vliyanie dinamiki rezaniya na vybor tekhnologicheskikh rezhimov, obespechivayushchikh minimal'noe iznashivanie rezhushchikh instrumentov [Influence of cutting dynamic on the selection of the technological regimes to ensure minimal wear of cutting tools]. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2020, vol. 22, no. 4, pp. 54–70. DOI: 10.17212/1994-6309-2020-22.4-54-70.

Conflicts of Interest

The authors declare no conflict of interest.