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Influence of stiffness of the mechanical part of the drive and cutting parameters on the shaping elastic deformation control

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Introduction. One of the ways to improve the accuracy of manufacturing parts by cutting is related to the control of elastic deformations of the tool and the workpiece. This is particularly true for slender parts, whose stiffness law along the tool path is given. In this case, the control parameter, as a rule, is the return flow rate, which affects the cutting forces, whose change causes variations in elastic deformations. To provide the specified accuracy of the diameter, it is required to coordinate the controlled trajectory of the feed drive speed with the feed rate and a priori given law of change in the stiffness of the workpiece or the law of variation of the cutting process parameters. To do this, it is required to determine the law of converting the engine speed into the feed rate, and, ultimately, into elastic deformations. This law depends on the stiffness of the mechanical part of the feed drive and the changing parameters of the cutting process.

Materials and Methods. The paper presents mathematical modeling and, on its basis, analysis of the conversion of the feed rate into cutting forces, taking into account the final stiffness value of the mechanical part of the drive and the evolutionary parameters of the cutting process.

Results. It is shown that, starting from a certain critical value, the law of converting the feed rate into cutting forces becomes fundamentally dependent on the stiffness of the mechanical part of the drive. At the same time, there is an increase in time for setting a new force value when the feed rate varies, which affects the accuracy of providing forces that are consistent with the stiffness law of the part. The paper presents algorithms for calculating elastic deformations for a given stiffness law, as well as algorithms for calculating the trajectory of the feed rate at which the deformations remain constant. It is shown that the law of conversion is also affected by variations in the cutting parameters.

Discussion and Conclusion. The frequency and time characteristics of the conversion are discussed. A conclusion is made about the accuracy of the diameter formed through cutting, depending on the stiffness of the mechanical part of the feed drive and on some parameters of the cutting process.

Keywords: cutting forces, control of elastic deformations, stiffness of the mechanical part of the feed drive.

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Introduction. The synergetic paradigm has provided a revision of many approaches to the analysis of the properties of systems interacting with different environments [1−19]. It is used under the study of the cutting process as a single nonlinear dynamic system, which considers various physical processes that characterize the state of the system [10–18]. The system-synergetic approach forms the basis of the synergetic control theory, as well as the control of processing on machine tools [18–24]. In this case, the external control is coordinated with the internal cutting dynamics [23−25]. The problems of synergetic matching are relevant when processing slender parts, for which the law of its change along the toolpaths is set a priori [13, 26–29]. In all these cases, it is required to control the elastic deformation displacements of the tool tip and the workpiece at the point of contact with the tool. It should be noted that the errors in the geometric topology of the part formed by cutting are 60-80% due to elastic deformation displacements of the cutting system elements [11, 13, 30]. The main directions of improving the control systems of machining are associated with the integration of the machine itself and the computer [30−33]. The problem of controlling the elastic deformation displacements of the tool and the workpiece is formulated in [34]. Finally, the synergetic approach to the analysis and synthesis of control systems for machining processes formulated in [23−25], set the task of building control systems for processing on CNC machines based on the coordination of the program of the machine executive elements and the evolutionarily changing properties of the cutting process. This approach is also used to improve control systems for drilling deep holes of small diameter, as well as to provide the stability of the trajectories of forming movements [25, 35]. Thus, both when controlling the treatment processes on machine tools and when programming the trajectories of forming movements, it is required to know the laws of transforming the controlled trajectories of the machine operating elements into cutting forces, and, as a result, with the given elastic properties of the tool and workpiece subsystems – into their elastic deformations. They directly affect the accuracy parameters of the part-making. The laws of transformation are affected by the rigidity of the mechanical part of the drives of the machine actuators and the parameters that characterize the state of the cutting process. The research given in the paper considers the impact of these parameters on the conversion of programmable trajectories of servomotors into cutting forces. It is aimed at improving the efficiency of control over the precision of parts manufacturing.

Materials and Methods. Consider the longitudinal turning of a shaft of uniform diameter, in which the law of variation of its rigidity in the direction normal to the axis of rotation is given (Fig. 1). When describing the transformation of the trajectories of servomotors into forces acting on the tool, we accept the following hypotheses:

1. Consider the case in which stiffness $c(L)$ of the workpiece set along the axis of rotation is an order of magnitude less than the stiffness of the tool subsystem (Fig. 1). Therefore, the deformations of the tool relative to the machine bearing system can be neglected.

2. We will assume that the rotation paths of the spindle and the caliper drive are set and controlled within the bandwidth of the servomotors. The inertia of the mechanical part of the feed drive is related to the rotor of the feed motor. It affects the transients in the servomotor.

3. The reaction to the speed of the servomotors from the cutting process is neglected. This is true if the cutting power given to the motor rotors is significantly less than the power of the servomotors.

4. We will consider, in addition to the elasticity of the workpiece, the elasticity of the entire mechanical part of the feed drive, which we will take into account through the generalized stiffness c_0. Since there is no reversal of the feed drive during processing, stiffness c_0 can be considered constant over the entire trajectory of the caliper.

5. For the formation of forces at a constant cutting speed, we assume the hypothesis of their dependence on the area of the cut layer. The delay of forces in relation to the change in the cross-section area is neglected [23–24].

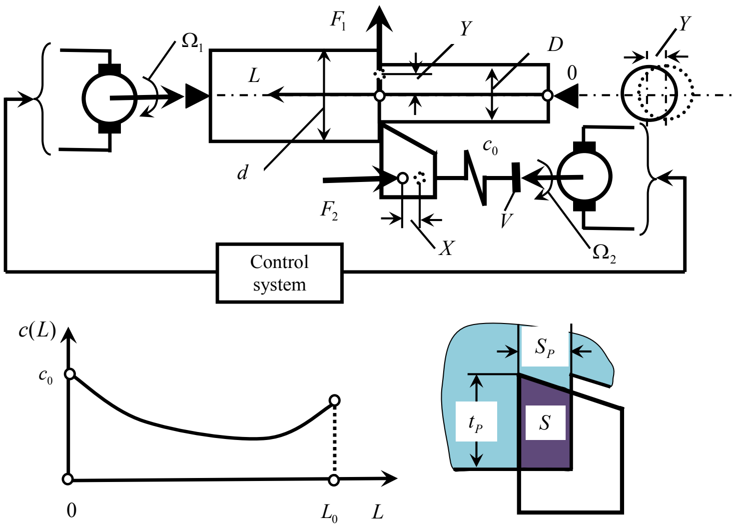

Fig. 1. Diagram of the dynamic system for converting the trajectories of the machine actuators into cutting forces

Then the cutting force modulus is proportional to the area of the cut layer

$$\mathrm{F(t)} = F_0\{\chi_1, \chi_2\}^T, \quad (1)$$

where $F_0 = \rho S$ — cutting force modulus in $[kg]$;

ρ — chip pressure on the front surface of the tool in $[kg/mm^2]$;

S — area of the cut layer in $[mm^2]$;

χ_1, χ_2 — nondimensional coefficients. The relationship between the feed rate V and the elastic deformation displacements X and Y is determined from the system (Fig. 1).

$$\begin{cases} c_0 X = \chi_2 \rho (t_P - Y) \int_{t-T}^{t} [V(\xi) - v(\xi)] d\xi; \\ c(L) Y = \chi_1 \rho (t_P - Y) \int_{t-T}^{t} [V(\xi) - v(\xi)] d\xi, \end{cases} \quad (2)$$

where $v(t) = dX/dt$; $V(t) = k\Omega_2(t)$;

k — coefficient that determines the relationship between the speed of the feed drive and the speed of the caliper in $[mm]$.

Frequencies Ω_1 and Ω_2 are considered in $[c^{-1}]$. Therefore, the time T in the integral operator of the feed formation is $T = (\Omega_1)^{-1} = const$.

It is convenient to study the conversion of feed rate to cutting forces in the frequency domain. To do this, we can use the Laplace and Fourier transforms [36]. However, system (2) has not only retarded arguments, but also multiplicative terms. The use of the Laplace and Fourier transform methods is possible only for linear systems. Therefore, the study is carried out in two stages. At the first stage, in (2), we put $Y \to 0$ in comparison with the cutting depth t_P. Then we analyze the conversion of the feed rate to forces based on the expression

$$c_0 X = \chi_2 \rho t_P \int_{t-T}^{t} [V(\xi) - v(\xi)] d\xi. \quad (3)$$

It is not difficult to show that the transfer function $W(p) = F(p)/V(p)$ is equal to

$$W(p) = c_\Sigma \frac{1 - exp(-Tp)}{p} \frac{1}{1 + \frac{c_\Sigma}{c_0}[1 - exp(-Tp)]} \quad (4)$$

where $c_{\Sigma} = \rho t_P \chi_2$ makes sense of the rigidity of the cutting process. Expression (4) enables to find out the frequency properties of the conversion of the feed rate V to the cutting force F depending on the nondimensional parameter $A = c_{\Sigma} / c_0$. This parameter determines the ratio of the cutting process rigidity to the rigidity of the mechanical part of the feed drive. At $A \to 0$, the transfer function is $W(p) \Rightarrow c_{\Sigma} \frac{1 - exp(-Tp)}{p}$. At $A \to \infty$ $W(p) \Rightarrow \frac{c_{\Sigma}}{p}$. These are two extreme cases. If the case $A \to 0$ is possible with a significant increase in the rigidity of the mechanical part of the drive compared to the rigidity of the cutting process, then the second case requires reducing the rigidity of the drive to zero, which is impossible for real systems. We give examples $W(j\omega)$ for different A (Fig. 2). The amplitude is considered per unit к $c_{\Sigma} = 1$.

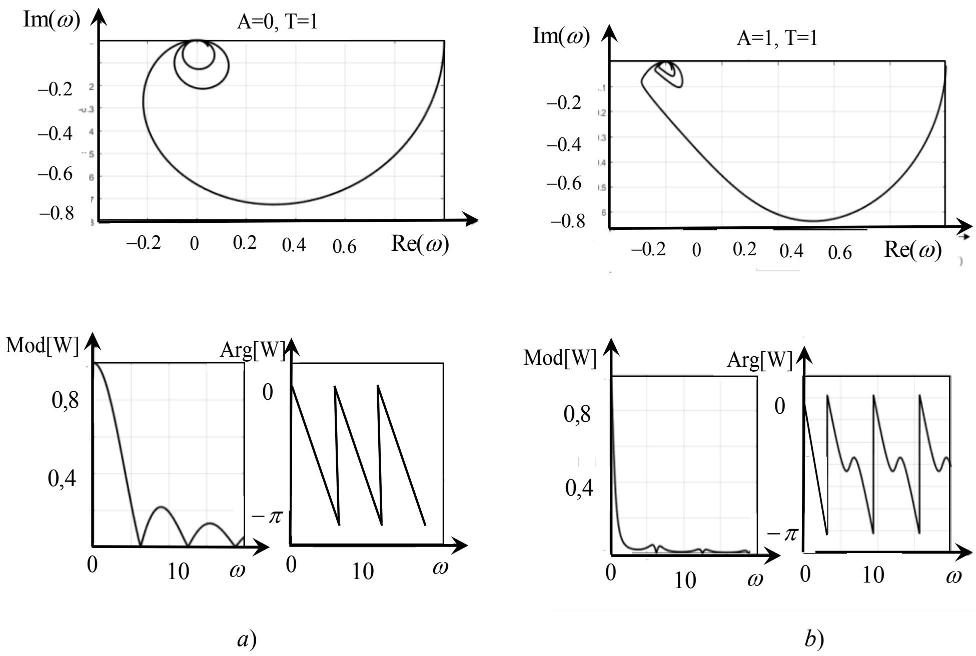

Fig. 2. Example of frequency characteristics of feed rate conversion to the cutting force module

First, let us consider the case when there are no deformations of the mechanical part between the rotor of the feed motor and the movement of the caliper (Fig. 2a). This frequency response is due to the property of the integral operator $\int_{t-T}^{t} V(\xi)d\xi$ for generating the feed rate, which discloses that the feed rate is the path traveled by the tool relative to the workpiece during the period of its rotation. Naturally, the components of the feed rate variation, whose frequency is equal to or a multiple of the workpiece rotational speed, after integration, turn to zero. These are frequencies at which $Mod[W(j\omega)] = 0$ (Fig. 2). In this case, there is a rapid rotation of the phase at frequencies close to the workpiece rotational frequency, which contributes to the self-excitation of the cutting process control systems. An increase in the compliance of the mechanical part of the drive corresponds to a change in the frequency properties of the conversion of speed into cutting forces. First, the bandwidth of this transformation is noticeably reduced, which should help to increase the transition time when setting a new value of the controlled cutting forces. Second, periodic phase variations are observed in the region of greater amplitude attenuation. Finally, with even greater increases in compliance, the characteristics of the speed-to-force conversion approach the integrator. The transient delaying mechanism is based on the redistribution of forces that affect the deformation displacements, and the deformation displacements that affect the forces. This functionally related process depends on the rigidity of the mechanical part of the feed drive.

The above analysis also enables to estimate the impact of deformation displacements of the workpiece in the direction of the axis of rotation on the dynamics of the conversion of speed V into cutting forces (Y direction in Fig. 1). It is obvious that when the stiffness c decreases, parameter A that affects the dynamics of the conversion of the feed rate into cutting forces also decreases.

Algorithm for calculating the feed rate trajectory. To provide the specified diameter values through controlling the deformation Y, it is required to select such trajectories of velocity at which V at which $Y = const$. For this purpose, instead of the integral operator in (2), let us consider its primitive, that is,

$$\begin{cases} c_0 X = \chi_2 \rho(t_P - Y)[L(t) - L(t-T) - X(t) + X(t-T)]; \\ c(L)Y = \chi_1 \rho(t_P - Y)[L(t) - L(t-T) - X(t) + X(t-T)], \end{cases} \quad (5)$$

where $L(t)$ — the trajectory of the caliper movement without taking into account elastic deformations, that is, $L(t) = \int_0^t V(\xi)d\xi$. В (5) $L(t) - L(t-T) = S_P^{(0)}(t)$ — the current feed value without taking into account deformation displacements. If $c(L) = const$ and the steady state is considered ($X(t) = X(t-T)$), then $S_P^{(0)} = S_P = VT$. Here, $S_P(t) = S_P^{(0)} - [X(t) - X(t-T)]$. We emphasize that the feed value $S_P^{(0)}$, which is assessed traditionally, differs from its real value $S_P(t)$.

We will calculate the deformation displacements in (5) sequentially after each turn of the workpiece and determine the sequences $\mathrm{X(iT)} = \{X(0), X(T), ...X(nT)\}$, $\mathrm{Y(iT)} = \{Y(0), Y(T), ...Y(nT)\}$, $\mathrm{S_P(t)} = \{S_P(T), ...S_P(nT)\}$, $\mathrm{c(T)} = \{c[S_P(T)], ...c[(\sum_{i=1}^{i=n} S_P(iT)]\}$. Thus, for n revolutions of the workpiece, the caliper travels the distance $L(n) = \sum_{i=1}^{i=n} S_P(iT)$. In these sequences, $X(0) = Y(0) = 0$. The solution to two problems can be considered.

The first task of analysis, i.e., determining the trajectories of deformation displacements $\mathrm{X(iT)}$ and $\mathrm{Y(iT)}$ at a constant feed rate. To calculate values $X(T), Y(T)$ and subsequent values of deformation displacements $X(iT), Y(iT)$, we can use the relations in which all the previous values are known $X[(i-1)T)], Y[(i-1)T)]$, as well as $c[(\sum_{l=1}^{l=i-1} S_P(lT)]$. Here, $V = const$, it follows that $c[(\sum_{l=1}^{l=i-1} S_P(lT)] = (c(iS_P)$. Thus, for calculating $X(iT), Y(iT)$ we can use the system

$$\mathrm{c}_\Sigma \mathrm{Z}^{(i)} = \mathrm{F}^{(i)}, \quad (6)$$

where $\mathrm{Z}^{(i)} = \{Y(iT), X(iT)\}^T$; $\mathrm{F}^{(i)} = \rho S_P^{(0)}[t_P + X((i-1)T)]\{\chi_2, \chi_1\}^T$;

$$\mathrm{c}_\Sigma = \begin{bmatrix} c_0 + \chi_2 \rho t_P & \chi_2 \rho S_P^{(0)} \\ \chi_1 \rho t_P & [(c(iS_P) + \chi_1 \rho S_P^{(0)} \end{bmatrix}.$$

In (5), the multiplicative terms of the deformation displacements, which are small quantities, are omitted. At a given speed $V = const$, we are primarily interested in the law of variation of deformation displacements $\mathrm{Y(iT)} = \{Y(0), Y(T), ...Y(nT)\}$, which characterizes the error of the diameter. On the basis of (6) for deformation displacements $Y(iT)$, that directly affect the diameter of the part, we obtain

$$Y(iT) = \frac{\chi_2 \rho c(iS_P) S_P^{(0)} \{t_P + X[(i-1)T)]\}}{c_0 c(iS_P) + \chi_1 \rho c_0 S_P + \chi_2 \rho c(iS_P) t_P}. \quad (7)$$

Thus, $Y(iT)$ depend not only on the law of the distribution of the stiffness of the workpiece $c(L)$ along the cutting path L, but also on $\partial c(L)/\partial L$, that affects $Y(t-T)$. The cutting forces, hence diameter D, are affected by the chip pressure ρ. It changes, for example, as the tool wear increases, due to its geometry variation, processing conditions and properties of the processed material.

The second task of synthesis, i.e., determining the sequence $\mathrm{S_P(t)} = \{S_P(T), ...S_P(nT)\}$ and the corresponding speed $V(t)$ in such a way that the condition $Y(iT) = const,\ Y(iT) \in \mathrm{Y(iT)}$ is met. This is the condition for the consistency of diameter under a given law $c(L)$, other conditions unchanged. Note that the constant components in the deformation displacements $\mathrm{Y(iT)}$ are not of fundamental importance, since they can be taken into account using the static tool setup [34]. To determine the law of variation in the feed value at each turn of the workpiece according to the criterion of the consistency of diameter, it is required to put $Y(iT) = const$ in (7). Then we need to calculate the sequence $S_P(t)=\{S_P(T),...S_P(nT)\}$. The procedure for calculating on i-th turn of the workpiece is to determine $S_P(iT)$, provided that the following parameters are specified $X(iT)=\{X(0),X(T),...X[(i-1)T]\}$, $Y(iT)=\{Y^*(0),Y^*(T),...Y^*[(i-1)T]\}$, therefore, all feed values are determined $S_P(t)=\{[S_P(T)=Y(T)-Y(0)],...S_P[(i-n)T=[Y((i-1)T)-Y((i-2)T)]\}$. From (7), we obtain

$$S_P(iT)=\frac{Y^*c[(\sum_{l=1}^{l=i-1}S_P(lT)]\{c_0+\chi_2\rho t_P\}}{\chi_1\rho c_0\{t_P+X[(i-1)T]-Y^*\}}, \qquad (8)$$

where $Y^*=const$ — the specified value of elastic deformation displacements.

In (8), the workpiece stiffness value is taken as the average for each feed. Then, based on the calculated $S_P(t)=\{S_P(T),...S_P(nT)\}$, the law of variation $V(t)$ and, consequently, the programmable trajectory of the feed rate in time or path are determined. The trajectory $V(t)$ is calculated based on the solution to inverse problems of dynamics [37–38].

Research Results. To provide accuracy of the production of low-rigidity shafts, it is required to coordinate the trajectories of the machine actuators with the changing rigidity of the workpiece along the toolpath. The alignment must also be performed if the evolutionary changes in the properties of the cutting process are taken into account, e.g., due to tool wear or thermodynamic processes, as well as regular perturbations, for example, variations in the allowance. For this purpose, first of all, you need to know the laws of converting the programmable feed rate of the caliper into cutting forces and then into the deformations themselves, which change the current value of the workpiece diameter. The performed studies have shown that the transformation law depends on the parameters of the stiffness of the interacting subsystems and the parameters of the dynamic coupling formed by the cutting process.

Among the stiffness parameters, the stiffness characteristics of the mechanical part of the feed drives are of fundamental importance, which can be estimated by the total reduced stiffness c_0. It changes the amplitude-phase frequency (AFF) response of the conversion of the feed rate to the cutting force (Fig. 2). As you can see, decreasing the drive stiffness significantly reduces the amplitude as the frequency increases, and the initial AFF, which had noticeable spikes, is converted into a characteristic with amplitude attenuation. This characteristic causes the transformation of vibrational transients into monotonic, close to aperiodic ones. As c_0 decreases, there is a decrease in the cutoff frequency in the conversion of the feed rate into cutting forces (Fig. 2), therefore, the transition time increases, e.g., the change in the cutting force when cutting the tool. Figure 3 shows changing the transients of force F_0 setting under turning a shaft made of 20X steel with a diameter of 80 mm. Turning is performed at the following modes: cutting speed is 4.0 m/s (spindle speed —1000 rpm), cutting depth t_P — 2.0 mm, feed rate S_P — 0.1 mm. for this case, $\rho=400\ kg/mm^2$

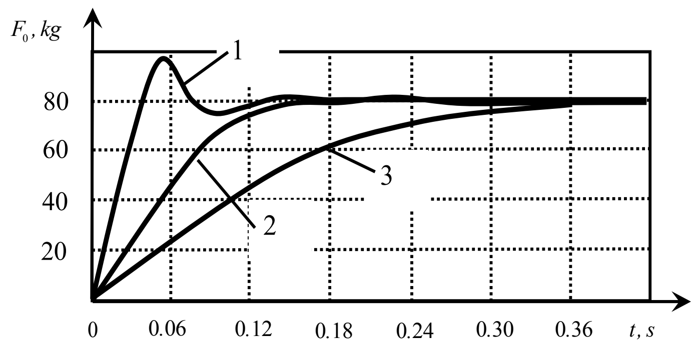

Fig. 3. Example of a change in the transient processes of establishing force –

F_0: 1 — c_0 = 1000 kg/mm, 2 — c_0 = 750 kg/mm, 3 — c_0 = 500 kg/mm

From the above-mentioned properties of the integral operator for the formation of the feed value, an important conclusion follows on the possibility of controlling the cutting forces, therefore, the elastic deformation displacements of the tool relative to the workpiece. When the feed rate is changed, the frequency components of the disturbances, equal to or multiples of the workpiece rotation frequency, get out of control by varying the feed drive speed. For example, these are variations in the allowance due to misalignment of the workpiece installation, radial spindle runouts, etc. Besides, the data show that the transients of the feed rate-to-force conversion also depend on the parameters of the dynamic coupling formed by the cutting process, and primarily — on the chip pressure parameter on the front surface of the tool. This parameter changes as tool wear develops. The dynamics of the transformation of the trajectories of the machine actuators into cutting forces are affected by all the factors that connect the cutting forces with the area of the cut layer. These factors limit the ability to control accuracy of manufacturing parts through varying the trajectories of the machine actuators. This applies primarily to the processing of parts of complex geometry.

Discussion and Conclusions. One of the ways to improve accuracy of manufacturing parts on machine tools is associated with the alignment of the CNC program with the changing dynamic properties of the cutting process. Moreover, these changes can be set a priori. For example, the law of variation in the stiffness matrices along the trajectory of the machine actuators can be set a priori. They can develop according to some random law, for example, due to the development of tool wear. In many cases, precision control is based on changes in the elastic deformation displacements of the tool and the workpiece. As shown in the paper, the law of transformation of the feed rate into cutting forces and elastic deformation displacements, first, depends on the elastic parameters of the mechanical part of the feed drives affecting not only the time of transients, but also their shape. Secondly, the regularities of the transformation of the feed rate into forces depend on the evolution of the parameters of the interacting subsystems on the part of the tool and the workpiece, as well as the parameters of the dynamic connection formed by cutting. The disclosed transformation patterns enable not only to find out the limitations imposed by the cutting system on the accuracy control capabilities, but also to increase their accuracy.

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V. L. Zakovorotny: basic concept formulation; research objectives and tasks; academic advising; analysis of the research results. V. E. Gvindjiliya: simulation of the cutting process; text preparation; formulation of conclusions. A. A. Zakalyuzhny: computational analysis; modeling of frequency and transient characteristics.

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