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Influence of dynamic characteristics of the turning process on the workpiece surface roughness

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ABSTRACT

Introduction. The formation of the surface of a part when processing it on a metal-cutting machine is based on properly selected cutting modes. Complex methods of ensuring the specified quality of the part surface also take into account the tool geometry, its condition, and include corrections for tool deviation from the trajectory set by the *CNC* system under the influence of kinematic disturbances and spindle wavering. **Subject.** The paper analyzes the relationship between cutting modes and dynamic characteristics of the turning process, and its mapping into surface roughness. **The aim of the work** is to evaluate the influence of technological cutting modes taking into account the vibration activity of the tool on the roughness of the machined surface by means of simulation modeling. **Method and methodology.** Mathematical simulation of the dynamics of the cutting process is given, on the basis of which a digital simulation model is built. A methodology of using the simulation model for determining optimal cutting modes and predicting surface roughness taking into account tool vibrations is proposed. By means of experiments and analysis of the frequency characteristics of tool vibrations, the created model is validated, parameters of the cutting forces model subsystem and dynamic tool subsystem are specified, and geometrical topologies of the part surface are constructed. The calculated cutting forces are compared with experimental forces, and similar patterns and levels of characteristics are observed. An assessment of the optimality of the selected cutting modes is proposed based on the analysis of the tool vibration spectrum relative to the workpiece and the results of the numerical model simulation. **Results and Discussion.** A comparison of the results of digital modeling of the geometrical surface of the workpiece and the real surface obtained during the field experiment is given. It is shown that the roughness of the real surface obtained by machining with constant cutting modes varies relative to the surface roughness of the simulation model within the limits of not more than 0.066 µm.

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Introduction

The problems of forming the required geometric profile of the surface of the part, taking into account its microrelief, deviations from linear dimensions and waviness, are particularly relevant to the engineering and aerospace industries. The solutions to this problem are based on the processing of experimental data, which results in empirical dependencies [1]. These empirical dependencies identified three main factors that affect the formation of the surface of a part during machining: the initial surface shape, the cutting tool geometry, perturbations such as runout from the spindle group, and kinematic perturbations from the drive group [1–4]. The next step in improving the methods of analyzing and predicting the geometrical profile of the surface of a part was the technological provision of parameters of its surface layer condition

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[5–10]. However, tool trajectories are determined not only by technological cutting modes, but also by deformation displacements of the tool relative to the workpiece, as well as vibrations, the source of which are oscillations caused by the regenerative effect [11–15].

Complex techniques for solving the problem of ensuring a given part surface quality and its prediction have been considered in many empirical and analytical studies. Attempts have been made to analyze and predict surface roughness based on regression models and response surface methodology (*RSM*) [16–18]. A great deal of current research is aimed at predicting surface roughness by means of artificial intelligence systems and simulation models [19–23]. In the works [21–23] *Y. Altintas et al.* consider the creation of simulation models of the dynamics of the cutting process, which are based on the analytical representation of the mutual influence of cutting parameters on the dynamics of machining and experimental identification of the coefficients of dynamic cutting forces in the resulting patterns. National studies consider a neural network model of the cutting tool kinematics, which allows the calculation of the optimal cutting speed according to the criterion of minimizing the tool wear intensity [24]. The complex simulation of the milling process with the estimation of the trajectory of formative tool motions is presented in [25]. The analytical dependence of the surface roughness on the elastic deformation displacements of the tool relative to the workpiece is presented [26]. In [27], a methodology for constructing the geometrical topology of the workpiece surface is proposed to evaluate the influence of tool deformation displacements on the geometrical profile of the workpiece based on stroboscopic *Poincaré* mapping. Taking into account the dependence of the dynamic link parameters on vibrations in the mathematical description of the dynamics of the cutting process is a necessary condition for simulating and predicting the output characteristics of part machining [28–31], since as a result of vibrations, a real change in the trajectory of the forming motions of the tool relative to the workpiece is observed.

The analysis of the research has shown the relevance and attention of scientists to the issues of creating various methods for evaluating and predicting the surface roughness of a part during machining. This paper proposes to consider the analytical dependence of cutting forces on technological modes, taking into account disturbance influences and tool deformation displacements. The geometrical topology of the workpiece surface is considered as a pointwise representation of the tool tip in the workpiece space, taking into account vibrations and deformation displacements. The aim of the work is to evaluate the influence of the properties of the dynamic characteristics of the cutting process on the geometry of the workpiece surface using simulation study of the dynamics of the cutting process.

Research methodology

Determination of the formative tool path

Let's consider a dynamic system of longitudinal turning of a non-deformable workpiece. The system model is represented in the form of a spatial finite-dimensional model of the motion of the tool tip interacting with the workpiece**.** The interaction is described by cutting forces, which are functions of tool deformation displacements $\boldsymbol{X} = \{X_1, X_2, X_3\}^T \in \Re^{(3)}$ and technological cutting modes (fig. 1, *a*).

Therefore, by considering the total cutting force $F_\Sigma(X)$ in the system model, a feedback between the dynamics of the cutting process and the tool subsystem is formed. This feedback can either stabilize the cutting process or lead to a loss of stability.

$$\boldsymbol{m}\frac{\boldsymbol{d^2X}}{\boldsymbol{dt^2}} + \boldsymbol{h}\frac{\boldsymbol{dX}}{\boldsymbol{dt}} + \boldsymbol{cX} = \boldsymbol{F}_\Sigma\left(X, t_P^{(0)}, S_P^{(0)}, V_P^{(0)}\right) \tag{1}$$

where ***m***, *kgs*^{2}*/mm;* ***h***, *kg*^{2}*/mm;* ***c***, *kg/mm* are symmetric, diagonal positive definite inertia, dissipation and stiffness matrices with dimension [3×3]; $\boldsymbol{X} = \{X_1, X_2, X_3\}^T \in \Re^{(3)}$ is the vector of elastic deformation displacements of the tool relative to the machine tool bearing system in space $\Re^{(3)}$, system state coordinates; $F_\Sigma(X, t_p^{(0)}, S_p^{(0)}, V_p^{(0)})$ are the total cutting forces acting in space on the cutting tool $\boldsymbol{F}_\Sigma = F^{(0)}\{\chi_1, \chi_2, \chi_3\}^T$, where χ_i is orientation coefficient of cutting forces in space, satisfying the normalization conditions; $t_p^{(0)}$,

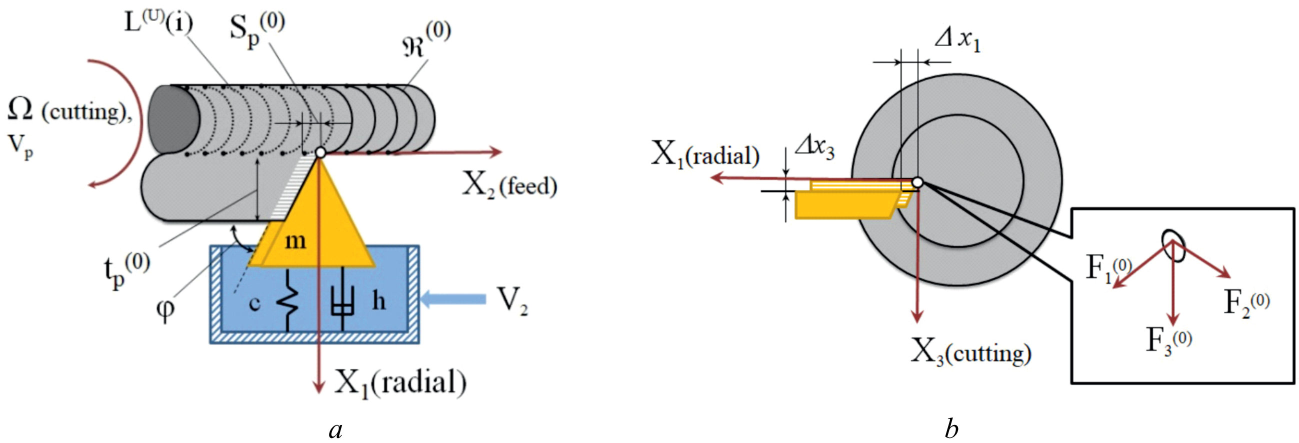


Fig. 1. Orientation of the deformation axes and cutting forces:
a – diagram of deformation axes in the plane $\boldsymbol{X_1}$-$\boldsymbol{X_2}$; *b* – diagram of force axes and deviations of tool path in the plane $\boldsymbol{X_1}$-$\boldsymbol{X_3}$

$S_p^{(0)}$, $V_p^{(0)}$ are the nominal technological cutting modes set by the *CNC* machine control system (depth of cut, feed rate and cutting speed).

Following the works [27, 30], spatial formative tool paths $\Phi_{(t)} = \{\Phi_1, \Phi_2, \Phi_3\}^T$ are defined as a set of motions specified by the machine control system $U(t)$, i.e., technological modes $t_p^{(0)}$, $S_p^{(0)}$, $V_p^{(0)}$, and motions $R(t)$ caused by the elastic and deformation properties of the tool subsystem, as well as by perturbing influences, i.e., deviations from the tool trajectory specified by the control:

$$\Phi(t) = U(t) + \boldsymbol{R}(t) = U(t) - \boldsymbol{X}(t) + \Delta\boldsymbol{x}(t)\,, \tag{2}$$

where $\boldsymbol{\Delta x(t)} = \{\Delta x_1, \Delta x_2, \Delta x_3\}$, $\boldsymbol{\Delta x_i(t)} = \sum_{k=1}^{n} A_k \sin(\omega_k t)$ are tool vibrations in the cutting zone; A_k, ω_k are the parameters of the frequency components in the tool vibration signal, considered as harmonic functions with constant orientation along the axes X_1, X_2, X_3, with a set of frequency components ω_k, Hz, and its corresponding amplitudes A_k, k = 1, 2, 3.

Taking into account $R(t)$, equation (1) is transformed into the form

$$\mathbf{m}\frac{\mathbf{d^2X}}{\mathbf{dt^2}} + \mathbf{h}\frac{\mathbf{dX}}{\mathbf{dt}} + \mathbf{cX} = \mathbf{F}_\Sigma(X, t_P, S_P, V_P)\,, \tag{3}$$

where $t_p(t) = t_p^{(0)} - X_1(t) + \sum_{i=1}^{n} A_i \sin(\omega_i t)$, mm; $S_p(t) = \sum_{i=1}^{n} A_i \cos(\omega_i t)\omega_i t + \int_{t-T}^{t} \left\{V_2^{(0)} - dX_2/dt\right\} dt$, mm/rev;

$T = (\Omega)^{-1}$ is a part turnover time, s; $V_p(t) = V_3^{(0)} - dX_3 / dt + \sum_{i=1}^{n} A_i \cos(\omega_i t)\cdot\omega_i t$, m/s.

Equation (3) presents a model of a perturbed dynamic system. Technological modes depend on tool deformation displacements and forced oscillations. Cutting forces, which are the link between the tool and workpiece subsystems, are represented as

$$T^{(0)} dF^{(0)} / dt + F^{(0)} = \rho\left\{1 + \mu \exp\left[-\varsigma \cdot V_p(t)\right]\right\} t_P(t) S_p(t), \tag{4}$$

where ρ is the chip pressure on the tool cutting face, kg/mm^2; μ is a dimensionless parameter; ς is the slope coefficient of non-linear change of cutting forces with speed $V_p(t)$, s·m^{-1}; $T_{(0)}$ is the chip formation time constant, which takes into account transients in the cutting zone, s.

System (3), (4) analytically defines the relationship between forces, deformations, vibration disturbances and control parameters of the dynamic cutting system.

The ideal case of longitudinal turning of a workpiece is considered, i.e. in the absence of tool deformation, displacements and disturbing vibrations $R(t) = 0$. Then, the trajectory of formative motions of the tool $\mathbf{\Phi}(t)$ at each moment of time τ_i is determined only by the values of the parameters of technological cutting modes and forms a set of segments of the tool path relative to the workpiece for each revolution $L^{(U)} = \sum_{i=1}^{i=n} V_\Sigma iT$, where this $\boldsymbol{L}^{(U)}$ is the tool path relative to the workpiece at constant values of cutting speed, depth and feed. In this case, the tool tip traces on the part surface form the reference geometrical topology of its surface $\boldsymbol{L}^{(U)} \subset \Re^{(0)}$ (fig. 1, *a*). However, taking into account vibrations and deformations, the tool path will differ from that specified by the machine control program, and the geometrical topology of the workpiece surface will be determined by the characteristics and properties of the cutting process $\boldsymbol{L}^{(\Phi)} \subset \Re^{(D)}$ (fig. 2).

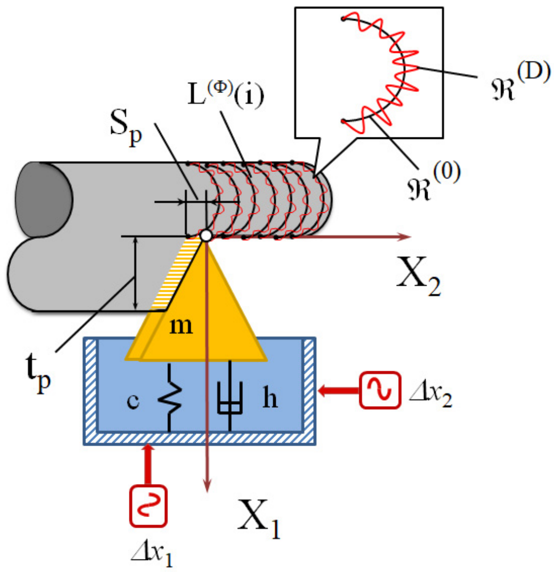


Fig. 2. Example of the tool trajectories of the forming motions $L^{(\Phi)}$ taking into account tool vibrations and the corresponding geometrical topology of the workpiece surface $\Re^{(D)}$

According to (2) $\boldsymbol{L}^{(\Phi)}$ is a pointwise representation of the tool path relative to the workpiece in each direction of its mobility and is represented as $L^{(\Phi)} = \left\{L_1^{(\Phi)}, L_2^{(\Phi)}, L_3^{(\Phi)}\right\}^T \in \Re^{(D)}$. The function takes into account the height $L_1^{(\Phi)}$ and step $L_2^{(\Phi)}$, $L_3^{(\Phi)}$ irregularities left by the tools during cutting. These are deviations of the geometrical surface of the tool from its reference shape $\boldsymbol{L}^{(U)} \subset \Re^{(0)}$. Then (2)–(4) is a basic mathematical model for simulation study of the dynamics of cutting process, estimation of roughness and waviness of the obtained surface. These models allow for a comprehensive study of the dynamics of the cutting process, taking into account various forced oscillations of the tool relative to the workpiece and predicting the output characteristics of the cutting process when changing the technological modes.

The basic model is valid in the case of small deviations of the motion trajectory of the machine tool actuators from the equilibrium point in the system. For practitioners, the adequacy of simulation modeling corresponds to workpiece machining in the period of normal tool wear or quasi-constant rate of dimensional wear.

Simulation study of the dynamics of the cutting process is carried out in several stages. Firstly, it is necessary to find out the parameters of the vibration characteristics of the machine from the spindle side and the tool drive subsystem, as it influences the trace left by the tool on the workpiece surface. Since the distribution of vibration energy losses depends on the materials of the "cutter-workpiece" pair, the vibration data recorded during the cutting process is the most informative. Measurement of vibration data is possible during the first technological operation in the process of part machining, as a result of which variations in the geometrical shape of the workpiece and physical and mechanical properties of the surface layer of the material, which occur during the cutting process, are eliminated. Data processing is based on spectral analysis methods. In the model of vibration disturbances it is also necessary to add a source of random noise component, which is always present in real technical systems, e.g. generated by chip formation processes.

In the second stage, numerical simulation of the dynamics of the cutting process is carried out using real data on the vibration characteristics of the process for a pair of materials at different cutting modes. As a result of the simulation, based on the analysis of the force characteristics, the modes are selected that provide the highest turning performance from the condition of minimisation of the components of the cutting forces $F_1^{(0)}$, $F_2^{(0)}$, $F_3^{(0)}$.

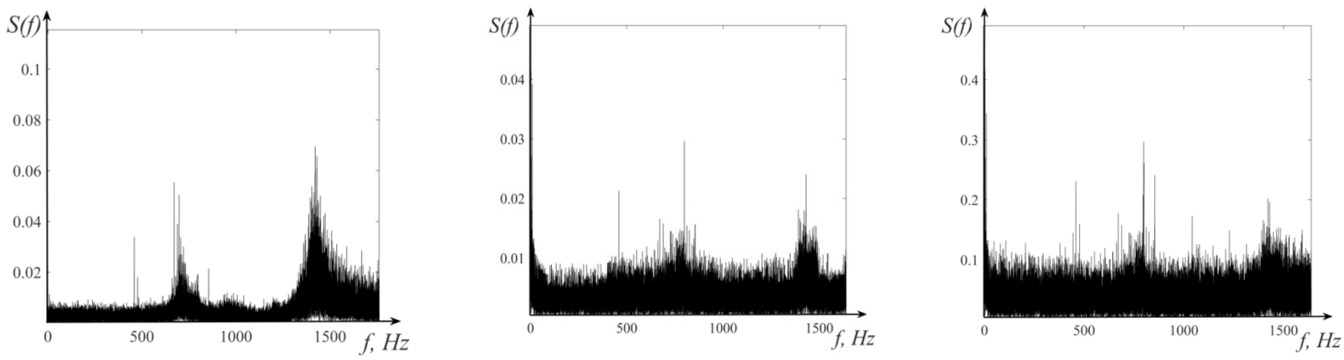
In the third stage, the geometric topology of the workpiece surface is constructed. Based on the calculated signal of tool deformation displacements, surface quality estimates are calculated, e.g. by the roughness parameter $\boldsymbol{R_a}$. The final result of the simulation study is the cutting modes that provide the highest turning performance and the required surface quality.

Simulating the dynamics of the cutting process and its representation in the geometrical topology of the workpiece surface

As an example for the simulation, a longitudinal turning of a part with a diameter D = 114 mm made of stainless steel *A508-3* (0.1 % *C-Mn*-2 % *Ni-Mo-V* in Russia) with coated carbide inserts *HS123* (79 % *WC*-15 % *TiC*-6 % *Co* in Russia) is considered. At the first stage, in order to clarify the frequency components of the tool vibrations, the vibration sequences in the directions X_1, X_2, X_3 were measured experimentally using vibration accelerometers mounted on the tool. The spectral characteristics of the signals are shown (fig. 3).

Three frequency peaks in each direction of the tool vibration activity are clearly visible in Figure 3 ω_1 = 460 Hz; ω_2 = 790 Hz; ω_3 = 1.42 kHz. The measured frequency components are the parameters of harmonic functions used in the simulation model of the cutting process as disturbances (4). According to the research methodology, the "white" noise signal on the perturbation channels was introduced into the simulation model during perturbation modelling for the qualitative simulation result. Parameters of the tool subsystem: stiffness and dissipation matrix coefficients are given in Table 1, taking into account that $\boldsymbol{m} = 0.27 \cdot 10^{-3}$ kgs^2/mm; front angle $\gamma = 10^{\circ}$, back angle $\alpha = 10^{\circ}$ and cutting edge angle $\varphi = 90^{\circ}$. The parameters of the dynamic coupling are given in Table 2.

The simulation results of the cutting process under various process conditions are shown in fig. 4, cutting depth is a constant value $t_p^{(0)}$ = 0.5 mm.



a *b* *c*

Fig. 3. Power spectra of vibration acceleration sequences in relative units to dispersion along the directions: *a* – $\boldsymbol{X_1}$; *b* – $\boldsymbol{X_2}$; *c* – $\boldsymbol{X_3}$ for modes $S_p^{(0)}$ = 0.15 mm/rev; $t_p^{(0)}$ = 0.5 mm; $V_3^{(0)}$ = 190 m/min

Table 1

Parameters of the tool subsystem

$h_{1,1}$, kg·s/mm	$h_{2,2}$, kg·s/mm	$h_{3,3}$, kg·s/mm	$h_{1,2} = h_{2,1}$, kg·s/mm	$h_{1,3} = h_{3,1}$, kg·s/mm	$h_{2,3} = h_{3,2}$, kg·s/mm
1.3	1.15	0.85	0.36	0.2	0.1
$c_{1,1}$, kg/mm	$c_{2,2}$, kg/mm	$c_{3,3}$, kg/mm	$c_{1,2} = c_{2,1}$, kg/mm	$c_{1,3} = c_{3,1}$, kg/mm	$c_{2,3} = c_{3,2}$, kg/mm
1.051	955	725	372	113	195

Table 2

Dynamic link options

ρ, kg/mm^2	ς, (mm/s)$^{-1}$	$T^{(0)}$, s	μ	χ_1	χ_2	χ_3
350	0.1	0.0005	0.5	0.7	0.5	0.5

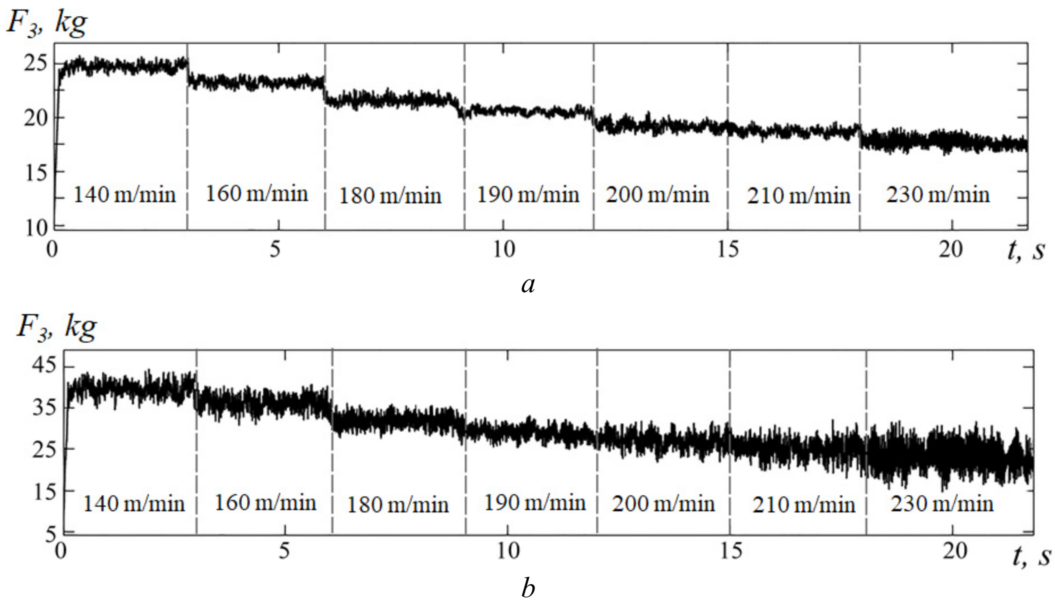
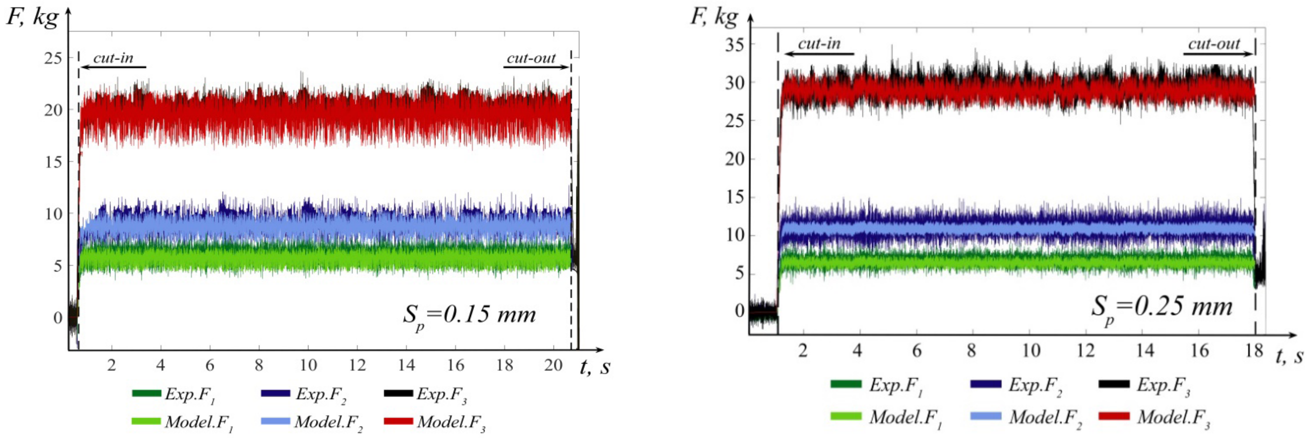


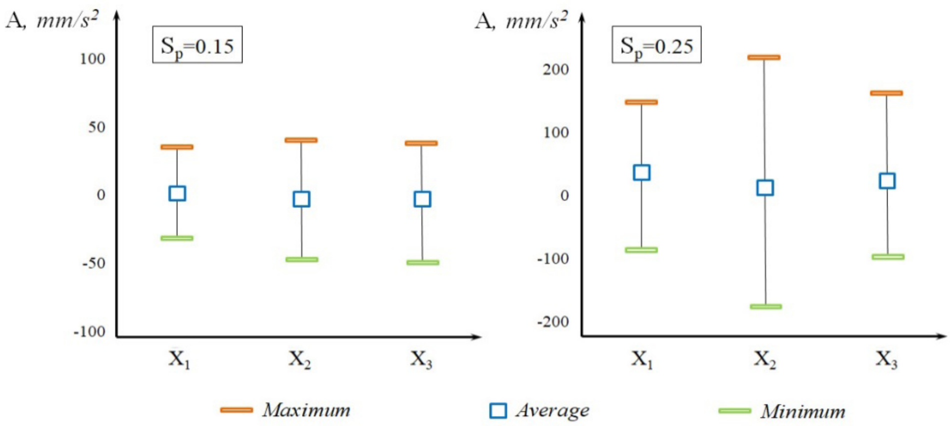
Fig. 4. Simulation of cutting forces in tangential direction at varying cutting speed: *a* – feed rate $S_p^{(0)}$ = 0.15 mm/rev; *b* – $S_p^{(0)}$ = 0.25 mm/rev

Fig. 4 shows examples of the temporal realization of the cutting forces for a given dynamic system (3)–(4) when the speed parameter $V_3^{(0)}$ is varied taking into account the characteristics of the real vibrational disturbance of the cutting process. It should be noted that when the cutting speed is changed, not only a decrease in the average values of the cutting force is observed, but also a change in the amplitude of the vibration perturbation associated with the non-linear properties of the system, which is manifested in the redistribution of the resonance frequency of the model when the control parameters are changed. According to the periodic changes in the vibration amplitude of the force characteristics, the most optimal values of the cutting speed can be selected, ensuring a high turning performance with the condition of minimising the components of cutting forces and vibrations, as it negatively affects the surface geometry of the machined part $V_3^{(0)}$ = 190 m/min. The final amplitude of the disturbance signal is limited by the maximum amplitude of the disturbances measured directly during the turning process (Fig. 5, *b*). In the second stage let us consider a simulation of the cutting process dynamics for two variants of part machining modes with $S_p^{(0)}$ = 0.15 mm/rev and $S_p^{(0)}$ = 0.25 mm/rev, and the selected optimal cutting speed $V_3^{(0)}$ = 190 m/min (fig. 5, *a*).

For a qualitative assessment of the reliability of the model characteristics, fig. 5, *a* shows its comparison with the results obtained during the final real experiments aimed at verifying the adequacy of the proposed method. It is possible to observe a significant influence of feed changes on the character of vibrations and the stability of the cutting process (Fig. 5, *b*), which in turn also leads to a decrease in the quality of the workpiece surface [32]. This follows naturally from equation (4), the development of which demonstrates that feed variations in the direction $\boldsymbol{X_2}$ directly affect the motion of the tool in a direction $\boldsymbol{X_1}$ that takes into account the surface irregularities left by the tool. In addition, in the experimental characteristics of tool vibrations it is found that in the direction $\boldsymbol{X_2}$ with increasing feed rate new frequency components appear in the region of 165 Hz, this is due to the increase in cutting forces along the auxiliary flank of the tool, which can also lead to undulations of the workpiece surface. The evaluation of this effect has an independent value.



a



b

Fig. 5. Example of changes in cutting characteristics at $t_p^{(0)} = 0.5$ mm; $V_3^{(0)} = 190$ m/min:
a – data obtained during the experiment $Exp.F_i$ and on the basis of simulation modelling $Model.F_i$, $i = 1,2,3$;
b – values of vibration acceleration amplitude during cutting for directions $\boldsymbol{X_1}, \boldsymbol{X_2}, \boldsymbol{X_3}$

In the third stage of the method under consideration, we consider the “skeletal” geometry of the part surface modelled by the digital model in the radial direction, i.e. for the height characteristics of the surface quality (Fig. 6), and the reconstructed geometrical topologies of the part surface for the final experiment. The “skeletal” surface topology is understood as a set of deviations of the observed topology, i.e. caused by vibratory tool displacements, from the reference topology formed by the geometric tool trace on the cutting surface without taking into account perturbations and tool deformation displacements $\boldsymbol{L}^{(\boldsymbol{U})} \subset \Re^{(0)}$.

As can be seen, the surfaces reconstructed on the basis of experimental data on the tool deformation displacements during cutting **1** and **3** (Fig. 6) show not only the successive passes of the cutting tool

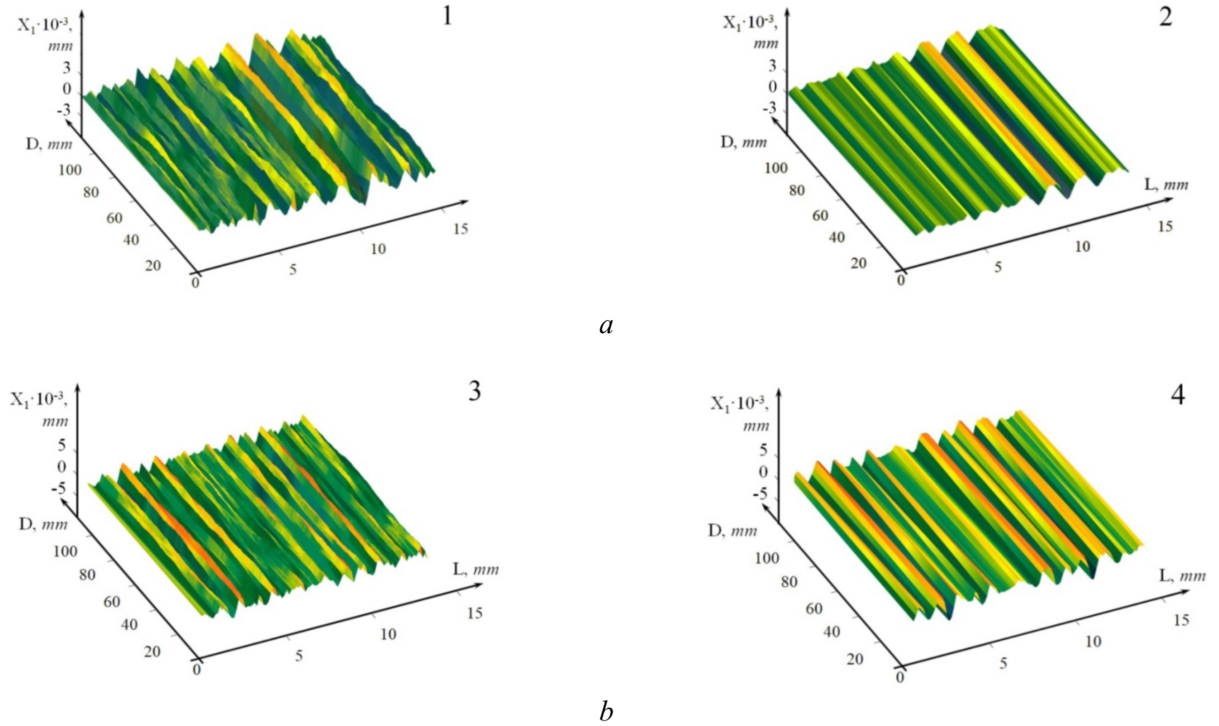


Fig. 6. Comparison of real (1, 3) and modeled (2, 4) geometrical topologies of the workpiece surface for:
a – $S_p^{(0)}$ = 0.15 mm/rev; *b* – $S_p^{(0)}$ = 0.25 mm/rev

along the workpiece, but also the irregularities caused by the random component of cutter oscillations. The distance L = 15 mm between the peaks along the surface in the direction $\boldsymbol{L}$ corresponds to the feed rate when turning a workpiece with a diameter D = 114 mm. The given “skeletal” topologies **2** and **4** (fig. 6) are obtained by simulation studying without taking into account the random component in tool vibrations, which is a consequence of continuously changing tool geometry, plastic deformation of the metal and other numerous factors randomly appearing in the cutting process. However, the reconstructed geometrical surfaces are qualitatively similar to each other, and estimates of the roughness of the real surface $\boldsymbol{R_{ai}}$ obtained by machining with constant cutting modes vary relative to the surface roughness predicted by simulation modeling $\boldsymbol{R_a^{(Model)}}$ within the limits of not more than 0.066 μm (Table 3) for different feed modes.

Table 3

Roughness for model and real data

$S_p^{(0)}$, mm/rev	$V_3^{(0)}$, m/min	$t_p^{(0)}$, mm	$Ra^{(Model)}$, μm	Surface roughness measurement result for different experiments, μm									
				R_{a1}	R_{a2}	R_{a3}	R_{a4}	R_{a5}	R_{a6}	R_{a7}	R_{a8}	R_{a9}	R_{a10}
0.15	190	0.5	0.94	0.934	0.937	0.960	0.967	0.964	0.964	0.966	0.985	0.985	1.001
0.25	190	0.5	1.25	1.184	1.200	1.237	1.243	1.214	1.217	1.279	1.240	1.305	1.304

The final experimental verification of the selected combinations of cutting modes was carried out on a modernized *16K20* universal lathe with a *Mitsubishi* stepless speed control system. Surface roughness was measured using a *Mitutoyo Surftest SJ-210* profilometer with a measurement resolution of 0.0064 μm (fig. 7).

On the basis of the obtained data of experimental and simulation realization of the workpiece surface, it can be concluded that the proposed methodology of simulation studying allows predicting the quality of the formed surface depending on the selected technological modes and vibration profile of the machine

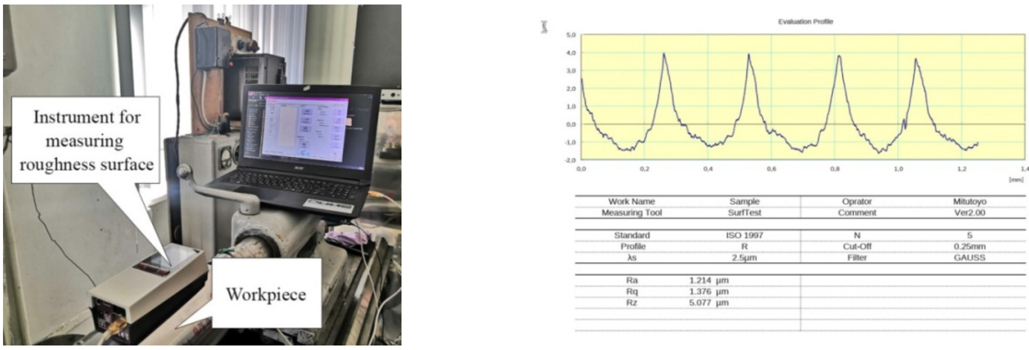
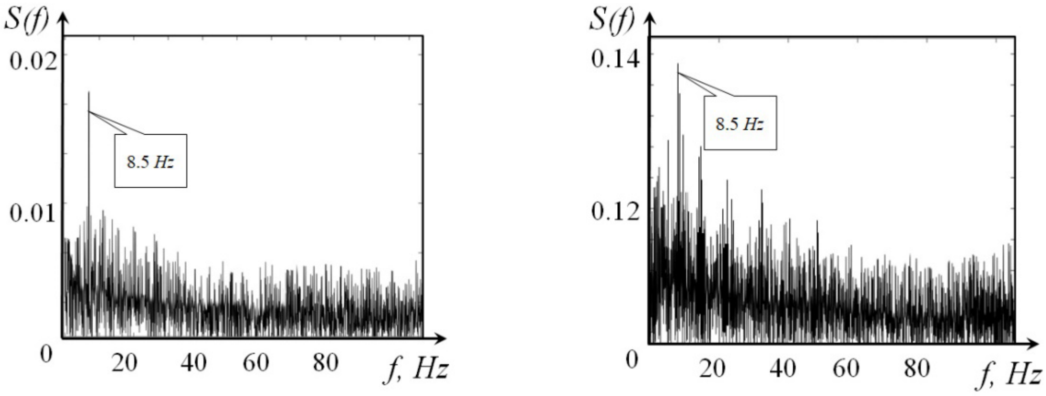


Fig. 7. Surface roughness measuring device *Surftest SJ-210* and an example of recorded data from the software of data exchange between the device and the computer

tool. However, it should be noted that at this stage of the model validation, its results are valid in the case of tool wear on the main cutting surface not exceeding 0.1 mm. When this wear threshold is exceeded, the system starts to be dominated by its own evolutionary processes, mainly related to the plastic deformation of the material in the contact zone between the tool and the workpiece. Then the discrepancy between the experimental and modelled surface estimates of the workpiece surface roughness varies within 0.61–1.36 μm as wear progresses.

Results and discussion

The evaluation of the output characteristics of the cutting process based on the information on the tool vibration dynamics showed that there is an observed dependence between high amplitudes of frequency components in the vibration acceleration signal of the system natural motions and the workpiece contour error with respect to its roughness parameter (Fig. 8).



a *b*

Fig. 8. Spectral characteristic of the vibration acceleration signal for radial direction: $a - S_p^{(0)} = 0.15$ mm/rev; $b - S_p^{(0)} = 0.25$ mm/rev

Figure 8 shows that an increase in feed rate leads to an increase in the amplitudes of the part rotation frequency, the appearance of a large number of frequency components in the vibration acceleration spectrum in the region of the part rotation frequency and an increase in its amplitudes. This behavior can be characterized by a sharp increase in temperature in the cutting zone, material breakouts along the cutting tool path or an increase in the influence of kinematic disturbances on the dynamics of the cutting process. The levelling of such effects before the moment of intensification of tool wear allows the correct selection of cutting modes, which can be carried out for the considered problem with the help of the created digital simulation model. In this article it is proposed to choose the value of the dispersion of the auto-spectrum of tool vibrations in radial and longitudinal directions as a diagnostic feature, as it has a greater influence on the formation of irregularities in the surface of the workpiece. Thus, the use of a simulation model reduces the number of real experiments in the search for optimal cutting modes according to the criteria of maximum tool wear resistance and preservation of the quality of the machined surface.

Conclusion

Experiments and numerical modeling have shown that the quality of the workpiece surface produced by cutting is influenced by the tool feed, together with the depth of cut. The characteristics of the vibration sequences measured during the cutting process change: as the tool feed increases, the vibration energy in the longitudinal direction increases, which according to (4) also affects the tool motion in the radial direction. Finally, the analysis of the adequacy of the calculated roughness of the workpiece surface on the basis of numerical simulation and experimentally measured roughness allows us to conclude that it is possible to use the considered technique as a basis for evaluating the influence of the dynamic characteristics of the cutting process on the roughness of the workpiece surface during turning.

The identified parameters of the force model are suitable for modeling the processes of machining the stainless steel *A508-3* (0.1 % *C-Mn*-2 % *Ni-Mo-V* in Russia) workpiece with coated carbide inserts *HS123* (79 % *WC*-15 % *TiC*-6 % *Co* in Russia) in the case of tool wear on the main cutting face not exceeding 0.1 mm. The presented parameters of the force model are valid for perturbed motion of the tool with the amplitude of vibration accelerations not exceeding that shown in fig. 5, *b*. In case of a deviation from the specified range or a change in the initial data of modelling, it is necessary to carry out all stages of the stated methodology for correcting the parameters of the model. Thus, the applied efficiency of using simulation studying will increase in case of forming a vibration database of a certain type of machine tool enterprise, determined by the nomenclature of parts, workpiece and tool materials, as well as its geometry.

The given example of simulation studying, which allows to determine the most optimal cutting modes according to the criterion of maximum productivity, taking into account the required surface quality of the part, gives an idea of how the proposed analytical model of the cutting process dynamics, refined by experimental data, can predict the surface roughness depending on the cutting modes, thus reducing the labour input of the production for conducting exploratory experiments. Thus, the presented results lead to the beginning of a deeper experimental-theoretical study of the mechanisms of mapping of tool deformation displacements in the part geometry.

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Conflicts of Interest

The authors declare no conflict of interest.