Alignment the controlled trajectories of the machine's executive elements with the properties of the cutting system

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Abstract. The article considers the task of alignment of trajectories of machine executive elements set by CNC-system with evolutionarily changing properties of the cutting process in such a way that minimize the wear intensity. Consequently not position optimizes in the space of the technological regimes but its trajectories are harmonized with changes of the properties of the manufacturing process. The definition of trajectories is considered from the point of view of synergetic mutually agreed interaction of external control and internal dynamic of the cutting system.

The study of alignment is performed on the basis of constructing mathematical models of a controlled dynamic system and performing digital experiments for a cutting system, the parameters of which and tool wear depend on the phase trajectory of the power of irreversible energy transformations in the cutting zone. Based on the research, new directions for improving the efficiency of cutting processes on CNC machines are proposed, which allow increasing the productivity of the cutting process without changing the requirements for the quality of manufacturing parts.

1. Introduction

After the publication of works on the synergy of interaction of systems with different environments [1,2] many issues of improving machine processing began to use the system-synergetic paradigm [3, 4]. It is uses to optimize of cutting process [5-14] take into account wear intensity of tools that is increment of wear along path. This is due to the fact that all the main characteristics of the process change with development of wear, including the quality indicators of parts. Therefore, the study of the influence of processing conditions, properties of tool materials, the lubricating and cooling medium, technological modes, tool geometry, vibrations, etc. on wear has been the subject of numerous studies [3-9]. It is show that the properties of the soldered zones change fundamentally, in which new dissipative structures are formed as power irreversible transformation increases. In particular, it is proved that when the speed increases, there is an optimal value at which the wear intensity is minimal. In this case, there is a transition from the prevailing adhesive to diffusion wear. This transition corresponds to a defined power of irreversible energy transformations, which is estimated by temperature during cutting. Therefore, article presents proven hypotheses about the existence of an optimal cutting temperature in which the wear intensity is minimal [15 - 18]. It is show that tool wear and indicators of the quality of manufacturing parts depend on the dynamics of the cutting process [19 - 29]. Moreover, the dynamic properties of the manufacturing process have the property of evolutionary changes [30 - 35]. Moreover, the evolution depends on the phase trajectory of the power of irreversible energy transformations in the cutting zone for perfect work. One of the manifestations of evolution is the development of tool wear [34, 35]. The improving the processing efficiency on the machines is the next step aimed at improving
the processing efficiency on the machines is to align the CNC program of the machine with the evolutionarily changing dynamic cutting system. The solution to this issue is discussed in the article.

2. Link between external control and internal dynamic of cutting system.

At first, the concept of the cutting system is described. Following coordinates of state and control are introduced (fig. 1).

1) Trajectories of executive elements of machines (TEEM) are set CNC-program and considered in the article as a control: \( I = \{l_1(t), l_2(t), l_3(t)\}^T \in \mathbb{R}_1^{(3)} \) and \( V = \{V_1(t), V_2(t), V_3(t)\}^T \in \mathbb{R}_1^{(3)} \). For turning machine these are trajectories of the cross-section \( l_3(t) \) and longitudinal \( l_2(t) \) calipers and the rotation of the spindle \( l_1(t) \). Derivatives \( \frac{dl}{dt} = V \) are the speeds of executive elements. The link of cutting force is obvious. The phase trajectories \( T_{lVlV} = (3,2,1) \) correspond to vectors \( I \) and \( V \). For instance, the trajectory of speed of the longitudinal caliper \( V_2 \) along the axes \( l_2 \) is desired phase trajectory. Modern machines ensure with high accuracy correspond of the programmed trajectories to the real ones within the bandwidth of the servomotors.

![Figure 1. Scheme of controlled dynamic cutting system](image)

2) The space of elastic deformation \( X = \{X_1(t), X_2(t), X_3(t)\}^T \in \mathbb{R}_X^{(3)} \). The tool deformations are considered in movable coordinates system \( I \) and relative to the machine carrier. Following the previously justified provisions, the dynamic subsystem of the tool in the movable coordinate system is represented as [35] (fig. 1)

\[
m \frac{d^2X}{dt^2} + h \frac{dX}{dt} + cX = F_{\Sigma}
\]

where \( m = \left[ m_{s,k} \right] \) in kgf \(^2\)/mm, \( h = \left[ h_{s,k} \right] \) in kgf/mm, \( c = \left[ c_{s,k} \right] \) are symmetrical, positively definite matrices of inertial, speeds and elastic coefficients; \( F_{\Sigma} = [F_{\Sigma,1}, F_{\Sigma,2}, F_{\Sigma,3}]^T \in \mathbb{R}_X^{(3)} \) - cutting force are represented in coordinates of state and control, allowing relate elastic deformation with \( X \) parameters of interacting subsystem and vectors \( I \) and \( V \). The force \( F_{\Sigma} \) is presented as sum \( F_{\Sigma} = F + \Phi \). There \( F = [F_1, F_2, F_3]^T \in \mathbb{R}_X^{(3)} \) and \( \Phi = [\Phi_1, \Phi_2, \Phi_3]^T \in \mathbb{R}_X^{(3)} \) is forces acting on the front and back face of the tool (fig.1). Following properties are taken into account for \( F \):
- \text{Mod}[\mathbf{F}] \text{ depends on the area of the cut layer } S; \\
- \text{proportional coefficient } \rho \text{ between } \text{Mod}[\mathbf{F}] = F_0 \text{ and area } S \text{ decrease in the medium speed range when the speed increases;}
- \text{lag of forces } F_0 \text{ in relation to the variations of the area } S \text{ is taken into account;}
- \text{orientation of forces in space with small variations } \mathbf{X} \text{ is represented by angular coefficients that is } \mathbf{F}(t) = F_0(t)\{\chi_1, \chi_2, \chi_3\}^T. \text{ Then}
\begin{equation}
T_0dF_0/ dt + F_0 = \rho\{1 + \mu\exp[-\alpha(V_3 - dX_3 / dt)]\}t_p(t)S_p(t)
\end{equation}
where \(T_0\) - the time constant of chip formation \(\text{[sec]}\); \(\rho\) - pressure chips in the region of small velocities \(kg/mm^2\); \(\mu\) - dimensionless coefficient; \(\alpha\) - coefficient that determines the decrease in forces as the speed increases.

Forces \(\Phi\) in the areas of contact of the back faces of the tool with the workpiece, disproportionately increase as they approach to the workpiece. Convergence is determined by changing the angles between the back faces (main \(\beta_{x,2}(t)\) and auxiliary \(\beta_{x,1}(t)\)) the direction of the cutting speed. Back angle \(\beta_{x,i}(t), i = 1,2\)
\begin{equation}
\beta_{x,i}(t) = \beta_i + \Delta\beta_i(t), \quad i = 1,2,
\end{equation}
where \(\beta_i\) - back angle of the tool in static; \(\Delta\beta_i = \arctg[V_2(t)/V_3(t)]\) - angle variations due to changes in \(V\) and \(X\). Value \(\beta_i\) and the radius at the top of the tool change due to the development of wear \(w\). In addition, the dependence of the coefficient of friction on the speed is taken into account. Fair enough then
\begin{equation}
\begin{bmatrix}
\Phi_1 = \rho_0d\int[V_2 - dX_2 / dt]dt\exp[\alpha_1\beta_{x,2}(t)]; \\
\Phi_2 = \rho_0[t^0_p - X_1(t)]\exp[\alpha_2\beta_{x,2}(t)]; \\
\Phi_3 = k_{\gamma}[\Phi_1 + \Phi_2],
\end{bmatrix}
\end{equation}
where \(\alpha_1, \alpha_2\) - growth factors; \(\rho_0\) - parameter that makes sense of stiffness; \(k_{\gamma} = k_{\gamma}[1 + \mu_0\exp(-\alpha_2V_3)]\) - coefficient of friction.

The vector of shape-generating movements \(\mathbf{U}(t) = \{U_1, U_2, U_3\}^T \in \mathbb{R}^3\), which differs from TEEM in the values of elastic deformations \(\mathbf{U}(t) = \mathbf{l}(t) - \mathbf{X}(t)\) is considered and also the relationship between \(\mathbf{U}(t), \mathbf{l}(t), \mathbf{X}(t)\) and technological modes (5) is determined
\begin{equation}
t_p(t) = \int_0^1V_1(\xi)d\xi - X_1(t); S_p(t) = \int_0^1[V_2(\xi) - v_2(\xi)]d\xi; V_3(t) = \pi\Omega - dX_3 / dt; \mathbf{U}(t) = \mathbf{l}(t) - \mathbf{X}(t),
\end{equation}
where \(t_p(t), S_p(t), V_p(t)\) - depth, feed and cutting speed; \(T = (\Omega)^{-1}\) - part turnaround time. It follows from (5) that for longitudinal turning \(\int_0^1V_1(\xi)d\xi = t_p^0 = const\). The feed change function \(S_p(t)\) is related to the feed speed and speed of deformation \(v_2(t)\) by an integral operator whose integration time depends on the spindle speed.
Cutting has evolutionary properties manifesting in changing the parameters of dynamic coupling, in the development of tool wear, in changing the output characteristics of processing. Moreover, the driving force of these changes is the power of irreversible transformations in the cutting zone. Previously, methods allowing model evolution based on analysis \( N(t) \) are developed. It relies on the Volterra integral equation of the second kind to calculate the reduced power \( N^{(II)}(t) \), in the function of which the wear rate changes [30 - 35]

\[
N^{(II)}(t) = \{ N(t) + \eta \int_0^t W(t - \xi)N(\xi)\,d\xi \}, \quad v_w = \Phi(N^{(II)})
\]

where \( \eta \) - coefficient \([\text{sec}^{-1}]\), \( W(t - \xi) \) - dimensionless core that simulates the dynamics of physical interactions that determine the wear rate \( v_w \). If \( v_w \) is set, then \( v_w^{(I)} = \partial w/\partial l \) and \( w \) wear are determined

\[
v_w^{(I)} = v_w \,(V_{S}) \quad w(t) = \int_0^t v_w(\xi)\,d\xi
\]

where \( V_{S} = \text{Mod}[dL^{(p)}/dt] \) - projection of the total speed on the direction of travel.

Trajectories \( w(t) \) correspond to trajectory of parameters system.

These models allow, first, to find out the dependence \( U(t) \) on \( V_\phi \), \( V \) and \( I \). Secondly, to determine the change of the system dynamic and its evolution depending on the TEEM. Many of these issues were discussed earlier [20 - 23]. Current task is to alignment the external control is set by \( V_\phi \), \( V \) and \( I \) and with the evolutionarily changing dynamic cutting system.

3. Optimal alignment strategy

The purpose of the cutting process is to produce a batch of parts of a requirement quality while minimizing the costs involved. One of the ways to achieve this goal is to alignment the TEEM \( V_\phi \), \( V \) and \( I \) with the dynamic properties of the cutting process. For this, the state vector of the process \( Q = \{Q_1, Q_2, ..., Q_n\}^T \in \mathbb{R}_Q^n \), as well as the set of acceptable variations of its components \( Q^{(0)} = \{Q_1^{(0)}, Q_2^{(0)}, ..., Q_n^{(0)}\}^T \) are introduced. The components of the vector \( Q \) are the assessment of condition process and the quality parameters of details are presented in the coordinate condition. The most important ones are highlighted below.

1) The first group of components \( Q \) describes the state of the processing process. Limited the most important characteristic of the power of irreversible energy transformations in the integration zone of the tool face and the workpiece \( Q_1 \) and used the known ideas about the existence of a power at which the wear intensity is minimal. Based on (4), the power \( N_\phi(t) \) and work \( A_\phi(t) \) in the contact area of the back face are calculated

\[
N_\phi(t) = \Phi_2(t)[V_2 - d(X_2)/dt] + k_2\Phi_2(t)[V_3 - d(X_3)/dt] \quad A_\phi(t) = \int_0^t N_\phi(t)\,dt \tag{8}
\]

Taken into account the forces caused by elastic deformations accumulated in the cutting zone during the transition of the processed material through the top of the cutting blade, and their power \( N_F(t) \), that is

\[
N_F(t) = k_F\,F_0(t)[V_3(t) - dX_3/dt], \quad N(t) = N_F(t) + N_\phi(t) \quad A(t) = A_F(t) + A_\phi(t) \tag{9}
\]
where \( k_F \) - transformation coefficient; \( N(t) \), \( A(t) \) - summary power and work. It is considered related to the contact length of the cutting blade with the workpiece. It follows from (8) and (9) that the conditions that minimize the intensity of wear depend on the speed and forces in the direction of speed.

2) The second group of vector \( Q \) components determines the parameters of accuracy and manufacturing quality. To do this, we can use the methods developed by us for reconstructing the geometric topology of the surface is formed by cutting [31, 32]. Based on the topology using different functionals, adopted in engineering practice evaluation of the geometry of the microrelief, waviness are determined. In the article two estimates are considered:

\[
Q_2(t) = \frac{1}{T^{(0)}} \int_{t-T^{(0)}}^t X_1(\xi) d\xi - \text{moving average in the time window } T^{(0)} \text{ of the deviation of the part radius from the set point of the tool tip in the machine bases;}
\]

\[
Q_3(t) = \frac{1}{T^{(0)}} \int_{t-T^{(0)}}^t (Q_2(\xi) - X_1(\xi))^2 d\xi - \text{moving average of the dispersion estimation of the microrelief.}
\]

The General algorithm for optimal alignment is represented below.

1. The surface length \( \Delta L \) of each of the \( n \) same-type parts to be processed is set. Then the total length of the cutting surface of \( n \) parts whose parameters meet the quality requirements: \( L = n\Delta L \).

2. For \( \Delta L \) there is a set \( V^{(0)}(\Delta L) = \{V_1^{(i)}, V_2^{(i)}, V_3^{(i)}\}^T \in \Re_i^{(0)}, i = 1, 2, ..., n \), which represents as piecewise constant approximation of the trajectories \( V^{(0)}_\Phi \).

3. For each \( \Delta L \), select \( V^{(0)}(\Delta L) \) meeting the conditions

\[
\tilde{N}^{(i)} = \frac{1}{\Delta L} \int_0^{\Delta L} N^{(i)}(\xi) d\xi \Rightarrow N^{(\text{comm.})} \text{ with } V^{(0)}_\Phi \subset V^{(0)}_\Phi, L = n\Delta L = \max \ , \ Q \subset Q^{(0)}.
\]

where \( N^{(\text{comm.})} \) - the power value in the integration zone of the tool face and the workpiece, at which the tool wear intensity is minimal: \( V^{(0)}_\Phi = \{V_1(l_1), V_2(l_1), V_3(l_1)\}^T \) - the set of acceptable variations of TEEM. It is determined by the kinematic relations between the speeds of the Executive elements are dictated by the requirements of cutting kinematics and the restrictions on the trajectory are determined by the properties of the drives. It is clear from (12) that in order to determine the optimal conditions, the TEEM must change as the work progresses. As a result, we get their optimal trajectories are adapted to the evolutionary changes in the dynamic cutting system.

4. Instance of alignment the CNC-program with the dynamic properties of the cutting process. The example of the effectiveness of alignment TEEM with an evolutionarily changing dynamic system of turning a shaft made of austenitic steel is shown below. Turning by perishable plates of company SANDVIK Coromant, hard alloys GC2015, plates form «W». Tool geometry: \( \alpha = 2^0 \), \( \gamma = 6^0 \), \( \varphi = 90^0 \). The axes of the ellipsoid of rigidity coincide with the axes of space \( \Re^{(3)} \). Parameters of the tool subsystem: \( m = \begin{bmatrix} m_{s,s} & m_{s,k} & m_{0} \end{bmatrix} \), \( h = \begin{bmatrix} h_{s,s} & h_{s,k} & h_{0} \end{bmatrix} \), \( m_{s,k} = h_{s,k} = h_{0} = 0 \), \( npu \) : \( s \neq k \), \( s,k = 1,2,3 \); \( h_{0} = 5,0 \ km \cdot c/ \text{mm} \); \( m_{0} = 0,025 k \km \cdot c^2/ \text{mm} \). The dynamic link parameters are shown in table 1. The parameters of the integral operator are shown in table 2. All parameters are given for a cutting speed of 1.2 m/s. In the future, the parameters varied.

\[
\text{(10)}
\]

\[
\text{(11)}
\]

\[
\text{(12)}
\]
Table 1. Parameters of dynamic link of the cutting process

| $\rho$, kg/mm$^2$ | $\alpha = \alpha_T \cdot f/m$ | $\mu = \mu_1$ | $\rho_0$, kg/mm | $k$, mm$^{-1}$ | $a_1 = a_2$, rad$^{-1}$ | $k_T$ |
|-------------------|-----------------------------|-------------|---------------|--------------|-----------------|-------|
| 500               | 2.0                         | 0.5         | 50.0          | 5×10$^{-3}$  | 20              | 0.2   |

Table 2. Parameters change of the integral equation when variation of cutting speed

| Speed, m/s | $T_1$, [s] | $T_2$, [s] | $\eta_1$, [s$^{-1}$] | $\eta_1$, [kg$^{-1}$] | $\eta_2$, [kg$^{-1}$] |
|------------|------------|------------|---------------------|----------------------|---------------------|
| 1.2        | 13         | 30         | 0.5                 | 8×10$^{-6}$          | 3×10$^{-6}$          |

Instances of evolutionary trajectories are shown in the fig.2. When processing in constant modes, there is usually a dynamic bifurcation of properties. As shown earlier [35], bifurcations of attractive sets of deformations are observed (an asymptotically stable point is transformed into a limit cycle and then chaotic dynamics is formed in the system). It is possible to improve the dynamic properties of the system based on the choice of parameters of the tool subsystem (compare the trajectories "1" and "2" in figure 2). Stability is lost in fig. 2, "2" – shows an example of forming a limit cycle. This significantly increases the work and power in the area of the intergrade of the back face of the tool with the workpiece (fig. 2, "3" shows an example of the formation of cyclic forces acting on the back face of the tool). According to our data when stability is lost the average power of irreversible transformations of the energy of the mechanical system supplied to cutting increases in all cases, so the necessary condition for optimal tool wear resistance is the asymptotic stability of the trajectories at all stages of evolution. In addition, due to the formation, for example, of a stable limit cycle (fig. 2, "2, 3"), a dynamic displacement of the equilibrium point $\Delta$ is formed in the system, which changes during the evolution of the system. The equilibrium point also shifts in the case of asymptotic stability of the evolutionary trajectory (Fig. 2 "4") due to an increase in all parameters depending on the volume of plastic deformation associated with the evolution of wear. The loss of stability as the cutting speed increases is determined based on a compromise between the two mechanisms. On the one hand, as the cutting speed increases the parameter $T_0$ from (2) decreases and, consequently, the stability margin increases. On the other hand, parametric self-excitation is observed due to an increase in the spindle speed.

Researches show that value of the cutting speed complying with maximum margin of stability, usually corresponds to the minimum intensity of tool wear. Examples show that the cutting system is characterized by the fact that all its main output characteristics change without external interference but due to irreversible transformations of the energy introduced into the cutting zone. The irreversibility of transformations determines the irreversibility of evolutionary changes in the properties of the system. For example, it is not possible to restore the geometry of a worn tool spontaneously, just as it is not possible to reverse changes in dynamic coupling parameters. In this regard, there is a work value after which at least one of the components of the vector $Q$ achieves its terminal value $Q^{(0)}$. Once achieved $Q^{(0)}$, the tool system of the machine must be reconfigured. In our example, to provide $Q_2 \leq Q_2^{(0)}$ and $Q_3 \leq Q_3^{(0)}$, it is necessary to reduce the area of the cut layer, that is the amount of feed, in the course of evolution.
Figure 2. An example of changes of the trajectory of the deformation displacement in the direction of $X_1$ and force $\Phi_1$. 1- constant cutting conditions: $S_p^{(0)} = 0.1 \text{mm}$, $V_3^{(0)} = 1.2 \text{m/s}$, the stiffness parameters $c_{1,0} = 3000 \text{ kg/mm}$, $c_{2,0} = 1000 \text{ kg/mm}$, $c_{3,0} = 600 \text{ kg/mm}$. 2 - constant cutting conditions: $S_p^{(0)} = 0.1 \text{ mm}$, $V_3^{(0)} = 1.2 \text{ m/s}$, the stiffness parameters $c_{1,0} = 3000 \text{ kg/mm}$, $c_{2,0} = 2000 \text{ kg/mm}$, $c_{3,0} = 1000 \text{ kg/mm}$. 3 - a fragment of the strength $\Phi_1$ in section formation of a limit the formation of the limit cycle (section A-B) for the curve 2. 4 - the trajectory with the modes corresponding to paragraph 2, but with a cutting speed 1.6 m/s. 5 - in contrast to 4 it is further reduced $S_p(I)$

In this section, we analyze the effectiveness of control algorithms (fig. 3). Path $L = \max$ is passed by the tool under the condition $Q \in Q^{(0)}$ that there is an optimality condition. Therefore the concept of critical wear is replaced by the concept of the terminal state of the cutting system. Three algorithms of alignment of CNC-program with dynamic properties of cutting process during the evolution are considered.
The first algorithms. The cutting speed and the feed speed corresponding to cutting speed remain constant and equal \( S_p^{(0)} = 0.1 \text{mm}, \ V_3^{(0)} = 1.2 \text{m/s} \).

Second algorithm. The cutting speed decreases linearly from a value \( V_3^{(0)} = 1.4 \text{m/s} \) to \( V_3^{(0)} = 0.9 \text{m/s} \), and the feed remains constant \( S_p^{(0)} = 0.1 \text{mm} \). Third algorithm. The cutting speed decreases linearly from a value \( V_3^{(0)} = 1.4 \text{m/s} \) to \( V_3^{(0)} = 0.9 \text{m/s} \), and the feed also decreases from \( S_p^{(0)} = 0.1 \text{mm} \) to \( S_p^{(0)} = 0.05 \text{mm} \). The results of algorithms based on the adjustment of all components of the vector to the processing conditions that change in the course of evolution are shown in fig. 3 and allow to increase the number of processed parts without changing the tool system by a factor of (1.5 – 2.0).

5. Conclusion
The evolution of the properties of a dynamic cutting system depends on its initial parameters and uncontrolled disturbances depending on the accuracy of the machine and its current state. Depending on the initial parameters in the course of evolution depending on the phase trajectory of the power of irreversible transformations for perfect work, the output characteristics of processing change, considered in the unity of the geometric quality of the surface formed by cutting and the intensity of tool wear. This unity characterizes the state vector of the process. Its components can reach their limit value (the limit set) in the course of evolution. Moreover, the limit set, as a rule, does not correspond to the maximum wear of the tool. The parameters of the dynamic connection is formed by cutting depend not only on the properties of interacting subsystems, such as tool geometry, but to a greater extent on the technological modes are set by the machine’s TEEM, in particular, the CNC program. Therefore, when designing technological manufacturing process, including the CNC program, it is necessary to alignment the trajectories are set by the external control with the dynamics of the system that characterizes the internal control. The solution to this problem allowing to increase the processing efficiency, is nothing other than providing a condition for interaction between external and internal controls, that it is known in synergetic.

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