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STOCHASTIC DIAGNOSTICS OF TOOL AND WORKPIECE INTERACTION

Sergey Bratan
Sevastopol State University

Milan Sága
University of Žilina

Boris Yakimovich
Sevastopol State University

Pavol Božek
University of Žilina

Nikolay Pokintelista
Sevastopol State University

Chingiz Yakubov
Crimean Engineering and Pedagogical University

Abstract:
Development is an integral part of research, since the study of specifics and characteristics in such a unique topic as the quality of processed products cannot be done without extraordinary equipment, fixtures and a laboratory. Laboratory equipment has been created that combines all hardware aspects of the development of the quality of processed products, where it analyzes the quality of workpieces that depend on the processing technology. However, this depends largely on the technological system used. The paper includes measurements, data acquisition and back-checking of the logic of the study of grinding operations. In the introduction, it must be shown that the correct selection and strength characteristics of the tool associated with the cutting mode of grinding determine the accuracy and quality of the surfaces of the ground part. The impact on the service life of the grinding tool was also monitored. The 4th partial result is also the knowledge that the correct selection of the tool characteristics and cutting mode predicts the quality of the workpiece surface. The operating conditions of the manufactured parts significantly affect the operating values of the production parameters. By appropriate diagnostics in the research process and precise measurements using sensitive sensors, deviations can be minimized. Without this apparatus, it is possible that deviations increase significantly during the operation of the technological system. The size of the deviation during grinding is explained in practice by the presence of vibrations in technological processes. They cause instability of the parameters of the technological system. To stabilize the quality indicators, a mathematical apparatus was also used, which takes into account changes in the technological regime. They are determined by designing adverse conditions, e.g. restoration of the cutting properties of a worn grinding wheel. Therefore, its replacement is logically carried out earlier than its replacement is planned.

Key words: research, machining, grinding, quality, diagnostics, lifespan

INTRODUCTION

The quality of processed products depends both on the quality of the workpiece, processing technology, and on the properties of the technological system [1, 2, 3]. Studies of grinding operations show that, as a rule, at the initial moment of time, with the correct selection of tool characteristics, cutting modes, and optimal construction of the grinding cycle, the specified parameters of accuracy

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and quality of the surfaces of the part are ensured [4, 5, 6, 7]. However, the operational properties of products are significantly affected not only by the nominal values of these parameters, but also by their deviations, which increase significantly during the operation of the technological system. The presence of deviations is explained by the presence of disturbing influences in technological processes caused by the instability of the parameters of the technological system. In addition, the instability of the parameters of parts is determined by the impact of changing external factors on the technological system during their production, some of which are unknown and not controlled during processing [3]. This problem is especially relevant for finishing operations, where the quality parameters of finished products are finally formed, and which are most sensitive to disturbing influences.

In modern conditions, about 15-20% of finishing operations are per-formed using external cylindrical grinding methods. Operations are designed using traditional methods that do not fully take into account the influence of random factors that reduce the stability of the quality indicators of manufactured products. To stabilize quality indicators, technological modes are assigned based on unfavorable conditions, for example, the restoration of the cutting properties of a worn grinding wheel is carried out much earlier than its actual condition requires [8].

MATERIALS AND METHOD

When predicting the state of an equipment, deterministic models of the technological process, traditional methods of diagnostics and control are used. At the same time, grinding processes have a complex stochastic nature, which leads to scattering of product quality indicators [9, 10].

Thus, for finishing processes on cylindrical grinding machines, a diagnostic task arises – the need to determine during the processing process a number of parameters of the technological system, including those that are not directly measurable, which is the purpose of this article [11]. Such parameters include, for example, the actual cutting depth, which largely determines the patterns of material removal and wear of an abrasive [12, 13] tool [14, 15].

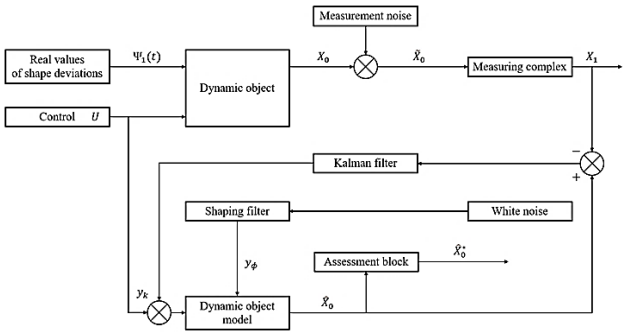


Fig. 1 Scheme of stochastic diagnostics

The problem of its assessment (diagnosis), and therefore a number of other process parameters, can be solved using the theory of dynamic observers [3, 6]. For polishing, the diagram of the dynamic diagnostics system [6, 16], Figure 1, in addition to the actually existing dynamic object (upper part of the diagram), includes a model of the dynamic object, an assessment block, the Kalman filter, a shaping filter, which operate in real time.

THORETICAL PREREQUISITES OF THE MATHEMATICAL MODEL

A mathematical description of the process that characterizes the interaction of the grinding wheel and the workpiece is given to develop a model of the behavior of the grinding wheel and the workpiece during processing.

The interaction of the grinding wheel and the workpiece is primarily characterized by the shape parameters of the grinding wheel and the workpiece, their mutual position, elastic, damping and other properties of the technological system. A rotating disk can be considered as a mathematical model of a grinding wheel, and a rotating circle can be the one in its one-dimensional representation. The center of rotation inevitably does not coincide with the center of the form, which determines the imbalance of the wheel. This usually explains the appearance of periodically changing forces that arise during grinding. In addition, the wheel's surface does not have ideal geometry. Regular and random deviations in shape and waviness are detected, the amplitude, frequency and phase of which change over the period of tool life [7].

The pattern of interaction for the external cylindrical grinding process has the form shown in Figure 2.

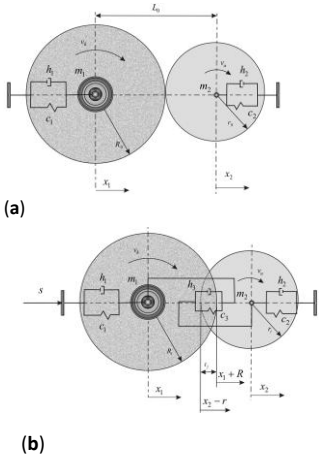


Fig. 2 Equivalent diagram of the dynamic system of a cylindrical grinding machine: (a) Initial position of the workpiece; (b) Depth of cut in the process of external circular grinding

The model for the system shown in Figure 2 based on the principle of possible movements was built in the form of a set of differential equations characterizing the dynamics of movements of the centers of the circle, the workpiece and changes in the actual depth of cut in the process of external circular grinding:

$$\begin{cases} m_1\ddot{x}_1 + h_1\dot{x}_1 + c_1x_1 + h_3\dot{t}_f + c_3t_f - h_1\dot{s} - c_1s = 0, \\ m_2\ddot{x}_2 + h_2\dot{x}_2 + c_2x_2 - h_3\dot{t}_f - c_3t_f = 0 \end{cases} \quad (1)$$

where:

m_1, m_2 are the reduced masses of the workpiece with centers and the circle with the spindle; h_i is the damping coefficient;
c_i is the stiffness coefficient;
x_1 and x_2 are the coordinates of the centers of rotation of the circle and the workpiece respectively;
s path travelled by the feed mechanism during time t;
t_f is the actual cutting depth.
The actual cutting depth (size of the contact area between the workpiece and the tool along the line of centers), according to Figure 2b, is determined by the equation:

$$t_f = R + r - L \tag{2}$$

where:
$R = R_0 + \Delta R$ is the current radius vector of the circle surface considering its runout and shape deviations ΔR;
$r = r_0 + \Delta r$ is the current radius vector of the workpiece considering material removal and shape deviation Δr and $L = L_0 + \Delta L = L_0 + x_2 - x_1$ is the current distance between the centres of rotation of the circle and the component part.
Taking into account the obtained definition of t_f and its constituent elements, system (1) can be written:

$$\begin{cases} m_1\ddot{x}_1 + h_1(\dot{x}_1 - \dot{s}) + h_3(\dot{R} + \dot{r} - \dot{x}_2 + \dot{x}_1) + \\ +c_1(x_1 - s) + c_3(R_0 + \Delta R + r_0 + \Delta r - L_0 - x_2 + x_1) = 0, \\ m_2\ddot{x}_2 + h_2\dot{x}_2 + c_2x_2 - h_3(\dot{R} + \dot{r} - \dot{x}_2 + \dot{x}_1) - \\ -c_3(R_0 + \Delta R + r_0 + \Delta r - L_0 - x_2 + x_1) = 0. \end{cases} \tag{3}$$

For the initial position of the workpiece, Figure 2a, at the moment of the beginning of its contact with the tool ($L_0 = R_0 + r_0$, $s_0 = 0, x_{10} = 0, x_{20} = 20, t_f = 0$) system of equations (3) in deviations can be determined by the equation:

$$\begin{cases} m_1\ddot{x}_1 + h_1(\dot{x}_1 - \dot{s}) + h_3(\dot{R} + \dot{r} - \dot{x}_2 + \dot{x}_1) + \\ +c_1(x_1 - s) + c_3(R_0 + \Delta R + r_0 + \Delta r - L_0 - x_2 + x_1) = 0, \\ m_2\ddot{x}_2 + h_2\dot{x}_2 + c_2x_2 - h_3(\dot{R} + \dot{r} - \dot{x}_2 + \dot{x}_1) - \\ -c_3(R_0 + \Delta R + r_0 + \Delta r - L_0 - x_2 + x_1) = 0. \end{cases} \tag{4}$$

Due to the rotation of the wheel and the workpiece, variations in geometric dimensions are periodic or almost periodic, which explains the appearance of internal exciting forces that largely determine the dynamics of the grinding process. For further analysis, it is advisable to reduce the dynamic system (4) as follows:

$$\begin{cases} \ddot{x}_1 = \frac{1}{m_1}[-(h_1 + h_3)\dot{x}_1 - (c_1 + c_3)x_1 + h_3\dot{x}_2 + c_3x_2] - \\ -\frac{1}{m_1}\left[h_3\left(\dot{R} + \dot{r}\right) + c_3(\Delta R + \Delta r)\right] + \frac{1}{m_1}[h_1\dot{s} + c_1s], \\ \ddot{x}_2 = \frac{1}{m_2}[-(h_2 + h_3)\dot{x}_2 - (c_2 + c_3)x_2 + h_3\dot{x}_1 + c_3x_1] + \\ +\frac{1}{m_2}\left[h_3\left(\dot{R} + \dot{r}\right) + c_3(\Delta R + \Delta r)\right]. \end{cases} \tag{5}$$

The first terms of the right-hand sides of relations (5) are components with derivatives of the deviations of the positions of the centers of the circle and the part, depending directly on the internal generalized coordinates of the dynamic system (geometric and kinematic). The second terms reflect the influence of deviations in the shapes of the circle and the part. The third term of the first equation in system (5) reflects the impact of the cutting path and feed of the grinding wheel on the dynamic system.
With designations $y_1 = x_1$, $y_2 = \dot{y}_1 = \dot{x}_1$, $y_3 = x_2$, $y_4 = \dot{y}_3 = \dot{x}_2$ (5) can be reduced to the normal Cauchy form [11]:

$$\begin{cases} \dot{y}_1 = y_2, \\ \dot{y}_2 = -\frac{1}{m_1}[(c_1 + c_3)y_1 + (h_1 + h_3)y_2 - c_3y_3 - h_3y_4] - \\ -\frac{1}{m_1}\left[c_3(\Delta R + \Delta r) + h_3\left(\dot{R} + \dot{r}\right)\right] + \frac{1}{m_1}[h_1\dot{s} + c_1s], \\ \dot{y}_3 = y_4, \\ \dot{y}_4 = -\frac{1}{m_2}[(c_2 + c_3)y_3 + (h_2 + h_3)y_4 - c_3y_1 - h_3y_2] + \\ +\frac{1}{m_2}[c_3(\Delta R + \Delta r) + h_3(\dot{R} + \dot{r})] \end{cases} \tag{6}$$

and written in matrix form:

$$\dot{\boldsymbol{y}}_{\boldsymbol{0}} = \boldsymbol{A}_{\boldsymbol{0}} \cdot \boldsymbol{y}_{\boldsymbol{0}} + \boldsymbol{B}_{\boldsymbol{0}} \cdot \boldsymbol{\psi} + \boldsymbol{C}_{\boldsymbol{0}} \cdot \boldsymbol{u} \tag{7}$$

It is advisable to write down relation (7) together with the equation of observations to solve problems of modelling the dynamics of a process [17].
In the matrix form of the states' space, system takes the form:

$$\dot{\boldsymbol{y}}_{\boldsymbol{0}} = \boldsymbol{A}_{\boldsymbol{0}} \cdot \boldsymbol{y}_{\boldsymbol{0}} + \boldsymbol{B}_{\boldsymbol{0}} \cdot \boldsymbol{\psi} + \boldsymbol{C}_{\boldsymbol{0}} \cdot \boldsymbol{u}, \tag{8}$$

$$\boldsymbol{Z}_{\boldsymbol{0}} = \boldsymbol{E}_{\boldsymbol{0}} \cdot \boldsymbol{y}_{\boldsymbol{0}} + \boldsymbol{F}_{\boldsymbol{0}} \cdot \boldsymbol{V}_{\boldsymbol{0}}, \tag{9}$$

$$\begin{gathered} \boldsymbol{f} = \boldsymbol{y}_{\boldsymbol{0}} - \boldsymbol{B}_{\boldsymbol{02}} \cdot \Psi_1 \\ \boldsymbol{T}_{\boldsymbol{0}} = \boldsymbol{Q}_{\boldsymbol{0}} \cdot \boldsymbol{Z}_{\boldsymbol{0}} \end{gathered} \tag{10}$$

where:
y_0 is the vector of derivative states of the system – $y_0 = [y_1 \quad y_2 \quad y_3 \quad y_4]^T$,
$\dot{y}_0$ is the vector representing the system state vector – $\dot{y}_0 = [\dot{y}_1 \quad \dot{y}_2 \quad \dot{y}_3 \quad \dot{y}_4]^T$,
ψ is the state vector of deviations of the shape of a part and a circle from the nominal parameters – $\psi = \left[\psi_1 \quad \psi_2\right]^T$,
$\psi_1 = [\Delta R + \Delta r], \psi_2 = \left[\dot{R} + \dot{r}\right])$,
u is the vector of control actions associated with transverse feed – $u = [s \quad \dot{s}]^T$,
A_0 is the matrix characterizing the dynamic properties of the system,
B_0 is the matrix of parameters of the influence of deviations in the shape of the part and the circle,
C_0 is the process control matrix,
E_0 is the measurement state matrix,
F_0 is the noise intensity matrix of the meters,
V_0 is independent Gaussian white noise matrix of unit intensity meters,
T_0 is the cutting depth matrix,
Q_0 is the cumulative measurement transformation matrix:

$$A_0 = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\frac{c_1+c_3}{m_1} & -\frac{h_1+h_3}{m_1} & \frac{c_3}{m_1} & \frac{h_3}{m_1} \\ 0 & 0 & 0 & 1 \\ \frac{c_3}{m_2} & \frac{h_3}{m_2} & -\frac{c_2+c_3}{m_2} & -\frac{h_2+h_3}{m_2} \end{bmatrix},$$

$$B_0 = [B_{01} \quad B_{02}]\ B_{01} = \begin{bmatrix} 0 \\ -\frac{c_3}{m_1} \\ 0 \\ \frac{c_3}{m_2} \end{bmatrix}, B_{02} = \begin{bmatrix} 0 \\ -\frac{h_3}{m_1} \\ 0 \\ \frac{h_3}{m_2} \end{bmatrix},$$

$$C_0 = \begin{bmatrix} 0 & 0 \\ \frac{c_1}{m_1} & \frac{h_1}{m_1} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, E_0 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix},$$

$$F_0 = \begin{bmatrix} f_{11} & f_{12} \\ f_{21} & f_{22} \end{bmatrix}, V_0 = \begin{bmatrix} v_1 \\ v_2 \end{bmatrix}, T_0 = \left[t_f\right], Q_0 = [-1 \quad 1].$$

The cutting depth assessed in this way is not free from both errors determined by the quality of the

measurement process by the noise of the meters, and from the influence of random components of deviations of the shapes of the part and the circle from the nominal ones. Direct obtaining of the rate of change in the cutting depth dt_f/dt by differentiation determined in accordance with the ratios of the cutting depth t_f is impractical due to the presence of additive noise in the aggregate measurements.

An observation system in the form of the Kalman filter can be constructed to solve the problem of determining the speed of the cutting process.

However, direct application of model (8) when constructing an observer is impractical due to the need to differentiate the control signal and deviations of the shapes, which, in the presence of noise in the control channel [16] and computational errors in the implementation of differentiation, can lead to significant difficulties in applying this approach. This is neither a feature of the matrix representation of the model nor the description of the dynamic system in deviations but is already manifested in the initial representation (4) of the technological system.

To eliminate this drawback, it is necessary to construct a «recovery equation», which, in case of shape deviations, will have the expression:

$$\boldsymbol{X_0} = \boldsymbol{D_0} \cdot \boldsymbol{y_0}$$

where:

D_0 is a matrix characterizing the composition of estimates of state space parameters and the structure of their linear combinations.

If estimates of the entire state space are needed, then D_0 represents a unit matrix. Let us introduce a modified system state vector of the form:

where:

y_0, B_{02}, ψ_1 correspond to the expressions presented in dependence (8).

From the writing of relation (8) it immediately follows that $\Psi_1 = \Psi_2$ and from equation (10) it follows:

$$\boldsymbol{y_0} = \boldsymbol{f} + \boldsymbol{B_{02}} \cdot \Psi_1 \tag{11}$$

It is known, for example , that for any matrices that are compatible in form $\alpha(t)$ and $\beta(t)$ the following relation holds true: $\frac{d[\alpha(t)\cdot\beta(t)]}{dt} = \alpha(t)\frac{d\beta(t)}{dt} + \beta(t)\frac{d\alpha(t)}{dt}$.

The derivative $\dot{y}_0$ of the state vector (11), obtained taking into account equality (11) and the matrix identity given above, has the form:

$$\dot{\boldsymbol{y}}_{\boldsymbol{0}} = \dot{\boldsymbol{f}} + \dot{\boldsymbol{B}}_{\boldsymbol{02}} \cdot \boldsymbol{\Psi_1} + \boldsymbol{B_{02}} \cdot \boldsymbol{\Psi_2} \tag{12}$$

With the disclosure of split forms, matrix equations (8) can be rewritten as:

$$\dot{\boldsymbol{y}}_{\boldsymbol{0}} = \boldsymbol{A_0} \cdot \boldsymbol{y_0} + \boldsymbol{B_{01}} \cdot \Psi_1 + \boldsymbol{B_{02}} \cdot \Psi_2 + \boldsymbol{C_0} \cdot \boldsymbol{u} \tag{13}$$

Substitution into the right side of equation (13) Y_0 from (10) leads to the result:

$$\dot{\boldsymbol{y}}_{\boldsymbol{0}} = \boldsymbol{A_0} \cdot [\boldsymbol{f} + \boldsymbol{B_{02}} \cdot \Psi_1 + \boldsymbol{B_{01}} \cdot \Psi_1 + \boldsymbol{B_{02}} \cdot \Psi_2 + \boldsymbol{C_0} \cdot \boldsymbol{u} \tag{14}$$

From a comparison of the left sides of (12) and (14) it follows:

$$\dot{\boldsymbol{f}} + \dot{\boldsymbol{B}}_{\boldsymbol{02}} \cdot \Psi_1 + \boldsymbol{B_{02}} \cdot \Psi_2 = \boldsymbol{A_0} \cdot [\boldsymbol{f} + \boldsymbol{B_{02}} \cdot \Psi_1] + \boldsymbol{B_{01}} \cdot \Psi_1 + \boldsymbol{B_{02}} \cdot \Psi_2 + \boldsymbol{C_0} \cdot \boldsymbol{u} \tag{15}$$

After appropriate transformations and grouping, a modified equation of state can be written that does not contain ψ_2, and, therefore, does not require differentiation of the form parameters ψ_1:

$$\dot{\boldsymbol{f}} = \boldsymbol{A_0} \cdot \boldsymbol{F} + \left[\boldsymbol{A_0} \cdot \boldsymbol{B_{02}} + \boldsymbol{B_{01}} - \dot{\boldsymbol{B}}_{\boldsymbol{02}}\right] \cdot \Psi_1 + \boldsymbol{C_0} \cdot \boldsymbol{u} \tag{16}$$

Comparison of equation (16) for the modified state space F and the original relation (8) for the state space y_0 allows us to consider the coefficient in front of the matrix ψ_1:

$$\boldsymbol{B_1} = [\boldsymbol{A_0} \cdot \boldsymbol{B_{02}} + \boldsymbol{B_{01}} - \dot{\boldsymbol{B}}_{\boldsymbol{02}}] \tag{17}$$

as a modified matrix of the influence of the deviation of the shape of the part and the circle [8, 18].

If, in addition, the damping parameters of the contact zone, the mass of the workpiece and the grinding wheel during processing are taken to be independent of time, then the elements of the matrix $\dot{B}_{02}$ are equal to zero and expression (17) takes the form:

$$\boldsymbol{B_1} = [\boldsymbol{A_0} \cdot \boldsymbol{B_{02}} + \boldsymbol{B_{01}}] \tag{18}$$

The modified matrix differential equation of state space has the form:

$$\dot{\boldsymbol{f}} = \boldsymbol{A_0} \cdot \boldsymbol{F} + \boldsymbol{B_1} \cdot \Psi_1 + \boldsymbol{C_0} \cdot \boldsymbol{u} \tag{19}$$

Both the systems of differential equations (8) and (19) correspond, coinciding up to notations y_0, $\dot{y}_0$ and f, $\dot{f}$, to the systems of homogeneous linear differential equations:

$$\dot{\boldsymbol{y}}_{\boldsymbol{0}} = \boldsymbol{A_0} \cdot \boldsymbol{y_0} \tag{20}$$

and

$$\dot{\boldsymbol{f}} = \boldsymbol{A_0} \cdot \boldsymbol{f} \tag{21}$$

Consequently, the first equation of system (8) and relation (19) are equivalent in the sense of Lyapunov.

State assessment of X_0 based on the results of modelling the modified system (19) can be restored in states (9) by applying transformation (13) to the results (19):

$$\boldsymbol{X_0} = \boldsymbol{D_0} \cdot \boldsymbol{f} + \boldsymbol{D_0} \cdot \boldsymbol{B_{02}} \cdot \boldsymbol{\Psi_1} \tag{22}$$

where:

the matrices X_0, D_0, B_{02}, Ψ_1 correspond to the matrices used in (8), and the modified state vector f is determined by (22).

Using the considered approach, we represent the product of matrices $C_0 \cdot U_0$ of system (8) in the form:

$$\mathrm{C_0} \cdot \boldsymbol{U_0} = \mathrm{C_{00}} \cdot s + \mathrm{C_{01}} \cdot \dot{s} \tag{23}$$

where:

$\mathrm{C_{00}} = \left[\frac{c_1}{m_1}\right]^T$, $\mathrm{C_{01}} = \begin{bmatrix} 0 & \frac{h_1}{m_1} & 0 & 0 \end{bmatrix}^T$ and rebuild the model of system (8) in a form that does not require differentiation of the control signal. In this case, it is also necessary to transform the observation equations of the system in order to restore the states to be con-trolled, which allows us to obtain:

$$\begin{gathered} \dot{F} = \boldsymbol{A_0} \cdot \boldsymbol{f} + \boldsymbol{B_1} \cdot \Psi_1 + \boldsymbol{C_1} \cdot \boldsymbol{u}, \\ \boldsymbol{Z_0} = \boldsymbol{E_0} \cdot \boldsymbol{f} + \boldsymbol{F_0} \cdot \boldsymbol{V_0} + D_M \cdot s, \\ \boldsymbol{T_0} = \boldsymbol{Q_0} \cdot \boldsymbol{Z_0} \end{gathered} \tag{24}$$

where:

the matrices A_0, E_0, Z_0, F_0, V_0, T_0, Q_0 coincide with the same matrices in relations

(8) – $F = [F_1 \quad F_2 \quad F_3 \quad F_4]^T$, $\dot{F} = [\dot{F}_1 \quad \dot{F}_2 \quad \dot{F}_3 \quad \dot{F}_4]^T$, $C_1 = \begin{bmatrix} 0 & \frac{h_3 h_2}{m_1 m_2} & 0 & \frac{(h_3+h_2)h_2}{m_2^2} - \frac{c_2}{m_2} \end{bmatrix}^T$, $D_M = \begin{bmatrix} 0 & \frac{h_2}{m_2} \end{bmatrix}^T$.

ANALYTICAL SOLUTION TO THE PROBLEM

Each of the deviations of the form from the nominal ΔR_i, Δr_i their derivatives are random in nature, and can be characterized by second-order Gaussian-Markov random processes with correlation functions of the form [19, 20], which are presented in the form:

$$K_i(v_i,\tau) = \mathrm{K}_{0i} \cdot exp(-\alpha_i v_i|\tau_i|) \cdot cos(\beta_i v_i \tau_i) \qquad (25)$$

where:

ν_i is the peripheral speed of the circle or component part, respectively,

K_{0i}, α_i, β_i are parameters of the correlation function that can be determined experimentally.

In practically important cases, the effects caused by the mutual correlation functions of the processes and the corresponding energy mutual spectral densities are small relatively to the energy spectral characteristics of the circle and the part.

For such random processes, an extended forming filter was constructed using the same method, which makes it possible to represent the second term of the first equation of system (8) with equivalent parameters and variables of the state equations of the forming filters:

$$\begin{gathered} \dot{G} = A_f \cdot G + B_f \cdot W, \\ R = C_f \cdot G, \\ H_f = Q_f \cdot R, \end{gathered} \qquad (26)$$

where:

$G = \begin{bmatrix} G_1 \\ G_2 \end{bmatrix}$, $\dot{G} = \begin{bmatrix} \dot{G}_1 \\ \dot{G}_2 \end{bmatrix}$, $A_f = \begin{bmatrix} A_{f1} & A_k \\ A_k & A_{f2} \end{bmatrix}$, $B_f = \begin{bmatrix} B_{f1} & 0 \\ 0 & B_{f2} \end{bmatrix}$, $i \in \{к, д\}$, $G_i = \begin{bmatrix} g_{1i} \\ g_{2i} \end{bmatrix}$, $\dot{G}_i = \begin{bmatrix} \dot{g}_{1i} \\ \dot{g}_{2i} \end{bmatrix}$, $A_{fi} = \begin{bmatrix} 0 & 1 \\ \frac{1}{T_{1i}^2} & \frac{T_{2i}}{T_{1i}^2} \end{bmatrix}$,

$B_{fi} = \begin{bmatrix} k_{fi} \cdot T_{3i} \\ -1 - k_{fi} \cdot T_{3i} \cdot T_{2i} \end{bmatrix}$, $C_{fi} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, $H_f = \begin{bmatrix} \Delta\tilde{r}_i + \Delta\tilde{r}_i \\ \dot{\tilde{r}}_i + \dot{\tilde{r}}_i \end{bmatrix}$,

$Q_f = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix}$, $\Psi_w = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, $T_{1i} = \frac{1}{\nu_i{}^2(\alpha_i{}^2+\beta_i{}^2)}$, $T_{2i} = \frac{2\alpha_i}{\nu_i(\alpha_i{}^2+\beta_i{}^2)}$, $k_{fi} = \sqrt{\frac{2K_{0i}\alpha_i}{\nu_i(\alpha_i{}^2+\beta_i{}^2)}}$,

$g_{1i}, g_{2i}; g_{1i} = \dot{g}_{2i}$ are the auxiliary states of the shaping filter, w_1 and w_2 are independent of each other and the measurement noise V_0 Gaussian white noise of unit intensity.

$$\begin{gathered} \begin{bmatrix} \dot{F} \\ \dot{G}_f \end{bmatrix} = \begin{bmatrix} A_0 & B_1 \cdot Q_f \\ 0 & A_f \end{bmatrix} \cdot \begin{bmatrix} F \\ G_f \end{bmatrix} + \begin{bmatrix} C_1 \\ 0 \end{bmatrix} \cdot U + \begin{bmatrix} 0 \\ B_f \end{bmatrix} . W \\ Z_0 = E_0 \cdot Q_0 \begin{bmatrix} F \\ G_f \end{bmatrix} + F_0 \cdot V_0 + D_M \cdot U \\ \boldsymbol{T_0 = Q_0 \cdot Z_0} \end{gathered} \qquad (27)$$

Taking into account (26), the extended model of system (8) takes the form:

where:

additionally, $Q_f = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}$.

It is advisable to represent the first and second equations of system (27) in the form:

$$\begin{gathered} X = A \cdot X + B \cdot U + E \cdot W \\ Z = C \cdot X + R \cdot V \end{gathered} \qquad (28)$$

The form and structure of matrices in relations (28) are unambiguously determined by system (27).

It is possible to construct estimates of the state of the system that are optimal in the mean square sense in the form of the Kalman filter for system (28).

The minimum achievable dispersion of assessments of the system's state (28) can be estimated by the matrix Riccati equation of the form [9]:

$$\dot{\tilde{V}} = A \cdot \tilde{V} + \tilde{V} \cdot A^T + E \cdot \Psi_w \cdot E^T - \tilde{V} \cdot C^T \cdot \Psi_v^{-1} \cdot C \cdot \tilde{V} \qquad (29)$$

which is solved before the start of the processing of a specific part, due to the fact that it lacks the results of observations of the dynamic system.

The matrix coefficients of the reinforcement of the Kalman filter are determined by the following relationship:

$$K = \tilde{V} \cdot C \cdot \Psi_v^{-1} \qquad (30)$$

Taking into account (29), (30), the algorithm for filtering observations is determined by the matrix equations:

$$\dot{\hat{Y}} = A \cdot \hat{Y} + B \cdot U + K \cdot [Z - B \cdot U - C \cdot \hat{X}] \qquad (31)$$

and:

$$\begin{bmatrix} \hat{t}_f \\ \hat{t}_f \end{bmatrix} = \begin{bmatrix} -1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \cdot \hat{Y} \qquad (32)$$

Relations (30), (31) and (32) make it possible to use the results of coordinate measurements during the processing of a part in order to construct assessments of the parameters of the processing. These assessments are optimal provided that the measurement and excitation noises are Gaussian.

SUMMARY AND CONCLUSIONS

In the conditions of laboratory and research methods, as well as when estimating directly unmeasured parameters, additional frequencies caused by noise in the exterior were detected. With a correctly established diagnosis and evaluation of the results, it was recommended to use the proposed approach presented in the paper. Such a scientifically established approach, based on scientific apparatus and mathematical expressions, allows reducing the impact of measurement noise and noise associated with the calculation procedures of the relevant assessments. All this is also conditioned by the correct selection of sensors, filtering their outputs and using Kalman filters. They will allow us to register the source of frequencies caused by vibrations from the environment.

The above logic must be directly used in the implementation of stochastic observation and filtering procedures. This guarantees increased machining quality in the process of grinding workpieces. This significantly affects the process, especially when finishing operations by grinding. In the finishing process, the quality parameters of the finalized product are accumulated. And this time and the process of finalizing finishing work are most sensitive to external disturbing moments.

In current production facilities, up to 20% of the finishing operations of roller grinding are carried out in external conditions. They are designed using traditional methods. They reduce the stability of the grinding production process. Therefore, it is necessary to change these conditions

of precision manufacturing according to the research-based results presented in the article.

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Sergey Bratan
ORCID ID: 0000-0002-9033-1174
Sevastopol State University
33 Universitetskaya St., 299053 Sevastopol
e-mail: serg.bratan@gmail.com

Milan Sága
ORCID ID: 0000-0002-0938-8772
University of Zilina
Univerzitná 8215/1, 010 26 Žilina, Slovakia
e-mail: Milan.Saga@fstroj.uniza.sk

Boris Yakimovich
ORCID ID: 0000-0001-7363-1071
Sevastopol State University
7 Kurchatova St., 299015 Sevastopol
e-mail: yakimovich52@gmail.com

Pavol Bozek (corresponding author)
ORCID: 0000-0002-3891-3847
University of Zilina
Univerzitná 8215/1, 010 26 Žilina, Slovakia
e-mail: pavol.bozek@fstroj.uniza.sk

Nikolay Pokintelista
ORCID ID: 0000-0002-0277-8252
Sevastopol State University
33 Universitetskaya St., 299053 Sevastopol
e-mail: nik.pokintelitsa@mail.ru

Chingiz Yakubov
ORCID ID: 0000-0003-4029-8553
Crimean Engineering and Pedagogical University
Uchebniy side St. 8, 295055 Simferopol
e-mail: yakubov_chingiz@mail.ru