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Method of building dynamic relations, estimating product and grinding circle shape deviations

Stanislav Roshchupkin[1,*], and *Alexander* Kharchenko[1]

[1]Sevastopol State University, Department of Mechanical Engineering, 299053 Sevastopol, Russia

Abstract. The article deals with the method of constructing dynamic relations in the synthesis of automatic control systems for finishing machining processes, including smooth and fine grinding. A method is developed of estimating workpiece shape and grinding wheel deviations when external disturbances impact the object. The application of the proposed approach is useful while estimating non-measurable parameters, which allows to reduce influence of the measurement noises and noises associated with the computational procedures of the corresponding estimation.

The improvement of products processing quality requires the use of automatic control systems for handling technological operations. The mentioned task is becoming more relevant for finishing machining processes, including smooth and fine grinding [1-4]. When building such systems, it is required to obtain reliable information about the values and trends of changing of the technological process output parameters in real time [5-7]. However, not all the necessary parameters are available for immediate measurement, or their measurement can be followed by great technical difficulties. These parameters include, for example, the actual depth of cut, to determine the values of which it is advisable to use the estimations obtained by the methods of the theory of dynamic estimates and filtering using available for direct measurement data on the technological process [8]. At the same time, it is necessary to describe the technological process in the states space and the equations for reconstructing the desired technological process parameters from the technological process simulation results [9].

When constructing automatic systems it is necessary to solve the problem connected with the fact that the measurements results of the technological process parameters are not free from errors that are both natural and random, reflecting the processes of different physical nature that are not taken into account in the building of the system and lead to dynamic deviations in the computational models (including the parameters of the instrument). Errors in such information signals directly affect the detected feedback signals of automatic control systems and lead to the corresponding processing errors and the scatter of the product quality indicators.

[*] Corresponding author: st.roshchupkin@yandex.ru

To increase the sensitivity of control systems to deviations of parameters and, especially to tendencies of their change, control systems with feedback including the derivative are used. However, the errors of the measuring signal increase substantially due to the dependence not only on the error amplitudes of the initial representations, but also on the rates of their change.

Such problem is relevant in the synthesis of control systems for smooth and fine grinding processes. Its solution requires the modification of dynamic relations that do not require differentiation of measurements [10].

Modifications of the state space (“system model”) and the corresponding changes in the “observation equations” are rational to represent as a separate subsystem of the “states recovery equations” and “subsystem of observations”. In [11], the method [8] based on the method of undetermined coefficients was used to solve the problem, but the formulation of the “equation of state recovery” is associated with significant difficulties.

The aim of this work is to develop a method for building dynamic relations that do not require differentiation of measurement signals when estimating product shape and grinding wheel deviations for smooth and fine grinding.

In accordance with the method [8], the dynamic description of the processes of smooth and fine grinding in the form of a state space has the form:

$$\dot{Y}_0 = \mathrm{A}_0 \cdot \mathrm{Y}_0 + \mathrm{B}_0 \cdot \Psi + \mathrm{C}_0 \cdot \mathrm{U}, \tag{1}$$

$$\text{где } \dot{Y}_0 = \begin{bmatrix} \dot{y}_1 \\ \dot{y}_2 \\ \dot{y}_3 \\ \dot{y}_4 \end{bmatrix}, \ Y_0 = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix}, \ B_0 = \begin{bmatrix} B_{01} & B_{02} \end{bmatrix}$$

$$\mathrm{U} = \begin{bmatrix} \Delta\mathrm{L} \\ \dot{\mathrm{L}} \end{bmatrix}, \ \Psi = \begin{bmatrix} \Psi_1 \\ \Psi_2 \end{bmatrix}, \ \Psi_1 = [\Delta R + \Delta r],. \ \Psi_2 = [\Delta\dot{R} + \Delta\dot{r}] \ ,$$

$$B_{01} = \begin{bmatrix} 0 \\ -\dfrac{c_3}{m_1} \\ 0 \\ -\dfrac{c_3}{m_2} \end{bmatrix}, \ B_{02} = \begin{bmatrix} 0 \\ -\dfrac{h_3}{m_1} \\ 0 \\ -\dfrac{h_3}{m_2} \end{bmatrix}, \ C_0 = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \dfrac{c_2}{m_2} & \dfrac{h_2}{m_2} \end{bmatrix},$$

Y_0 – vector (matrix-column) representing the state vector of the system; $\dot{Y}_0$ – vector of the derivative states of the system; A_0 – matrix characterizing the dynamic properties of the system; B_0 – matrix of influence parameters of detail and circle shape deviation; Ψ – vector of states of detail and circle shape deviations from the nominal parameters; C_0 – process control matrix (due to transverse feed); U – vector of control actions associated with the transverse feed.

To describe the process, the following notations are introduced:

L, x_1, x_2 – center-to-center distance, grinding wheel and the details center coordinates deviations relative to the corresponding positions of dynamic equilibrium;

R_k, c_1, h_1, m_1 – radius of the circle, its unit stiffness, damping coefficient and mass;

$r_\partial, c_2, h_2, m_2$ – radius of the detail, its unit stiffness, damping coefficient and mass;

c_3, h_3 – equivalent parameters of the circle and detail contact zone.

$$\mathrm{L}(\tau) = R(\phi(\tau)) + r(\varphi(\tau)) - t_f(\tau) - \int_{\tau_0}^{\tau} \dot{S} d\tau + y_T - y_{УП} \quad (2)$$

where t_f is the depth of insertion of the cutting circle grains into the workpiece material, counted from its original surface; $\dot{S}$ – transverse feed; y_T, $y_{УП}$ – temperature and elastic deformations of the technological system

In expression (1), the matrix B_0 представлена is represented in block form in a split in columns form. The purposefulness of such a description will be shown below.

To restore the variables in the form corresponding to (1), it is necessary to construct a "state recovery equation", which in this case will have the expression:

$$X_0 = D_0 \cdot \mathrm{Y}_0, \quad (3)$$

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

If the estimates of the entire state space are required, then it is an identity matrix.

As mentioned above, the direct application of matrix representations (1) in modelling is inexpedient because of the need to differentiate the form deviations. To overcome these difficulties, we introduce a modified system state vector in the form of:

$$F = Y_0 - B_{02} \cdot \Psi_1, \quad (4)$$

where Y_0, B_{02}, Ψ_1 correspond to expressions represented in the dependence (1).

It follows directly from the relation (1) that $\dot{\Psi}_1 = \Psi_2$. And from equation (4) it follows:

$$Y_0 = F + B_{02} \cdot \Psi_1. \quad (5)$$

It is known, for example [12], that for any matrices compatible in form $\alpha(t)$ and $\beta(t)$ the relation $\frac{d[\alpha(t) \cdot \beta(t)]}{dt} = \alpha(t)\frac{d\beta(t)}{dt} + \beta(t)\frac{d\alpha(t)}{dt}$ is just.

The derivative $\dot{Y}_0$ of the state vector (4), obtained taking into account equality (5) and the above-mentioned matrix identity, has the following form:

$$\dot{Y}_0 = \dot{F} + \dot{B}_{02} \cdot \psi_1 + B_{02} \cdot \psi_2. \quad (6)$$

With the decomposition of the split forms, the matrix equation (1) can be rewritten as:

$$\dot{Y}_0 = \mathrm{A}_0 \cdot \mathrm{Y}_0 + \mathrm{B}_{01} \cdot \Psi_1 + \mathrm{B}_{02} \cdot \Psi_2 + \mathrm{C}_0 \cdot \mathrm{U} \tag{7}$$

Substitution in the right-hand side of equation (7) Y_0 from (4) from (4) leads to the result:

$$\dot{Y}_0 = A_0 \cdot [F + B_{02} \cdot \Psi_1] + B_{01} \cdot \Psi_1 + B_{02} \cdot \Psi_2 + C_0 \cdot U \,. \tag{8}$$

Comparison of the left-hand sides of (6) and (8) implies:

$$\dot{F} + \dot{B}_{02} \cdot \psi_1 + B_{02} \cdot \psi_2 = A_0 \cdot [F + B_{02} \cdot \Psi_1] + B_{01} \cdot \Psi_1 + B_{02} \cdot \Psi_2 + C_0 \cdot U \,,$$

that after the corresponding transformations and realignments enables to write down a modified equation of state that does not contain Ψ_2 and, therefore, does not require differentiating the parameters of the forms Ψ_1:

$$\dot{F} = A_0 \cdot F + [A_0 \cdot B_{02} + B_{01} - \dot{B}_{02}] \cdot \Psi_1 + C_0 \cdot U. \tag{9}$$

Comparison of equation (9) for the modified state space F and the initial relation (1) for the state space Y_0 allows us to consider the coefficient before the matrix Ψ_1:

$$B_1 = [A_0 \cdot B_{02} + B_{01} - \dot{B}_{02}], \tag{10}$$

as a matrix of the influence of the detail and the circle shape deviation for the modified state. If, in addition, the parameters of damping of the contact zone, workpiece and grinding wheel mass during the processing can be adopted independent of time, then the elements of the matrix $\dot{B}_{02}$ equal zero and the expression (10) takes the form:

$$B_1 = [A_0 \cdot B_{02} + B_{01}].$$

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

$$\dot{F} = A_0 \cdot F + B_1 \cdot \Psi_1 + C_0 \cdot U. \tag{11}$$

Both the system of differential equations (1) and the system (11) corresponding with an accuracy to the notations $Y_0, \dot{Y}_0$ и $F, \dot{F}$ systems of homogeneous linear differential equations $\dot{Y}_0 = \mathrm{A}_0 \cdot \mathrm{Y}_0$ and $\dot{F} = A_0 \cdot F$. Consequently, systems (1) and (11) are equivalent in the sense of Lyapunov [13].

The state estimation X_0 based on the simulation results of the modified system (11) can be reconstructed in states (3) by applying the transformation (7) to the results (11):

$$X_0 = D_0 \cdot F + D_0 \cdot B_{02} \cdot \Psi_1 \,, \tag{12}$$

where the matricies X_0, D_0, B_{02}, Ψ_1 correspond to the matrices used in (1), and the modified state vector is determined by (11).

The application of the proposed approach is useful when estimating directly non-measurable parameters (for example, the actual depth of cutting) and allows to reduce the influence of both measurement noise and noises associated with the computational procedures of the corresponding estimations. It must be directly used in the implementation of procedures for stochastic observation and filtration in the building of control systems for technological processes of smooth and fine grinding.

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