Synthesis of the subsystem of supervision for grinding operation

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Abstract. The article discusses the issues of building a dynamic system for assessing the state of a flat grinding operation, taking into account the statistical characteristics of the disturbances. To build the Kalman-Bucy filter, a program has been developed that allows solving the Riccati equations of the object and the filter. The calculation of the Kalman-Bussy filter coefficients for the stationary mode of the flat grinding process has been performed. This allows you to assess the state of the system in real time, and even in the case of measuring only one coordinate, the filter gives estimates of all coordinates, and the maximum estimation errors do not exceed 10%.

1. Introduction
One of the most common methods for machining parts is grinding. Achieving the specified quality parameters during processing is possible by taking into account the dynamics of the technological system [1, 2]. Under these conditions, the task of assessing the state of the operation on the basis of statistical characteristics of disturbances for the stationary mode of the grinding process, as well as creating and improving highly effective finishing methods for processing products, under which the system state is evaluated in real time to form the specified quality parameters, becomes particularly relevant.

2. Modeling process dynamics
Based on the analysis of the interaction of the elements of the dynamic system, taking into account the presentation of the grinding process in the form of a mathematical model, one can construct a description of the dynamics of the machining process in the form [1]:

\[
\begin{align*}
    m_1 \ddot{x}_1 + h_1 \dot{x}_1 + c_1 (x_{10} + x_1) + h_3 (\dot{x}_1 + \Delta \dot{R}) + c_3 (x_{10} + x_1 + R + \Delta R) - h_2 (\dot{x}_2 - \Delta \dot{R}) - \\
    - c_3 (x_{20} + x_2 - k - \Delta k) &= 0, \\
    m_2 \ddot{x}_2 + h_2 \dot{x}_2 + c_2 (x_{20} + x_2) + h_3 (\dot{x}_2 - \Delta \dot{R}) + c_3 (x_{20} + x_2 - k - \Delta k) - h_2 (\dot{x}_1 + \Delta \dot{R}) - \\
    - c_3 (x_{10} + x_1 + R + \Delta R) - h_2 L - c_2 (L + \Delta L) &= 0,
\end{align*}
\]

where \( m_1, m_2 \) – the reduced mass of the workpiece with the device and the circle with the spindle; \( h_i \) – the coefficient of resistance of the \( i \)-th link; \( c_i \) – the stiffness coefficient of the \( i \)-th link; \( x_{10}, x_{20}, x_1, x_2 \) – coordinates of the center of rotation of the circle and the base surface of the part and their...
increments, respectively; \( R \) – the radius of the circle; \( k \) – the corresponding linear size of the part; \( \Delta R, \Delta k \) – variations of the radius of the circle and the linear size of the workpiece, respectively; \( L, \Delta L \) – the distance from the base surface of the part to the center of rotation of the circle and its change along the machine limb.

Under the condition of the power circuit of the technological system and the nominal processing modes, relations are constructed characterizing the dynamics of the process in variations:

\[
\begin{align*}
\dot{m}_1 x_1 + h_1 x_1 &+ c_1 x_1 + h_3 (x_1 + \Delta R) + c_3 (x_1 + \Delta R) - h_3 (x_2 - \Delta k) - c_3 (x_2 - \Delta k) = 0, \\
\dot{m}_2 x_2 + h_2 x_2 &+ c_2 x_2 + h_3 (x_2 - \Delta k) + c_3 (x_2 - \Delta k) - h_3 (x_1 + \Delta R) - c_3 (x_1 + \Delta R) - h_2 L - c_2 \Delta L = 0.
\end{align*}
\]

It is expedient to present the system (2) in the form of the Frobenius state space:

\[
\dot{Z}_0 = A_0 Z_0 + B_0 W_0 + C_0 U_0
\]

or

\[
\begin{bmatrix}
\dot{z}_1 \\
\dot{z}_2 \\
\dot{z}_3 \\
\dot{z}_4
\end{bmatrix} =
\begin{bmatrix}
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
-\alpha_0 & 0 & 0 & 1 \\
-\alpha_4 & -\alpha_3 & -\alpha_2 & -\alpha_1
\end{bmatrix}
\begin{bmatrix}
z_1 \\
z_2 \\
z_3 \\
z_4
\end{bmatrix} +
\begin{bmatrix}
\gamma_1 \\
\gamma_2 \\
\gamma_3 \\
\gamma_4
\end{bmatrix} (R_1 + R_2) + 
\begin{bmatrix}
0 \\
\lambda_1 \\
\lambda_2 \\
\lambda_3
\end{bmatrix} S,
\]

where \( z_1 = x_1, \ z_2 = z_1 p = \dot{x}_1, \ z_3 = z_2 p = \dot{x}_1, \ z_4 = z_3 p = \ddot{x}_1, \ z_5 = z_4 p = \dddot{x}_1; \)

\( R_1 = \Delta R; \ R_2 = \Delta k; \ \Delta L = S; \ \lambda_1 = \beta_1; \ \lambda_2 = \beta_1 - \alpha_3 \lambda_1; \ \lambda_3 = \beta_0 - \alpha_3 \lambda_2 - \alpha_3 \lambda_1; \)

\( \alpha_1 = (m_1 m_2); \ \alpha_2 = (h_2 h_3 + h_2 h_2 + c_1 m_2 + c_1 m_1 + c_3 m_2 + c_2 m_1); \)

\( \alpha_3 = (h_3 m_2 + h_2 m_2 + h_2 m_1 + h_3 m_1); \ \alpha_4 = (c_2 h_2 + c_1 h_2 + c_1 h_1 + c_1 h_1); \)

\( \alpha_0 = (c_1 c_2 + c_1 c_3 + c_1 c_3); \)

\( \chi_1 = h_3 m_2; \ \chi_2 = (c_3 m_2 + h_2 h_3); \ \chi_3 = (c_3 h_2 + c_2 h_3); \)

\( \beta_1 = h_2 h_3; \ \beta_0 = c_2 c_3; \)

\( \gamma_1 = -h_3 m_2 = -\chi_5; \)

\( \gamma_2 = -(c_3 m_2 + h_2 h_3) - (h_3 m_2 + h_2 m_2 + h_2 m_1 + h_3 m_1) (-h_3 m_2) = -\chi_2 - \alpha_3 \chi_1; \)

\( \gamma_3 = -(c_3 h_2 + c_1 h_2) - (h_3 m_2 + h_2 m_2 + h_2 m_1 + h_3 m_1) (-h_3 m_2) = -\chi_3 - \alpha_3 \gamma_2 - \alpha_2 \gamma_1; \)

\( \gamma_4 = -c_2 c_3 - (h_3 m_2 + h_1 m_2 + h_2 m_1 + h_3 m_1) (-h_3 m_2) = -\chi_0 - \alpha_4 \gamma_3 - \alpha_3 \gamma_2 - \alpha_2 \gamma_1; \)

\( \gamma_5 = -(c_3 m_2 + h_2 h_3) - (h_3 m_2 + h_2 m_2 + h_2 m_1 + h_3 m_1) (-h_3 m_2) = -\chi_1 - \alpha_3 \gamma_3 - \alpha_2 \gamma_1; \)

\( \gamma_6 = -(c_3 h_2 + c_1 h_2) - (h_3 m_2 + h_2 m_2 + h_2 m_1 + h_3 m_1) (-h_3 m_2) = -\chi_2 - \alpha_3 \gamma_2 - \alpha_2 \gamma_1; \)

\( \gamma_7 = -c_2 c_3 - (h_3 m_2 + h_1 m_2 + h_2 m_1 + h_3 m_1) (-h_3 m_2) = -\chi_0 - \alpha_4 \gamma_3 - \alpha_3 \gamma_2 - \alpha_2 \gamma_1; \)
The controllability of system (3) can be analyzed using the numerical values of the above parameters for the matrices of the object $A_0$ and the control $C_0$.

Analysis of work in the field of research into the dynamics of grinding processes [1-4] shows that the most unstable link in the dynamic system under consideration is the grinding wheel. In accordance with model (2), the main parameters of the grinding wheel, which influence the dynamics of the machining process, are static (deviations of the circle shape from the ideal in the static mode) and dynamic (deviations of the shape, caused directly by the machining process) variations of its profile. The latter include the deviations of the trajectory of the surface of a circle from the given trajectories due to its imbalance, which have a deterministic character. They can be significantly reduced by known technological methods, such as pre-balancing a circle. The deviations of the grinding wheel shape in the static mode are random and can be taken into account by introducing into the system (3) an additional link - the corresponding shaping filter [5, 6]. Such a filter can be built, for example, on the basis of an analysis of the profile of any particular grinding wheel with a representation of the effect on the system (3) in the state space as equations of state (4) and observation (5):

\[
\dot{G}_1 = A_1 G_1 + B_1 w_1, \quad y_1 = D_1 G_1 + E_2 v_2
\]

where $G_1 = \begin{bmatrix} \psi_1 \\ \psi_2 \end{bmatrix}$, $A_1 = \begin{bmatrix} 0 & \frac{1}{T_2} \\ -\frac{T_2}{T_1^2} & \frac{1}{T_1^2} \end{bmatrix}$, $B_1 = \begin{bmatrix} K T_3 \\ -1 - KT_2 T_3 \end{bmatrix}$, $D_1 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$, $E_2 = \rho$.

$w_1, v_2$ – uncorrelated single generating Gaussian white noises,

\[
T_1 = \frac{1}{v^2 (\alpha^2 + \beta^2)}, \quad T_2 = \frac{2 \alpha}{v (\alpha^2 + \beta^2)}, \quad T_3 = \frac{1}{v (\alpha^2 + \beta^2)}, \quad K = \sqrt{2} \frac{D \alpha}{v (\alpha^2 + \beta^2)},
\]

$D$ – the dispersion of the heights of the irregularities of the relief of the grinding wheel; $v$ – its speed of movement; $\alpha, \beta$ – the corresponding correlation coefficients.

Taking $w_0 = y_1$ into account the introduction of the shaping filter (4), the system (3) takes the form:

\[
\begin{cases}
\dot{x}_o = A_o x_o + B_o y_1 + C_o u_o \\
\dot{G}_1 = A_1 G_1 + B_1 w_1 \\
y_1 = D_1 G_1 + E_2 v_2 \\
y_o = D_o x_o + E_o y_o
\end{cases}
\]

where it immediately follows:

\[
\begin{cases}
\dot{x}_o = A_o x_o + B_o D_1 G_1 + B_o E_2 v_2 + C_o u_o \\
G_1 = A_1 G_1 + B_1 w_1 \\
y_o = D_o x_o + E_o y_o
\end{cases}
\]

that allows us to represent the equation of state of the grinding process, taking into account the disturbances determined by the statistical characteristics of the circle as the state of the expanded object in the form:
The object is subject to random effects. Therefore, in solving control problems, the results of assessing the state of the technological system, which have a statistical connection with observational data, are measured with significant random errors or are not measured at all. In this case, the movement of the control object are measured with significant random errors or are not measured at all. In this case, the measurement of all state variables of an object and the availability of complete a priori information about the parameters of the technological system [7-11].

Analysis of the grinding operation shows that the phase coordinates necessary for controlling the grinding operation imply the possibility of accurate measurements of the technological system [7-11]. Denote random noise vector accompanying measurements,

System (7) represents the standard form for describing a dynamic system in terms of the theory of state space.

Solving problems of optimal control of grinding operations implies the possibility of accurate measurement of all state variables of an object and the availability of complete a priori information about the parameters of the technological system [7-11].

Analysis of the grinding operation shows that the phase coordinates necessary for controlling the object are measured with significant random errors or are not measured at all. In this case, the movement of the control object is subject to random effects. Therefore, in solving control problems, the use of deterministic methods is not acceptable. In such a situation, it is necessary to have the results of assessing the state of the technological system, which have a statistical connection with observational data.

To construct a stochastic observer, consider the dependences (7), (6).

Denote by

\[
Z(t) = \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \\ \psi_1 \\ \psi_2 \end{bmatrix} - \text{system state vector, } U(t) = S - \text{control, } W(t) = \begin{bmatrix} V_2 \\ W_1 \end{bmatrix} - \text{random action vector, } v(t) = v_0 - \text{random noise vector accompanying measurements,}
\]

\[
A(t) = \begin{bmatrix}
0 & 1 & 0 & 0 & \gamma_1 & 0 \\
0 & 0 & 1 & 0 & \gamma_2 & 0 \\
-\frac{\alpha_0}{\alpha_4} & -\frac{\alpha_1}{\alpha_4} & -\frac{\alpha_2}{\alpha_4} & -\frac{\alpha_3}{\alpha_4} & \gamma_3 & 0 \\
0 & 0 & 0 & 1 & \gamma_4 & 0 \\
0 & 0 & 0 & 0 & -\frac{1}{T_1} & \frac{T_2}{T_1} \\
0 & 0 & 0 & 0 & -\frac{1}{T_2} & \frac{T_2}{T_1} 
\end{bmatrix}, \quad B(t) = \begin{bmatrix}
\rho \gamma_1 & 0 \\
\rho \gamma_2 & 0 \\
\rho \gamma_3 & 0 \\
\rho \gamma_4 & 0 \\
kT_3 & 0 \\
0 & -1 - kT_2 T_3 
\end{bmatrix},
\]
Then the equations of motion of the system and the measured output coordinates can be represented as:

\[
\begin{align*}
\dot{z} &= A(t)z(t) + B(t)w(t) + C(t)u(t) \\
y(t) &= H(t)z(t) + E(t)v(t)
\end{align*}
\] (8)

A graphical interpretation of system (8) is presented in Fig. 1. It is assumed that random effects \( w \) and interference \( v \) are random Gaussian processes such as white noise with zero expectation \( \mathbb{E}[w(t)] = 0, \mathbb{E}[v(t)] = 0 \), then their correlation matrices are described by the expressions:

\[
\text{cov}(w(t), w(\tau)) = M[w(t)w(\tau)^\top] = Q(t)\delta(\tau - \tau),
\]

\[
\text{cov}(v(t), v(\tau)) = M[v(t)v(\tau)^\top] = R(t)\delta(\tau - \tau),
\]

where \( \delta(t) \) – Dirac delta function; \( Q(t) \) – symmetric, non-negative definite intensity matrix of the white noise system \( w(t) \); \( R(t) \) – symmetrical, positive-definite white noise intensity matrix of measurements \( v(t) \).

Given that the initial state of the system \( z(t_0) \) is a random Gaussian vector with a known expectation \( \mathbb{E}[z(t_0)] = \bar{z}_0 \)

and correlation matrix \( \text{cov}(z(t_0), \bar{z}_0) = M[z(t_0)\bar{z}_0]^\top = P(t_0) = P_0 \),

and the fact that random effects and measurement errors for all \( t \geq t_0 \) are not mutually correlated [5-8]:

\[
\text{cov}(z(t_0), w(t)) = M[z(t_0) - \bar{z}_0][w(t)]^\top = 0, \text{cov}[z(t_0), v(t)] = M[z(t_0) - \bar{z}(t_0)][v(t)]^\top = 0,
\]

\[
\text{cov}[w(t), v(\tau)] = M[w(t)v(\tau)^\top] = 0,
\]

find a linear unbiased vector estimate

\[
\hat{Z}(t) = \begin{bmatrix} \hat{z}_1 \\ \hat{z}_2 \\ \hat{z}_3 \\ \hat{z}_4 \\ \hat{y}_1 \\ \hat{y}_2 \end{bmatrix},
\]

built on the basis of observations \( y(\tau), (t_0 \leq \tau \leq t) \).
We denote this estimate by \( \hat{x}(t) = z(t) \). Such an estimate can be obtained at the output of the filter described by the vector differential equation [5]:

\[
\dot{x}(t) = F(t) + G(t)u(t) + K(t)y(t)
\]

(9)

with estimation error
\[
e(t) = z(t) - \hat{x}(t).
\]

(10)

In order for the process at the output of the filter to be an unbiased estimate, the following equality must be satisfied:
\[
M[\hat{z}(t)] = M[z(t)] = \bar{z}(t).
\]

(11)

Calculating the expectation of both sides of equation (10), we get:
\[
M[\hat{x}(t)] = F(t)M[x(t)] + G(t)u(t) + K(t)M[y(t)].
\]

Then, given that \( M[y(t)] = H(t)M[z(t)] \), based on (11), the differential equation for the average value of the state vector of the system is written in the form:
\[
\dot{\bar{z}}(t) = [F(t) + K(t)H(t)]\bar{z}(t) + G(t)u(t).
\]

(12)

After calculating the expectation from both sides of equation (8), we obtain the equation for the technological system
\[
\dot{\bar{z}} = A(t)\bar{z}(t) + C(t)u(t)
\]
or
\[
\begin{bmatrix}
\dot{\bar{z}}_1 \\
\dot{\bar{z}}_2 \\
\dot{\bar{z}}_3 \\
\dot{\bar{z}}_4 \\
\end{bmatrix} =
\begin{bmatrix}
0 & 1 & 0 & 0 & \gamma_1 & 0 \\
0 & 0 & 1 & 0 & \gamma_2 & 0 \\
0 & 0 & 0 & 1 & \gamma_3 & 0 \\
\alpha_0 & \alpha_1 & \alpha_2 & \alpha_3 & \gamma_4 & 0 \\
\end{bmatrix}
\begin{bmatrix}
\bar{z}_1 \\
\bar{z}_2 \\
\bar{z}_3 \\
\bar{z}_4 \\
\end{bmatrix} +
\begin{bmatrix}
\lambda_1 \\
\lambda_2 \\
\lambda_3 \\
\end{bmatrix}
\times S.
\]

(13)

Comparing (12) and (13), we write the first condition for unbiasedness of the state vector estimate using the considered filter:
\[
F(t) = A(t) - K(t)H(t); \; G(t) = C(t).
\]

(14)

The second condition is that equations (11) and (12) are solved with the same initial condition:
\[
\bar{z}_0 = M[\hat{z}(t_0)] = M[z(t_0)] = \bar{z}_0.
\]

(15)

If the conditions of unbiasedness (14) and (15) are met, then the filter equation (9) takes the form:
In expression (16), the matrix of gains of the filter $K(t)$ remains unknown, which provides an optimal estimate at which the components of the estimation error have a minimum variance.

The matrix of coefficients of such a filter is determined by the expression [5]:

$$
K(t) = P(t)H^T(t)R^{-1}(t),
$$

(17)

where $P(t)$ – error correlation matrix for $M[e(t)] = 0$ $P(t) = M[e(t)e^T(t)]$.

Since the initial value of the matrix $P(t)$:

$$
P(t_0) = M\left[z(t_0) - z_0\right]\left[z(t_0) - z_0^T\right]^T
$$

(18)

and $z(t_0) = x_0$, $x(t_0) = z_0$ then according to (16):

$$
P(t_0) = P_0.
$$

The correlation error matrix is a solution to the matrix Riccati differential equation [5,12]:

$$
\dot{P}(t) = A(t)P(t) + P(t)A^T(t) - P(t)H^T(t)R^{-1}(t)H(t)P(t) + B(t)Q(t)C^T(t),
$$

which should be solved under the initial conditions (18). When grinding products for each specific mode of the matrix $A, B, C$ and $H$ are constant.

Let's pretend that $Q = M\left[W(t)W^T(\tau)\right]$ and $R = M\left[V(t)V^T(\tau)\right]$, describing the statistical characteristics of noise are constant when processing the surface of a single part, then the technological system defined by equations (8) is stationary (Figure 1).
Figure 1. Block diagram of a stationary system with a Kalman filter.

For such a system, the Kalman-Buss filter equation takes the form:

\[
\begin{bmatrix}
\hat{z}_1 \\
\hat{z}_2 \\
\hat{z}_3 \\
\hat{z}_4 \\
\hat{\psi}_1 \\
\hat{\psi}_2
\end{bmatrix}
= \begin{bmatrix}
0 & 1 & 0 & 0 & \gamma_1 & 0 \\
0 & 0 & 1 & 0 & \gamma_2 & 0 \\
0 & 0 & 0 & 1 & \gamma_3 & 0 \\
0 & 0 & 0 & 0 & \frac{1}{\alpha_4} & \gamma_4 \\
0 & 0 & 0 & 0 & 0 & \frac{1}{\alpha_4}
\end{bmatrix}
\times
\begin{bmatrix}
\hat{z}_1 \\
\hat{z}_2 \\
\hat{z}_3 \\
\hat{z}_4 \\
\hat{\psi}_1 \\
\hat{\psi}_2
\end{bmatrix}
+ \begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
0 \\
0
\end{bmatrix}
\times S
+ \begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
0 \\
0
\end{bmatrix}
\times
\begin{bmatrix}
K_1 \\
K_2 \\
K_3 \\
K_4 \\
K_5 \\
K_6
\end{bmatrix}
\times
\begin{bmatrix}
y
\end{bmatrix}
\]

Then the matrix of filter gains is constant and is determined by the expression:

\[
\hat{K} = \hat{P} \hat{H} R^{-1},
\]

where \( \hat{P} \) – positive definite matrix that is a solution of the algebraic matrix Riccati equation:
As a result of the program, we obtained numerical data characterizing the quality of the filter operation (Figure 2 and Figure 3).

From here, the matrix $\hat{P}$ can be obtained as a steady-state solution of a differential equation:

$$\dot{\hat{P}} = A\hat{P} + \hat{P}A^T - PH^T R^{-1} HP + CQC^T,$$

at $P = \lim_{t \to \infty} P(t)$. The constancy of the matrix $\hat{K}$ allows you to implement a family of linear software filters using a computer.

3. Perspective of use

To build the Kalman-Bucy filter, a program has been developed that allows solving the Riccati equations of the object and the filter [13-15].

To illustrate the work of the program, the coefficients of the Kalman-Bussy filter are calculated for the stationary mode of the camshaft journal grinding process with the following initial data: $m_i = 150, \ m_{iz} = 15, \ c_1 = 1e7, \ c_2 = 1.5e7, \ c_3 = 1e7, \ h_1 = 2.1e4, \ h_2 = 1.3e4, \ h_3 = 1e4, \ D_\nu = 0.36\times10^{-12}, \ \alpha = -0.033, \ \beta = 2.93$.

As a result of the program, we obtained numerical data characterizing the quality of the filter operation (Figure 2 and Figure 3).

Figure 2. Dependence of filter gains on time.  

Figure 3. The dependence of the variance of estimates from of time.
4. Conclusions
An analysis of the results of the calculations shows that the steady state of the filter occurs in 0.4 seconds (which corresponds to one revolution of the part during round grinding). This allows you to assess the state of the system in real time, and, even in the case of measuring only one coordinate, the filter gives estimates of all coordinates, and the maximum estimation errors do not exceed 10%.

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