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Method of Individual Forecasting of Technical State of Logging Machines

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Abstract. Development of the model that evaluates the possibility of failure requires the knowledge of changes’ regularities of technical condition parameters of the machines in use. To study the regularities, the need to develop stochastic models that take into account physical essence of the processes of destruction of structural elements of the machines, the technology of their production, degradation and the stochastic properties of the parameters of the technical state and the conditions and modes of operation arose.

1. Introduction.
In the process of development, the method of individual forecasting the initial data was the provision that at any time technical condition of the logging machines can be characterized by the set of parameters $X(t_i) = \{X_{i1}, X_{i2}, X_{i3}, ..., X_{im}\}$ that determine the state of its individual elements ($i=1, 2, ..., m$). The technical condition of the logging machines is changed by a random action of a large number of operational factors (e.g., conditions and modes of operation, performance of maintenance and repair, training of operators, etc.). Therefore, the law of the output parameters $X_i(t)$ change are formed due to the occurrence of random processes of destruction of structural elements of the logging machines.

2. Materials and methods.
To predict the behaviour of the logging machines in use, selection of the optimal decisions on maintenance and repair direct dependence of the processes of destruction in time are desirable. At present however, the complexity of the phenomenon does not allow one to obtain empirical regularities of the development of a process of destruction. This leads to the necessity of accounting for the uncertainty in actual operating conditions by employing modern methods of statistical analysis and the applied theory of random functions [1-4].

The process of changes of technical condition of logging machines can be represented as random vector process $X(t)$, i.e., in the form of a matrix of random values of the parameters characterizing the technical condition of the individual elements ($i=1, 2, ..., m$) at discrete points in time ($t_j = t_{j-1} + \Delta t, j=1, 2, ..., n$)
where \( m \) is the number of items, limiting the reliability of the logging machines;
\( n \) is the number of measurement of the values of the process of changing technical condition of the logging machine.

Operating capacity of the logging machine is considered as a set of states \( G \) defined by the sets of random parameter values \( X_j = \{ X_{1j}, X_{2j}, \ldots, X_{mj} \} \) when the failure does not occur. In other words, state \( X_j \) of set \( G(X \in G) \) means that logging machine at time \( t_j \) is working. The boundaries of set \( G \) is determined by maximum permissible values of parameters \( X_{1} = \{ X_{11}, X_{12}, \ldots, X_{1n} \} \). The output of any parameter \( X_i(t) \) for the boundary of set \( G \) implies the denial of the \( i \)-th element of the logging machine.

The task of individual prediction of the technical state of logging machines is to determine time points \( t^k \), which are beyond the boundary of set \( G \) of at least one of parameters \( X_i(t) \), i.e. when the condition (Figure 1).

\[
X_i(t^k) = X^n_i, \quad i = 1, 2, \ldots, m. \tag{2}
\]

The main reason for the failure of the logging machines in use are various processes of destruction that lead to irreversible changes in the structural elements. These changes arise from wear, accumulation of strain and fatigue, corrosion, diffusion of one material into another, etc. [5]. In a single logging machine and even in the same structural element, these processes are imposed, interact and ultimately cause a change of the parameters characterizing the technical condition. Therefore, the value of the parameter of the technical condition of the \( i \)-element of a logging machine at time \( t_j \) can be determined according to the expression:

\[
X_{ij} = X_{i0} + \sum_{k=1}^{j} \varphi_i(t_k) \Delta t, \tag{3}
\]

where \( X_{i0} \) is the initial value of the parameter;
\( \varphi_i(t_k) \) is the value of random function of rate of change of the technical condition; \( i \) is the element construction on the \( k \)-th interval.

\[\text{Figure 1.} \quad \text{Realization of the process of change of the parameter of technical condition.}\]

In the process of development, a method of individual forecasting the following theoretical background is used.

The rate of change of each parameter of the technical condition of \( \varphi_i(t_k) \) is a random process which can be described by the expression:
where \( V_i(t) \) is some deterministic function;
\( \rho_i(t) \) is a stochastic process having the property of stationarity. This means that the mathematical expectation of process \( M[\rho_i(t)] \) does not depend on \( t \) and correlation function \( R(t-S) \) depends only on difference \( t-S \) (Figure 2). Such submission rate of change of the parameter of the technical condition is rather real for most items of logging machines (about 80%), failures of which are associated with wear. The wear process has the property of strong mixing, i.e., the asymptotic independence of increments of wear [9].

Change in the value of each parameter of the technical condition of \( \Delta X_{ij} = X_{ij} + 1 - X_{ij} \) \((j = 1, 2, ..., n)\) for equal intervals of time \( \Delta t \), is a random process that can be represented as:

\[
\Delta X_i(t) = \phi_i(t) \Delta t = V_i(t) \ast \rho_i(t) \ast \Delta t.
\] (5)

This random process, in turn, can be converted by dividing the right and left parts on deterministic function \( V_i(t) \) to a stationary form:

\[
R(t-s) = \frac{\Delta X_i(t)}{V_i(t)} = \rho_i(t) \Delta t.
\] (6)

![Figure 2. A schematic diagram of the behaviour of the normalized correlation function of the random process involving strong mixing.](image)

Accordingly, in general vector-process \( X(t) \) can also be converted to a fixed sight:

\[
\Delta Z(t) = \begin{pmatrix}
\Delta Z_{11} & \Delta Z_{12} & \ldots & \Delta Z_{1j} & \ldots & \Delta Z_{1n} \\
\Delta Z_{21} & \Delta Z_{22} & \ldots & \Delta Z_{2j} & \ldots & \Delta Z_{2n} \\
\vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
\Delta Z_{i1} & \Delta Z_{i2} & \ldots & \Delta Z_{ij} & \ldots & \Delta Z_{in} \\
\vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
\Delta Z_{m1} & \Delta Z_{m2} & \ldots & \Delta Z_{mj} & \ldots & \Delta Z_{mn}
\end{pmatrix},
\] (7)

where \( \Delta Z_{ij} = x_{ij+1} - x_{ij} \) \( V_{ij} \)

As the following theoretical background, the famous theory of academician A. N. Kolgomorov on the possibility of presenting some of the future value of a stationary random process in the form of a linear combination of previous values of the process is used. As the forecast data of the previous predictions:

\[
\Delta Z_{i,n+1} = \sum_{t=0}^{p-1} a_{i,t+1} * \Delta Z_{i,n-t} + \sum_{t=0}^{g-1} b_{i,t+1} * \Delta Z_{i,n-t},
\] (9)

where \( p \) is the number of the last observations;
\( g \) is the number of previous predictions.

The last premise is that changes in one of processes \( \Delta X_i(t) \) can be explained by changes in other components of vector \( X(t) \), in the last moments of time. In other words, the presence of correlation between processes \( \Delta Z_i(t) \) is assumed. This assumption is generally true for the processes of change in output parameters due to the sediment of the machine elements. For example, the rate of wear of the connecting rod bearings of a crankshaft of the engine substantially depends on the magnitude of the
The presence of such properties is due to the use of the forecast \( \Delta Z(t) \) in other processes of the vector \( \Delta Z(t) \), i.e., methods of multivariate forecasting:

\[
\Delta Z_{i,n+1} = \sum_{k=1}^{m} \sum_{l=0}^{p-1} \Delta Z_{k,n-l} \ast a_{ik,l+1} + \sum_{k=1}^{m} \sum_{l=0}^{g-1} \Delta Z_{k,n-l} \ast b_{ik,l+1}.
\]

In matrix form, this expression will take the form:

\[
\Delta Z_{i,n+1} = [\Delta Z] \ast \Delta Z^T \ast [a_{ik,l+1}]^T \ast [b_{ik,l+1}]^T.
\]

where

\[
A_i = \{A_{i1}, \ldots, A_{im}\}, \quad A_{ik} = \{a_{ik1}, \ldots, a_{ikp}\}
\]

\[
B_i = \{B_{i1}, \ldots, B_{im}\}, \quad B_{ik} = \{b_{ik1}, \ldots, b_{ikp}\}
\]

\[
\Delta Z = \{\Delta Z_1, \ldots, \Delta Z_m\}
\]

\[
\Delta Z^* = \{\Delta Z^*_1, \ldots, \Delta Z^*_m\}
\]

\[
\Delta Z_k = \{\Delta Z_{kn}, \Delta Z_{kn-1}, \ldots, \Delta Z_{kn-p+1}\}
\]

\[
\Delta Z^* = \{\Delta Z^*_1, \ldots, \Delta Z^*_m\}
\]

\[
\Delta Z^*_k = \{\Delta Z^*_{kn}, \Delta Z^*_{kn-1}, \ldots, \Delta Z^*_{kn-p+1}\}
\]

In the given expressions, triple indexes are introduced, for example, \( a_{1kj} \) is the coefficient at \( j \)-th observed value of the \( k \)-th component of the process in the equation of the forecast of the \( i \)-th component of the process.

Values of the coefficients \( C_i = [A_i B_i] \) are found using the least squares method:

\[
\sum_{j=0}^{l} (\Delta Z_{in-j} - \Delta Z^*_{in-j})^2 \rightarrow \min.
\]

The system of equations is used:

\[
\Delta Z^*_i = \sum_{k} [\Delta Z] \ast [a_{ik}] \ast [b_{ik}] + \sum_{k} [\Delta Z^*] \ast [b_{ik}].
\]

The system of conditional equations of this type are based on statistical material using the method of a sliding interval and is designated as following:

\[
\Delta Z^*_i = \{\Delta Z^*_{in}, \Delta Z^*_{in-1}, \ldots, \Delta Z^*_{in-l+1}\}
\]

In practical calculations, one should observe the conditions:

\[
l >> m(p-g)
\]

Expressing the law of large numbers is applied to the problem being solved.

Information matrix in equation (14) has the form:

\[
||\Delta Z|| = \begin{bmatrix}
\Delta Z_{kn-1} & \Delta Z_{kn-2} & \ldots & \Delta Z_{kn-p} \\
\Delta Z_{kn-2} & \Delta Z_{kn-3} & \ldots & \Delta Z_{kn-p-1} \\
\vdots & \vdots & \ddots & \vdots \\
\Delta Z_{kn-l} & \Delta Z_{kn-l-1} & \ldots & \Delta Z_{kn-l-p+1} \\
\end{bmatrix}
\]

\[
||\Delta Z^*|| = \begin{bmatrix}
\Delta Z^*_{kn-1} & \Delta Z^*_{kn-2} & \ldots & \Delta Z^*_{kn-q} \\
\Delta Z^*_{kn-2} & \Delta Z^*_{kn-3} & \ldots & \Delta Z^*_{kn-q-1} \\
\vdots & \vdots & \ddots & \vdots \\
\Delta Z^*_{kn-l} & \Delta Z^*_{kn-l-1} & \ldots & \Delta Z^*_{kn-l-q+1} \\
\end{bmatrix}
\]

A short record for equations (2.14) in matrix form takes the view:

\[
\Delta Z^*_i = \{||\Delta Z|| \ast ||\Delta Z^*||\} \ast [A_i | B_i].
\]

Developing the normal equations, let us obtain the system to determine the required coefficients:

\[
C_i = (\{\Delta Z\}^T \ast \{\Delta Z^*\})^{-1} \ast \{\Delta Z^*\} \ast \Delta Z^*_i,
\]

where \( \{\Delta Z\} = [\Delta Z | \Delta Z^*] \) is the block information matrix of dimension:

\[
l \ast m(p+g);
\]

\[
\Delta Z^*_i = \{\Delta Z_{in}, \ldots, \Delta Z_{in-l+1}\}^T
\]

is the column vector obtained by past observations of process \( X_i(t) \).

Found by statement (20), coefficients \( C_i = [A_i B_i] \) are used to predict the \( i \)-th component of the vector-process \( \Delta Z(t) \) in equation (10). To forecast other components, the procedure of determination is the same.

For elements of logging machines and mechanisms, there are the most essential processes that proceed by the contact of mated surfaces, in other words different wearing processes lead to the change of space between details, of friction ratio and other parameters by integration. Considering that fracture processes become irreversible, the parameter of the engineering status in temporal value \( t \) can be found by statement:

\[
X(t) = X_0 + \int_0^t \varphi(t) \, dt
\]

where \( X_0 \) an initial parameter, set by manufacturing technique;
φ(t) – random function of the fracture processes speed.

Therefore in the model, there should be considered degradation characteristics of engineering status parameters and technology of production machine elements.

Fracture processes speed can be described as a function of some input parameters Y₁, Y₂, …, Yₙ and time t. Such connections ensue from physical-chemical rules by testing of material damage:

\[ \frac{dx}{dt} = \varphi(Y₁, Y₂, \ldots, Yₙ, t). \]  (22)

Parameters Yᵢ characterize application environment (capacity, speed, temperature etc.), a material status from which elements of the construction are produced (hardness, resistance, surface quality etc.) and other factors.

The important characteristic of the stochastic process is the marginal distribution leading to distribution of values X(t) in k various time points:

\[ F[X(tₖ)] = P[X(tₖ) < X] \]  (23)

Marginal distributions help to consider stochastic parameters of technical condition; therefore the model of degradation takes a form:

\[ f[X(t)] = F \varphi[f(X₀), f[\varphi(t)]] \]  (24)

where \( f[X(t)] \) – distribution density of technical condition parameter at an operating time (t), \( f(X₀) \) – distribution density of the initial parameter value; \( f[\varphi(t)] \) – distribution density of stochastic speed values of the destruction process in timepoint (t).

An empirical function of distribution density is determined by a formula:

\[ f_{,j}(t) = \frac{m_{j} + mj/2}{n} \]  (25)

In case of completely certain samples, empirical function of distribution is determined by a formula:

\[ F_{,j}(t) = \frac{y_{j-1} m_{j} + mj/2}{n} \]  (26)

where \( m_k \) – the number of the observations which are on K interval.

By the small volumes of samples, the function of distribution is calculated by a formula:

\[ F_{,j}(t) = \frac{1}{n}(j-0.5) \]  (27)

For accidentally truncated sample including g refused and z put on hold objects, calculation \( F_{,j}(tj) \) by Johnson’s method leads to definition of the average serial number of everyone refused sample and to probability of his refusal taking into account quantity of the put on hold objects:

\[ m_{j} = m_{j-1} + \Delta j \]  (28)

where \( m_{j-1} \) – average serial number of the previous refused object in a variation row in which the refused objects are grouped after the ones put on hold.

3. Conclusions.

Thus, an individual prediction of the technical condition of the car is to estimate the values of vector process \( X^*(t) \) at future time points \( t_{n+1}, t_{n+2}, \ldots \) and identify situations when at least one of the components of process \( X^*(t) \) is condition:

\[ X_{i,n+1}^* = X_{in} + \sum_{k=1}^{l} \Delta Z_{in+k} V_{in+k} \geq X_i^n, \]  (29)

where i=1, 2, …, m.

In this case the predicted time of failure of the i-th element of the machine is determined by the formula:

\[ t^* = t_n + \Delta t. \]  (30)

Currently as a rule, records of the information on change of parameters of technical condition of machines in use are not kept, thereby to define original vector process \( X(t) \) is not possible. Therefore, the first stage is to define it by statistical modelling and estimate the coefficients of the forecast. Then, using the information obtained on each machine performing maintenance and repair, it is necessary to
refine the coefficients of the forecast, i.e. to solve the problem of individual predicting by the adaptive way.

References
[1] Bially T, Mc Laughlin A and Weinstein C Voice 1980 IEEE Trans. On Commun 9 1478-1490
[2] Briion W Transp. Res 11 95-107
[3] Park K, Hwang Y, Seo S, Asce M and Seo H 2003 Journal of Construction Engineering and Management 129 (1) 25–31
[4] Kopriva P 1990 Vybrane problemy teorie apdehilvesty. Lausch-mann 99
[5] Skrypnikov A V, Dorokhin S V, Kozlov V G and Chernyshova E V 2017 Journal of Engineering and Applied Sciences 2 511-515
[6] Oliver R M 1962 Operat. Res 2 197-217
[7] Pestigay S 1961 Annales des Fonts et Chaussees 2 145-225
[8] Phillips W S 1979 Transportation Planning and Technology 3 131- 158
[9] Berestnev O, Soliterman Y, and Goman A 2000 International Symposium on History of Machines and Mechanisms Proceedings 325-332