Forecasting characteristics affecting the reliability of the operation of the machine and tractor fleet over time

T V Bodyakina¹, P A Boloev², N O Shelkunova¹, S N Krivtsov³, T I Krivtsova³

¹Irkutsk State Agrarian University, Molodezhny settlement, Irkutsk district, Irkutsk region, 664038, Russia
²Buryat State University, 24a, Smolin Str., Ulan-Ude, 670000, Russia
³Irkutsk National Research Technical University, 83, Lermontova Str., Irkutsk, 664074, Russia

E-mail: tatyana_krivcova1985@mail.ru

Abstract. This article discusses the prediction of the characteristics of the technical condition of machines and their effectiveness. The task of predicting the parameters of the changes the technical state of agricultural machinery during operation is to determine the numerical characteristics for future points in time based on the results of abbreviated or incomplete tests.

When choosing and justifying a mathematical model, one should proceed primarily from the physical essence of the phenomena leading to a change in the nature of products during operation. A model reflecting the rate of change of parameters is used to describe the processes. In forecasting, to increase the efficiency of the mathematical model, generalized physical laws are used that determine the process of changing the resource. Based on this model, it is possible to build a methodology for calculating the reliability. The set of process characteristics characterizes the change in parameters and makes it possible to predict torque functions during operation.

1. Introduction

The development of technology and its application in production processes has made the issue of predicting the characteristics of the technical condition of machines and their efficiency urgent. The efficiency of using machines is associated with their ability to continuously and efficiently perform the functions assigned to them. However, due to breakdowns or malfunctions, the quality of the machines is reduced, forced downtime occurs in their work, there is a need for repairs to restore the operability and the required technical characteristics of the machines. The concept of reliability is associated with the ability of a technical device to perform the functions assigned to it for the required time and with the required quality. With the development and complication of technology, the problem of its reliability became more complicated and developed [1, 2].

2. Materials and methods

The task of predicting the parameters of the changes in the technical state of agricultural machinery during operation is to determine their numerical characteristics for future points in time based on the results of abbreviated or incomplete tests.

When choosing and justifying a mathematical model, one should proceed primarily from the physical essence of the phenomena leading to a change in the nature of products during operation [4]. The most frequently used model to describe the rate of change of parameters is the stationary random function...
where $m_z(t)$ is the mathematical expectation of the function $z(t)$; $z(t)$ is a centered random process.

A vivid example of such a process is the process of increments of the values of the cyclic fuel supply by the high pressure pump. The test experience shows that the process characterizing the random component of the rate of change of the parameters of many types of products, in the overwhelming majority of cases, is a stationary normally distributed random process with an exponential or exponential-oscillatory correlation function [6, 7].

A stationary random function is one whose probabilistic characteristics do not change over time. These include, first of all, the mathematical expectation and the correlation function.

The stationarity conditions for a random function can be written as:

$$m_z(t) = \text{const}; \quad K_z(t, t + \tau) = K_z(\tau)$$

For, $\tau = 0$ the value of the correlation is the variance in the section of the random:

$$K_z(\tau) = D_z(t) = \text{const.}$$

The normalized correlation function of a random process is the function

$$k_z(\tau) = K_z(\tau)/[D_z(\tau)]$$

The expression for the normalized exponential correlation function of a stationary random process can be written in the form

$$k_z(\tau) = e^{-|\tau|}$$

Estimation of the mathematical expectation of a random process according to the results of measurements of the increments of the parameters of products for the test period is made according to the formula

$$\hat{M}[\Delta X(t)] = \frac{1}{N} \sum_{j=1}^{m} \sum_{i=1}^{l} \Delta x_{ji},$$

where $N$ is the total number of measurements of quantities $\Delta x_{ji}$ in the experiment; $l$ is the number of tested products, $m$ is the number of parameter measurements for the $i$-th product.

The variance of a random process is found from the relation

$$\hat{D}[\Delta X(t)] = \frac{1}{N-1} \left\{ \sum_{j=1}^{m} \sum_{i=1}^{l} (\Delta x_{ji}^2) - \frac{1}{N} \left[ \sum_{j=1}^{m} \sum_{i=1}^{l} \Delta x_{ji} \right]^2 \right\}.$$ 

The estimation of the values of the correlation function of a random process is made with the formula

$$\hat{K}_{\Delta x}(t, t') = \frac{1}{ml-m-1} \left[ \sum_{i=1}^{ml-m} \Delta x_i(t) \Delta x_i(t') - \frac{1}{ml-m} \left[ \sum_{i=1}^{ml} \Delta x_i(t) \right] \left[ \sum_{i=1}^{ml} \Delta x_i(t') \right] \right].$$

The values of the correlation function calculated in this way form the matrix
where \( k_{ij} = K_{ij} / (\sigma_i \sigma_j) \) - correlation coefficient of random variables of the function \( \Delta x(t), \Delta x(t') \).

For a stationary random function \( \Delta x(t) \) the matrix is written in the form

\[
\begin{bmatrix}
1 & K_{\Delta t_1} & K_{\Delta t_2} & K_{\Delta t_3} & \ldots & K_{\Delta t_m}
\end{bmatrix}
\]

where \( K_{\Delta t_1}, K_{\Delta t_2}, \ldots, K_{\Delta t_m} \) is the correlation coefficient of random variables of the function \( \Delta x(t) \) for discrete

\[
\tau_1 = \Delta t, \tau_2 = 2 \Delta t, \tau_3 = 3 \Delta t, \tau_m = m \Delta t.
\]

If the normalized correlation function of a random process is an exponent

\[
K_{\Delta t}(\tau) = e^{-|\tau|},
\]
For example, when testing 14 fuel pumps, the increments in the values of the cyclic fuel supplies were measured in the intervals of operating time $\Delta t_1 = t_1 - t_0 = \Delta t_2 = t_2 - t_1 = 1000 m/h$, given in work [5, 10]:

| Operating time interval | Increments (%) of the values of the cyclic fuel supply $\Delta x_q$ in the models of pumps |
|-------------------------|-------------------------------------------------------------------------------------|
| $\Delta t$ in m/h       | $1$ $2$ $3$ $4$ $5$ $6$ $7$ $8$ $9$ $10$ $11$ $12$ $13$ $14$ |
| $0 - 1000$              | $|+ 0.7||- 1.8| |+ 0.8| |+ 0.3| |+ 1.2| |+ 0.4| |+ 0.3| |- 1.9| |+ 2.2| |+ 2.5| |+ 1.4| |+ 1.6| |0.0| |0.0| |
| $1000 - 2000$           | $|- 0.7| |- 1.6| |+ 1.0| |+ 1.6| |+ 0.6| |- 0.3| |+ 0.5| |+ 0.5| |+ 0.4| |+ 1.9| |+ 1.2| |- 0.7| |+ 1.2| |- 0.7| |

It is required to determine the numerical characteristics of a random process based on the hypothesis of its stationarity.

We find an estimate of the mathematical expectation by substituting the tabular values of the quantities into the formula (2)

$$m_{\Delta t} = 11.8/28 = 0.4214.$$ 

To estimate the variance of the process, we use the formula

$$D_{\Delta t} = 1/(28-1)[40.56 - (1/28)1.8^2] = 1.318.$$ 

The value of the standard deviation is determined as follows:

$$\sigma_{\Delta t} = \sqrt{1.318} = 1.148.$$ 

The value of the correlation function for $\tau = 1000$ m/h calculated by the formula (3)

$$K_{\Delta t}(\tau) = [1/(14 * 2 - 14 - 1)]9.9 - (1/(14 * 2 - 14) * 6.9 * 4.9] = 0.575.$$ 

We find the corresponding value of the normalized correlation function as the quotient

$$K_{\Delta t}(\tau) = K_{\Delta t}(\tau)/D_{\Delta t} = 0.575/1.318 = 0.436.$$ 

The value of the coefficient in the formula (5) is found from the relation (6)

$$\alpha = ln0.436/1000 = -0.83*10^{-3}.$$ 

Thus, the expression for the correlation function of the process under consideration can be written as:

$$K_{\Delta t}(\tau) = 1.318 * e^{-0.83*10^{-3}\tau}.$$ 

The estimates of the moment functions of the parameter increment process obtained as a result of the calculation for calculations are conveniently represented as a series:
Table 2. The estimates of the calculated moment functions of the parameter increment process

| $m_{\Delta x}(t)$ | $D_{\Delta x}(t)$ | $\sigma_{\Delta x}(t)$ | $K_{\Delta x1}$ | $K_{\Delta x2}$ | $K_{\Delta x3}$ | $K_{\Delta x4}$ | $K_{\Delta x5}$ |
|------------------|------------------|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0.421            | 1.318            | 1.148            | 0.436           | 0.190           | 0.082           | 0.036           | 0.016           |

Set of indicators $m_{\Delta x}$, $D_{\Delta x}$, $K_{\Delta x}(\tau)$ process from the quantitative point of view characterizes the patterns of wear and aging of products and creates real opportunities for predicting the moment functions of the processes of changing the parameters of the equipment during operation.

3. Results and Discussion.

Torque function prediction $m_x(t), D_x(t), K_x(t, t')$ random process of parameter changes $x(t)$ can be successfully performed based on previously obtained estimates of these parameters. So, for continuous processes, the predicted values of the moment functions are found by integrating expressions (1) and (2).

$$m_x(t_n) = \int_0^{t_n} m_{\Delta x}(t)dt;$$  \hspace{1cm} (7)

$$K_x(t_m, t_n) = \int_0^{t_n} \int_0^{t_m} K_{\Delta x}(\tau)d\tau dt.$$  \hspace{1cm} (8)

For discrete processes, the predicted values of the mathematical expectation of a random function $x(t)$ determined by the formula

$$m_x(t_n) = m_{\Delta x}(t_n)$$  \hspace{1cm} (9)

where $t_n$ - time for which the predicted process characteristics are calculated $x(t)$.

Process variance $x(t)$ for predictable discrete $t_n$ is determined by the known correlation matrix (8) is determined by the known correlation matrix.

Considering that

$$D_x(t) = D\left[ \sum_{i=1}^{n} \Delta x_i \right],$$  \hspace{1cm} (10)

and applying the theorem on the variance of the sum of random variables, we obtain the following relations:

$$D_x(t) = D_{\Delta x};$$  \hspace{1cm} (11)

$$D_x(t) = D_{\Delta x} \sum_{k_{\Delta x1}}^{1} \frac{1}{k_{\Delta x1}};$$  \hspace{1cm} (12)

$$D_x(t) = D_{\Delta x} \sum_{k_{\Delta x1}}^{1} \frac{1}{k_{\Delta x1}} k_{\Delta x2},$$

$$D_x(t) = D_{\Delta x} \sum_{k_{\Delta x1}}^{1} \frac{1}{k_{\Delta x1}} k_{\Delta x2} k_{\Delta x3}.$$  \hspace{1cm} (13)
In general form, the formula for determining the variance of the process of changing a parameter over time can be represented as

$$D_x(t_n) = D_\Delta \sum_{i=1}^{n-1} \sum_{j=1}^{n-1} c_{K_{ij}}$$

(14)

where $D_\Delta$ - variance of the parameter increment function over time; $c_{K_{ij}}$ - elements of the normalized correlation matrix of the increment function.

All correlation moments of the process are determined in a similar way $x(t_n)$.

Considering that

$$x(t_n) = \sum_{i=1}^{n} \Delta x_i(t)$$

(15)

$$K_x(t_m, t_n) = M \{[x(t_m) - m_x(t_m)][x(t_n) - m_x(t_n)]\}$$

(16)

The general formula for calculating the correlation moments will be:

$$K_x(t_m, t_n) = D_\Delta \sum_{i=1}^{n-1} \sum_{j=1}^{n-1} c_{K_{ij}}$$

(17)

Below are the calculation formulas for determining the first 15 correlation moments of the process for discrete $t=2000,3000,\ldots,6000$ m h [11,13]:

1. $K_x(t_1, t_2) = D_\Delta (1 + k_1)$
2. $K_x(t_1, t_3) = D_\Delta (1 + k_1 + k_2)$
   ...
5. $K_x(t_1, t_6) = D_\Delta (1 + k_1 + \ldots + k_5)$
6. $K_x(t_2, t_3) = D_\Delta (2 + 3k_1 + k_2)$
7. $K_x(t_2, t_4) = D_\Delta (2 + 3k_1 + 2k_2 + k_3)$
   ...
9. $K_x(t_2, t_6) = D_\Delta (2 + 3k_1 + 2k_2 + 2k_3 + 2k_4 + k_5)$
10. $K_x(t_3, t_4) = D_\Delta (3 + 5k_1 + 3k_2 + k_3)$
11. $K_x(t_3, t_5) = D_\Delta (3 + 5k_1 + 4k_2 + 2k_3 + k_4)$
12. $K_x(t_3, t_5) = D_\Delta (3 + 5k_1 + 4k_2 + 3k_3 + 2k_4 + k_5)$
13. $K_x(t_4, t_5) = D_\Delta (4 + 7k_1 + 5k_2 + 3k_3 + k_4)$
14. $K_x(t_4, t_6) = D_\Delta (4 + 7k_1 + 6k_2 + 4k_3 + 2k_4 + k_5)$
15. $K_x(t_5, t_6) = D_\Delta (5 + 9k_1 + 7k_2 + 5k_3 + 3k_4 + k_5)$

Methods for constructing mathematical models of reliability

It is known that the wear rate is proportional to the friction power [8]:

$$\gamma = aFv$$

(18)

where $a$ is the coefficient; $F$ is the friction force; $v$ is the relative sliding speed of the rubbing bodies.proportional to the friction powe.

To increase the effectiveness of the mathematical model of reliability in forecasting, it is necessary.
to use generalized physical patterns that determine the process of resource exhaustion when constructing them.

The advantages of constructing mathematical methods of reliability is that the data used to calculate generalized patterns can be realistically evaluated at the design stage and on their basis it is possible to build a methodology for calculating reliability using the test results of the predecessor (analog).

Consider the process of mechanical wear. The wear attributed to a single cycle is written as [3]

\[ \gamma_1 = aA^m_{10} \] (19)

where \( \gamma_1 \) is the friction work for one cycle; \( m \) is the exponent (determined experimentally); \( A_{10} \) - the boundary value of the friction work per cycle.

Let's define the coefficient \( a \). Wear in \( n \) cycles

\[ U_n = \gamma_1 n = aA^m_{10}n. \] (20)

We will introduce the maximum wear and tear \( U_{np} \). Then the damage measure is

\[ D_n' = U_n / U_{np} = aA_{10}^m n / U_{np}. \] (21)

Let's enter the test database \( N_0' \) and the ultimate work of friction \( A_{10} \), which should be determined experimentally. Then when \( D_n = 1 \)

\[ a / U_{np} = 1 / N_0' A_{10}^m; D_n' = \frac{A_{10}^m n / A_{10}^m N_0'}. \] (22)

As \( n=N_0' \), we should understand the number of cycles at which the limit state is reached.

Based on the mathematical model of the object resource

\[ t = \varphi(x_1, x_2 \ldots) \] (23)

We determine the optimal reliability, which is provided by the minimum deviation of the object parameters from the desired value.

As a function that characterizes the deviation of the reliability capabilities from the desired one, we introduce the mathematical expectation of the square of the difference in the indicators

\[ \delta^2 = M (z_m - z)^2 \] (24)

where \( z_m \) - the desired value of the reliability indicators; \( z \) - its possible value.

Convert the expression by entering the average value \( z_{cp} \):

\[ \delta^2 = M [z_m - z_{cp} (z - z_{cp})]^2 = \ldots = (z_m - z_{cp})^2 + D_z. \] (25)

Let the reliability indicator be related to the factors by the following expression:

\[ z = a_0 + a_1 z_1 + a_2 z_2 + a_3 z_3 + \ldots \] (26)

Then

\[ z_{cp} = a_0 + a_1 z_{cp1} + a_2 z_{cp2} + \ldots; \] (27)

\[ D_z = a_1^2 D_{z1} + a_2^2 D_{z2} + \ldots; \] (28)

\[ \delta^2 = [z_{cpm} - (a_0 + a_1 z_{cp1} + \ldots)]^2 + a_1^2 D_{z1} + a_2^2 D_{z2} + \ldots \] (29)
As you can see, in order to achieve results, it is necessary to reduce the variance of factors that affect the reliability of machine and tractor units.

4. Conclusion
The set of process characteristics characterizes the change of parts in terms of wear and makes it possible to predict the torque functions during operation.
To achieve results, it is necessary to reduce the variance of the studied factors that affect the reliability of the machine and tractor units.

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