Reliability assessment of the stepless rotation mechanism of an industrial tractor with a tracking control system

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Abstract. The authors of the article assess the reliability and durability of a stepless turning mechanism of a 10-ton industrial tractor with a tracking control system at the stage of projecting.

Evaluating the reliability of a stepless differential turning mechanism (SDTM) for an industrial tractor with a tracking control system (TCS) at the design stage is an urgent task, the solution of which, based on the analysis of the structure of this mechanism and its operating conditions, is one of the stages of the development quality management process. Forecasting of reliability indicators of the designed products is performed by calculation methods using statistical data of failure rates or failure times obtained during testing of analogy devices.

To determine the achieved level of reliability, various methods are used: analytical and probabilistic modeling to obtain a priori estimates of reliability indicators; experimental methods; statistical methods for evaluating reliability indicators. Experimental and statistical methods become available at the stages of product manufacturing and operation. At the design stage, it is advisable to use computational methods for analyzing the reliability of products [1, 2, 3].

Stepless differential turning mechanism with a tracking control system (SDMTCS) should be presented [6] as a system consisting of a set of interrelated elements, considered from the point of view of performing the required functions as a whole. Therefore, reliability analysis of SDMTCS (due to the reliability of the complectrum parts (elements)) based on calculation of indicators of reliability and long eternity of a product taking into account only the catastrophic failure of the separate elements (characteristics are the abrupt transition element inoperable).

The reliability calculation begins with determining which failures are characteristic of the system elements. In SDMTCS experience the following failures:
1) broken teeth;
2) transmission jamming;
3) bearing damage;
4) damage (destruction) of loaded parts and assemblies (rupture of high-pressure hoses, damage of hydraulic equipment, etc.).
To calculate the reliability indicators (probability of failure-free operation, time to failure), consider the product without taking into account the restoration of its operability.

Before starting the calculation we will make the following assumptions:

1. Only one type of failure occurs in elements – "breakage", so you can use the reliability scheme to calculate reliability.

2. The time to failure of the i-th element is subject to exponential distribution; the failure rates of elements are constant and equal to \( \lambda_i, \ i=1,2, \ldots, n \), where \( n \) is the number of elements in the product.

3. The failure of the various elements of the product are independent events.

The assumption of the independence of failures of individual elements of the product as random events is not strict, since the independence of failures is ensured when designing the product using independent power sources, locks, safety valves, etc. Due to this, after the failure of one element, all the components stop functioning, and the reliability indicators of the remaining functional elements are stored at the same level as at the time of failure.

List the main stages of calculation of indicators of reliability of SDTMTCS:

1. Splitting the product into blocks, nodes; collecting reference data on the reliability of component elements of the product [5].
2. Drawing up a structural diagram of reliability.
3. Calculation of product reliability using the probability theory apparatus.
4. Analysis of results and decision-making.

Reference data on the reliability of components of the SDTMTCS are presented in table 1 [5].

The electrical equipment included in the tracking control system (turn control unit (joystick), microprocessor unit, electro-radio elements) are not reflected in table 1, since they are highly resistant to external influences, which is why their failures are relatively rare compared to failures of hydraulic system elements, hydrostatic drive of the turn mechanism, and mechanical elements (reducers). And even though the reliability of micro-gyroscopes (forward motion sensor, turn sensor) is described by Rayleigh's law with a failure rate that increases linearly with time of use, their failure rate does not affect the failure rate of the product as a whole, since the use of micro-gyroscopes in the control system is of a short-term discrete nature. Therefore, the product elements listed above will not be considered in further calculations.

Since the failure of each element of the product leads to the failure of the entire product, the reliability calculation scheme is a sequential structure (figure 1).

![Figure 1. Structural diagram of reliability of SDTMTCS.](image)

For the diagram (see figure 1), the average uptime \( T_0 \) of the product is defined by the expression

\[
T_0 = \frac{1}{\lambda},
\]

where \( \lambda \) is the calculated failure rate of the product, defined by the expression

\[
\lambda = \sum_{j=1}^{m} (N \cdot \lambda_j),
\]

where \( \lambda_j \) is the operating failure rate of the i-th group of components; \( N \) is the number of components in the j-th group; \( m \) is the number of groups of components in the product.

After calculating the failure rate of the product and the average uptime, the probability of uptime of the product is determined by the expression

\[
P(t) = e^{-\frac{t}{T_0}},
\]

where \( t \) – mechanism work time.
We apply the methodology described above to calculate the estimate of the average uptime of the SDTMTCS using data from table 1.

The calculation results are as follows:

\[ \lambda_{cp} = (4 \times 0.2 + 0.3 + 3 \times 8.74 + 3 \times 3.93 + 2 \times 5.6 + 4 \times 3.55 + 2 \times 6.1 + 1.8) \times 10^{-6} = 78.51 \times 10^{-6} \text{ (h}^{-1}) \],

then \( T_{0cp} = 12737 \) (h).

Then, according to (3) at \( t=2000 \) (h) probability of failure SDTMTCS will be \( P(2000)=0.85 \) and which is not contrary to the requirements for developing a mechanism.

Table 1. Reliability of components of the SDTMTCS

| №  | Block                        | Node                        | Element                              | Failure rate \( \lambda_i \times 10^{-6}, \text{ h}^{-1} \) |
|----|------------------------------|-----------------------------|--------------------------------------|-------------------------------------------------------------|
| 1  | Transmission box             | Summing planetary mechanism |                                      |                                                             |
|    | Transmission the left side   |                             |                                      |                                                             |
|    | The transmission side right  |                             |                                      |                                                             |
| 2  | lubrication system           |                             | filter                               | 0.3                                                         |
|    |                              |                             | the hydraulic pump                   | 8.74                                                        |
|    |                              |                             | SHP sleeves                          | 3.93                                                        |
|    | Braking system               |                             | the hydro-pneumatic accumulator (HPA)| 6.1                                                         |
|    |                              |                             | brake control unit (hand brake)      | 3.55                                                        |
|    |                              |                             | brake control unit (foot brake)      |                                                             |
|    |                              |                             | pressure valve;                      | 5.6                                                         |
|    |                              |                             | valve charging GPA                   |                                                             |
| 3  | control tracking system      |                             | hydraulic pump                       | 8.74                                                        |
|    |                              |                             | SHP sleeves                          | 3.93                                                        |
|    | hydraulic control system     |                             | hydraulic motor                      | 1.8                                                         |
|    | turning                      |                             | the hydraulic pump                   | 8.74                                                        |
|    |                              |                             | hydraulic distributor                | 3.55                                                        |
|    |                              |                             | electric hydro distributor           | 3.55                                                        |

For assessing the durability SDTMTCS imagine it as a recoverable product, because durability – property of object continuously to keep working capacity before the onset of the limit state when the installed system maintenance and repairs. Moreover, under the limit state of the developed SDTMTCS, we will consider the state in which its repair becomes economically impractical.

Before starting to evaluate the durability of the SDTMTCS we will add the following assumptions to the above assumptions:

1. Element failures are detected almost at the moment of their occurrence.
2. The time intervals for restoring the health of the i-th failed element (without taking into account the waiting time for maintenance) are distributed exponentially with the parameter \( \mu_i \).
3. No new failures occur in the failed element during recovery.

As the initial data for the calculation, it is necessary to know the recovery rate of the product elements \( \mu_i \)

\[ \mu_i = \frac{1}{t_{vi}} \]  \hspace{1cm} (4)
where $t_B$ is the average recovery time of the $i$-th element of the product, h (downtime caused by failure).

Since the average recovery time of the same device may differ significantly depending on the direct and indirect relationships between parts and assembly units in the product, it is advisable to use a generalized experience of typical machine parts and assemblies. So, in the system of indicators of reliability of tractors, the classification [7] of failures by complexity groups is traditionally used, depending on the method and time of their elimination:

failures of the I group of complexity are failures of easily accessible parts and assembly units, eliminated by replacing them or eliminated without removing the failed parts and assembly units from the tractor. The operational duration of elimination of the failure of the first group of complexity should be no more than 2 hours;

failures of the II group of complexity are failures of parts and assembly units that are eliminated by their repair, which requires the disclosure of internal cavities of assembly units. In this case, the operational duration of eliminating the failure of the second group of complexity should be no more than 8 hours;

failures of the III group of complexity are failures, the operational duration of which is more than 8 hours.

Given the design features SDTMTCS, when determination of reliability at the design stage, TCS failures can be attributed to the failure of the first group of complexity with the duration of the elimination of 2 h, and the bounce SDTM to the failure of group II of the complexity with the duration of elimination 8 h. Then, the recovery rate $\mu_i$ groups bounce SDTMTCS according to (5) has the values shown in table 2.

| The indicators       | Group of failures |
|----------------------|-------------------|
| How difficult it is to resolve a failure by groups of difficulty $t_B$, h | I | II |
| Failure elimination rate $\mu$, h⁻¹ | 0.5 | 0.125 |

To calculate the reliability of the restored product using data from tables 1 and 2, a state graph [4] is compiled (figure 2).

In figure 2 the following notation: 0 - healthy state SDTMTCS; 1 - failure condition SDTMTCS due to the failure of TCS; 2 - failure condition SDTMTCS due to the failure of SDTM; $\lambda_1$ is the failure rate TCS ($\lambda_1=(2\cdot8.74+2\cdot3.93+2\cdot5.6+4\cdot3.55+2\cdot6.1+1.8)\cdot10^{-6}=64.74\cdot10^{-6}$ h⁻¹); $\lambda_2$ is the failure rate SDTM, including the main transmission, the planetary gear set, the left and right side gears and the lubrication system ($\lambda_2=(4\cdot0.2+0.3+8.74+3.93)\cdot10^{-6}=13.77\cdot10^{-6}$ h⁻¹); $\mu_1$ is the recovery rate of each of the 13 elements of TCS ($\mu_1=0.5$ h⁻¹ (see table 2)); $\mu_II$ - the recovery intensity of each of the 7 elements of the SDTM ($\mu_{II}=0.125$ h⁻¹ (see table 2)).

To simplify calculations, let's expand the state graph (see figure 2) by combining States 1 and 2 into one with the designation of this state 12 (figure 3).
Figure 3. A global state graph SDTMTCS.

The Kolmogorov equations based on the graph (see figure 3) have the form

\begin{align*}
P_0'(t) &= -\lambda_0 P_0(t) + \mu_0 P_1(t), \\
P_{12}'(t) &= \lambda_0 P_0(t) - \mu_c P_{12}(t).
\end{align*}

(5)

For the solution (5) taking into account the initial conditions $P_0(0)=1$, $P_{12}(0)=0$, the equations are written in operator form

\begin{align*}
(s P_0(s) - 1) &= -\lambda_0 P_0(s) + \mu_0 P_{12}(s), \\
(s P_{12}(s)) &= \lambda_0 P_0(s) - \mu_c P_{12}(s).
\end{align*}

(6)

It follows from solution (6) that the readiness function of the SDTMTCS has the form

\[ K_c(t) = P_0(t) = \frac{\mu_c}{\lambda_c + \mu_c} + \frac{\lambda_0}{\lambda_c + \mu_c} e^{-(\lambda_c + \mu_c)t}, \]

and taking into account the numeric values $\lambda_c$ and $\mu_c$

\[ K_c(t) = P_0(t) = 0.9999894 + 0.0000106 \cdot e^{-7.3750785t}, \]

(7)

According to (7) in 5 years (43800 h) after the start of operation, the readiness coefficient will be

\[ K_c(43800) = 0.9999894 \]

that is, during the planned service life of the database with the installed maintenance and repair system, the product will not reach the limit state, in which further operation is unacceptable.

The indicators of reliability and durability were provided in the design process using a modular principle of construction products and competent selection of components.

Note 1. In the above calculations, when determining the failure rates of SDTMTCS elements, correction coefficients are not introduced that take into account the degree of rigidity of the product's operating conditions (due to the lack of information about models of similarity of modes), which means that the obtained values of reliability indicators are typical for laboratory operation mode. At the same time, it is obvious that the operating conditions of a product installed on a mobile object will differ significantly from the stationary operating conditions of this product. These differences are taken into account using the operation coefficient $a$, which shows how many times the failure rates of product elements increase. Thus, for elements of automotive equipment $a = 40$ [8].

To take into account the impact of the product's operating conditions on the failure rate of its elements you should increase the failure rate of elements by 40 times, as a result, we get $\lambda_c=3.14 \times 10^{-4}$ (h\(^{-1}\)). Then according to (7):

\[ K_c(t) = P_0(t) = 9.995744 + 0.0004256 \cdot e^{-7.37814t}, \]
Another approach to converting the availability coefficient to actual operating conditions requires the use of a conversion factor of 0.9 [2], then

\[ K_f(43800) = 0.9995744. \]

Note 2. When calculating reliability over time intervals exceeding 5 years, we should proceed from the assumption that sudden failures occur primarily over the considered time interval (as described in this paper), and proceed to accounting for gradual failures that occur under the influence of wear and aging of product elements, which requires a transition from the exponential reliability law to the Rayleigh law.

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