MACHINE BUILDING AND MACHINE SCIENCE
МАШИНОСТРОЕНИЕ И МАШИНОВЕДЕНИЕ

UDC 621.03.01
Original Theoretical Research
https://doi.org/10.23947/2687-1653-2025-25-2-112-119

A Method for Monitoring the Reliability of Technical Systems by Identifying the Entropy of the Causes of their Failures

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Abstract

Introduction. Under designing, a large safety margin of components and units is included at the calculation stage, which does not exclude premature failures that occur at random. The consequences of such failures are not only economic losses, but also threats to the safety of people and the environment. In modern literature, the topic of assessing the reliability of machines, considered as complex probabilistic systems that take into account not only the dynamic parameters under operation, but also the processes of manufacturing the components of the system, is not sufficiently covered. Therefore, to provide for the targeted management of the reliability of machines as complex technical systems, it is required to apply the principles of cybernetics. The research objective is to study the method of monitoring the reliability of technical systems by identifying the entropy of the causes of their failures.

Materials and Methods. The materials for the study were statistical data on machine part failures obtained through long-term observation of the working condition of basic parts of lifting-and-shifting machines, as well as road and construction machines. The paper used mathematical statistics and probability theory — a parametric method for assessing reliability with a simplified approach, which assumes the deterministic behavior of the machine as a system with a predetermined functioning that does not depend on external circumstances. The value of the safety margin is taken at a level greater than one.

Results. The degree of impact of the uncertainty of the reference values of the operating process, design features, manufacturing technique of machine parts and the malfunctions that occur in them, on the final probability of failure-free operation and reliability of machines is determined.

Discussion and Conclusion. The analysis of the theory of verification calculations of machines confirmed the compliance of the obtained results with regulatory requirements. The conducted studies have proven that machines are deterministic systems, whose behavior is specified in advance by the calculation. Therefore, it can be argued that the developed method of monitoring the reliability of technical systems, based on identifying the entropy of the causes of failures, will allow establishing a quantitative and qualitative relationship between the design, material, size, manufacturing technique of machine parts, and failures that occur in them.

Keywords: reliability control system, entropy, machine, failure, determined system

Acknowledgements. The authors would like to thank the Editorial board and reviewers for their attentive attitude to the article and the comments indicated, which allowed us to improve its quality.

For Citation. Rybak AT, Teplyakova SV, Olshevskaya AV, Prutskov AS. A Method for Monitoring the Reliability of Technical Systems by Identifying the Entropy of the Causes of their Failures. *Advanced Engineering Research (Rostov-on-Don).* 2025;25(2):112–119. https://doi.org/10.23947/2687-1653-2025-25-2-112-119

Оригинальное теоретическое исследование

Метод контроля надежности технических систем путем выявления энтропии причин их отказов

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Аннотация
Введение. При конструировании на этапе проведения расчетов закладывается большой запас прочности деталей и узлов, что не исключает преждевременные отказы, имеющие случайный характер. Последствиями таких отказов являются не только экономические потери, но и угрозы безопасности людям и окружающей среде. В современной литературе недостаточно освещена тема оценки надежности машин, рассматриваемых как сложные вероятностные системы, учитывающие не только динамические параметры при эксплуатации, но и технологические процессы изготовления составных деталей системы. Поэтому для обеспечения целенаправленного управления надежностью машин, как сложных технических систем, необходимо применять принципы кибернетики. Цель данной работы — исследование метода контроля надежности технических систем путем выявления энтропии причин их отказов.
Материалы и методы. Материалами для исследования послужили статистические данные отказов деталей машин, полученные путем многолетнего наблюдения за работоспособным состоянием базовых деталей подъемно-транспортных, дорожных и строительных машин. В работе применялась математическая статистика и теория вероятностей — параметрический метод оценивания надежности по упрощенному подходу, предполагающему детерминированное поведение машины как системы с заранее определенным функционированием, не зависящим от внешних обстоятельств. Значение запаса прочности принято на уровне больше единицы.
Результаты исследования. Определена степень влияния неопределенности исходных значений процесса эксплуатации, конструктивных особенностей, технологии изготовления деталей машин и возникающих в них неисправностей на итоговую вероятность безотказной работы и надежность машин.
Обсуждение и заключение. Анализ теории проверочных расчетов машин подтвердил соответствие полученных результатов нормативным требованиям. Проведенные исследования доказывают, что машины являются детерминированными системами, поведение которых заранее определяется расчетом. Поэтому можно утверждать, что разработанный метод контроля надежности технических систем, основанный на выявлении энтропии причин отказов, позволит устанавливать количественную и качественную взаимосвязь между конструкцией, материалом, размером, технологией изготовления деталей машин и отказами, возникающими в них.

Ключевые слова: система контроля надежности, энтропия, машина, отказ, детерминированная система

Благодарности. Авторы выражают благодарность редакции журнала и рецензентам за внимательное отношение к статье и указанные замечания, которые позволили повысить ее качество.

Для цитирования. Рыбак А.Т., Теплякова С.В., Рудой Д.В., Ольшевская А.В., Пруцков А.С. Энтропия как интегральный показатель надежности сложных технических систем. *Advanced Engineering Research (Rostov-on-Don).* 2025;25(2):112–119. https://doi.org/10.23947/2687-1653-2025-25-2-112-119

Introduction. Technological progress and the constant complication of technical systems and equipment make reliability a key factor in determining the efficiency of their operation. The importance of providing the required level of reliability of complex technical facilities is due not only to the possible emergence of economic costs, but also to the evolution of safety threats to people and the environment.

Conducting strength calculations when designing machines shows the adoption of significant reserve factors of parts, eliminating the possibility of breakdowns. Therefore, it can be mistakenly assumed that malfunctions and failures are caused by errors in design and/or low quality of manufactured mechanisms. Indeed, miscalculations by designers and calculators, poorly manufactured parts or materials can be the cause of individual breakdowns and malfunctions [1]. During the refining process, the vast majority of errors are eliminated, but this does not lead to a significant increase in the reliability of the machine [2].

As previously conducted studies show, the causes of failures are random, and the factors affecting the level of randomness may include changes in the following parameters: the interval between failures, the order of failure of parts or units, the time it takes to restore the machine functionality, etc. Therefore, a machine, as a complex system, exhibits various degrees of uncertainty while in operation, which is associated with entropy and makes it a probabilistic system [3]. The conducted analysis of the literature showed insufficient elaboration of the issue of monitoring the level of dependence of the reliability of a complex system not only on the operation process, but also on the manufacturing of the components of the system.

The method of managing the reliability level of technical systems with targeted identification of the entropy of the causes of failures, linking the design, material, size, manufacturing technique and operating features of parts, will allow predicting the frequency and intensity of failures, and this will have a positive effect on the level of failure-free operation of the entire mechanism.

Therefore, the objective of the presented research is to study the method of monitoring the reliability of technical systems through identifying the entropy of the causes of failures, that allow establishing quantitative and qualitative relationships between the designs, materials, sizes, and manufacturing techniques of machine parts with the failures that occur in them.

Materials and Methods. The materials for the study were data on failures of basic parts of lifting-and-shifting, road and construction machines, obtained as a result of long-term monitoring of their condition. The analysis of such information has confirmed that the practical level of reliability of machines is provided in the process of their design. Certain decisions taken in the process of designing and refining machines ultimately determine their reliability as a combination of trouble-free operation, durability and maintainability [4–5]. As practice shows, machine failures are fairly common phenomena that affect safety and the amount of damage caused to varying degrees (Fig. 1).

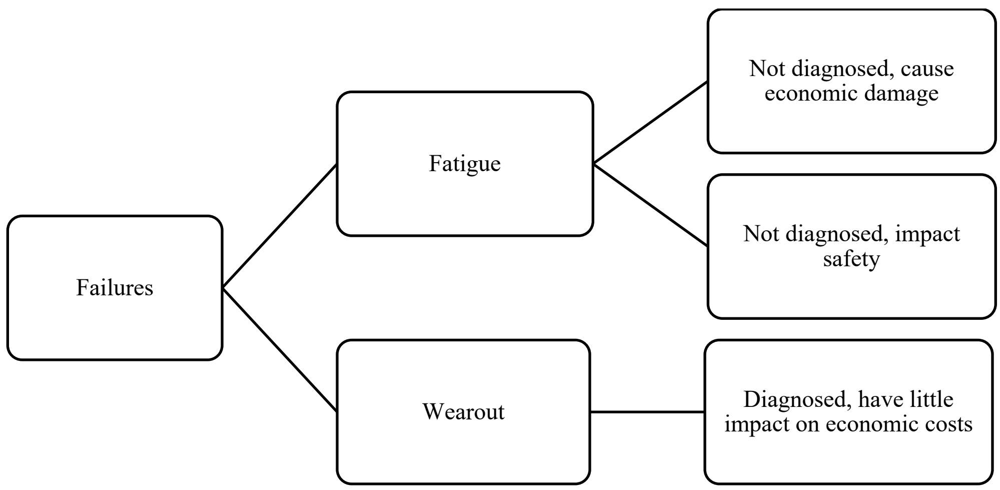

Fig. 1. Reasons for machine failures

As is known, at present, reliability calculations for machine components and parts are not performed. At the same time, the designer determines (albeit unconsciously) the reliability of parts, components and the machine as a whole — by establishing certain dimensions and shape of parts, accepting the value of the safety margin, assigning the grade of steel, heat treatment mode, surface purity, the nature of the mating and interaction with other parts, [6]. Therefore, the reliability parameters of machines manufactured in strict accordance with technical specifications are completely determined by the design organization — the author of the machine design [7].

In the process of serial production, deviations from drawings, technical conditions, obvious and hidden defects, etc., are possible. In some cases, engineering specifications contain unclear technical conditions for the manufacture and acceptance of parts and units, which allow for their free interpretation towards deterioration in quality. In order to eliminate obvious defects as much as possible, prior to putting the machines into operation, they are pre-run under load [8]. However, numerous machines do not undergo running-in due to the lack of required areas. Therefore, at the initial stage of machine operation, so-called running-in failures occur, whose frequency depends on the quality of the machine manufacture and gradually decreases to zero. Poor assembly quality leads to the need for additional maintenance of machines during the initial period of their operation.

It should be noted that running-in failures are caused by the most serious defects in the manufacture of machines. However, hidden defects (poor quality of heat treatment and welding, below-standard strength of the materials used, poorly executed sealing, etc.) manifest themselves in additional failures [9]. Thus, the design organization determines all the parameters of machine reliability, i.e., failure-free operation, durability and maintainability throughout their entire service life [10–12]. The manufacturer to a greater or lesser extent reduces the degree of reliability of machines, which manifests itself mainly at the beginning of their operation.

Even more significant damage is caused by so-called premature failures, which result in significant economic costs and can also be dangerous to human health and life [13].

As practice shows, reliability as a science does not lose its relevance over time, and ultimately, the objective of reliability management is to identify its quantitative parameters and actively affect them. This management consists in making the connection between the operation of machines, their design and manufacture [14].

Issues of rational control of complex probabilistic systems of any nature (from complex automatic self-guided systems to a living organism or community) with dynamic parameters are considered by cybernetics. These control processes include the collection, transmission, storage and processing of information. When analyzing a complex system, information from the external environment is also taken into account, which affects the behavior and state of the system [15]. Control is based on the principle of feedback, which allows the controlled process to be linked to the system under consideration.

Based on the principles of cybernetics, the process of machine operation can be controlled by less downtime, reduction of the volume of repair work and increase of the service life [16]. To provide the control process on the part of the manufacturer and/or design institute, it is necessary to set up feedback, i.e., to get comprehensive information on the operational reliability of the machine. To obtain reliable results, installations are used that allow resource tests to be performed under conditions close to real ones.

The question arises about the content and specificity of information suitable for targeted management of machine reliability for studying the method of monitoring the reliability of technical systems through identifying the entropy of the causes of failures in order to take into account the measure of uncertainty of the physical system under consideration [17]. In cybernetics, this value is entropy, which is defined as the sum of products of the probabilities of various states of the system multiplied by the logarithms of these probabilities taken with the opposite sign.

$$H = -\sum_{i=1}^{n} P_i \cdot log\, P_i, \tag{1}$$

where P_i — probability of the i-th state of the system; n — number of possible states of the system.

Entropy allows taking into account the amount of the eliminated uncertainty. The opposite sign shows the direction of the processes to indicate the nonequivalence of the direct (failure occurrence) and reverse (performance restoration) processes in real operating conditions.

Machines, as complex systems, consist of elements — parts. Each part/unit of machines can be considered as a simple system, which is in two states: serviceable or faulty. Thus, it becomes clear that the degree of uncertainty of the operation of the i-th part can be determined using formula [18, 19]:

$$H = -\left[K_{ip} \cdot log\, K_{ip} + K_{in} \cdot log\, K_{in} \right], \tag{2}$$

where K_{ip} — readiness coefficient of the i-th part; K_{in} — probability of a faulty condition of a part.

The readiness coefficient of a part is determined by the following relationship:

$$K_{ip} = \frac{T_i}{T_i + T_{iB}}, \tag{3}$$

where T_i — mean time between failures of the i-th part, i.e., its average time of nonfailure operation; T_{iB} — average time to restore the machine when the i-th part fails.

Relative duration of downtime of a part:

$$K_{in} = 1 - K_{ip}, \tag{4}$$

or

$$K_{in} = \frac{T_i}{T_i + T_{iB}}. \tag{5}$$

The reliability of a part is determined by its service life. If $t = Tp$ — service life of a part, then the service life distribution law:

$$Q_{(t)} = Tp\{Tp < t\}. \tag{6}$$

This function is the probability of failure of the part before moment Tp. It completely determines the reliability of this part [20, 21].

And the distribution density of this function is called the failure rate:

$$q_{(t)} = \frac{dQ_{(t)}}{dt}. \tag{7}$$

The following approximate relationship exists between the cycles to failure of a part and its reliability indicators:

$$T_{(t)} = \frac{\left[1 - Q_{(t)}\right]^2}{q(t)}. \tag{8}$$

In the statistical reliability theory, the reliability parameters of a part are expressed by the probability of failure-free operation $F(t)$ and failure rate $\lambda(t)$, which are determined from the following formulas:

$$F_{(t)} = 1 - Q(t), \tag{9}$$

$$\lambda(t) = \frac{q(t)}{F(t)}. \tag{10}$$

Hence,

$$Q_{(t)} = 1 - F(t), \tag{11}$$

$$q_{(t)} = F(t)\lambda(t). \tag{12}$$

Substituting the expression for $Q(t)$ and $q(t)$ into equation (7), we obtain

$$T(t) = \frac{q(t)}{\lambda(t)}. \tag{13}$$

Then, the part readiness coefficient

$$K_{ip} = \frac{F_1(t)}{F_1(t) + \lambda_1(t)T_{iB}}, \tag{14}$$

and the relative duration of downtime of the part

$$K_{ip} = \frac{\lambda_1(t) \cdot T_{iB}}{F_1(t) + \lambda_1(t)T_{iB}}. \tag{15}$$

We substitute expressions (11) and (12) into (2) and obtain an equation for the entropy of the part:

$$H_1(t) = -\left[\frac{F_1(t)}{F_1(t)+\lambda_1(t)T_{iB}} log \frac{F_1(t)}{F_1(t)+\lambda_1(t)T_{iB}} + \frac{\lambda_1(t)\cdot T_{iB}}{F_1(t)+\lambda_1(t)T_{iB}} log \frac{\lambda_1(t)\cdot T_{iB}}{F_1(t)+\lambda_1(t)T_{iB}}\right]. \tag{16}$$

Understanding that the failures of machine parts are independent of each other, the machine from a cybernetic point of view can be represented as a complex system obtained by combining simple systems — the parts that make up the machine.

Therefore, according to the entropy addition theorem, when combining independent systems, their entropies are added up. This means that the entropy of the machine operation is determined by the following formula:

$$H(t) = \sum_{i=1}^{m} H_i(t), \tag{17}$$

where m — number of parts that make up a machine.

Substituting value $H_i(T)$ here, we obtain the formula for determining the failure entropy of the entire machine:

$$H_1(t) = \sum_{i=1}^{m}\left[\frac{F_1(t)}{F_1(t)+\lambda_1(t)T_{iB}} log \frac{F_1(t)}{F_1(t)+\lambda_1(t)T_{iB}} + \frac{\lambda_1(t)\cdot T_{iB}}{F_1(t)+\lambda_1(t)T_{iB}} log \frac{\lambda_1(t)\cdot T_{iB}}{F_1(t)+\lambda_1(t)T_{iB}}\right]. \tag{18}$$

The authors of the article believe that the entropy value obtained for the entire machine with a significant exhausted resource will tend to unity.

Research Results. As an example, the study determined the entropy of one of the basic parts of a loader — a boom, whose availability factor (probability that the loader boom is currently in serviceable condition), adopted by the manufacturer, is equal to $K_{ip} = 0.9$, and the relative duration of downtime is $K_{in} = 0.1$. The entropy of the part, according to dependence (2), will be

$$H = -\left[0.9\, log\, 0.9 + 0.1\, log\, 0.1\right] = 0.14.$$

As the readiness coefficient increases to $K_{ip} = 0.95$, entropy H tends to zero:

$$H = -\left[0.95\, log\, 0.95 + 0.05\, log\, 0.05\right] = 0.08.$$

If we consider the issue of replacing the boom, the duration will be approximately one work shift, but the costs in this case will be high, since they include the purchase of a new boom (approximately 112 thousand rubles). Repairing the boom is cheaper in terms of components, but its duration increases by an order of magnitude depending on the complexity of the repair.

That is, if we consider a loader boom, for which the availability factor declared by the manufacturer is equal to K_{ip} = 0.9, and the relative duration of downtime is K_{in} = 0.1, then entropy will be:

$$H_1(t) = -\left[\frac{0.9}{0.9\cdot 0.1\cdot 10} log \frac{0.9}{0.9\cdot 0.1\cdot 10} + \frac{0.1\cdot 10}{0.9\cdot 0.1\cdot 10} log \frac{0.1\cdot 10}{0.9\cdot 0.1\cdot 10}\right] =$$
$$= -\left(0.47\, log\, 0.47 + 0.5\, log\, 0.5\right) = -\left(0.32 + (-28)\right) = 0.6.$$

Thus, the degree of impact of the uncertainty of the initial values on the final probability of failure-free operation and, as a consequence, on the reliability of the machine is determined. A method for monitoring the reliability of technical systems based on identifying the entropy of the causes of failures, taking into account the quantitative and qualitative relationships between the design, material, dimensions and manufacturing technology of machine parts with the failures that occur in them, is developed.

Discussion and Conclusion. The study of the method of monitoring the reliability of technical systems by identifying the entropy of the causes of failures is a method of simplifying calculations, consisting in the determination of the machine operation [5]. The use of entropy in calculations allows taking into account the amount of the uncertainty of the relationship between quantitative and qualitative characteristics with design features, materials, dimensions, and processes of manufacturing machine parts, and the malfunctions that arise in them.

The conducted study of this relationship shows that the entropy of the loader operation, changing over time, is determined by the reliability characteristics and conditions of restoration of the machine components (units and parts).

The entropy of a complex machine system grows with the extension of its lifetime. This is confirmed by the increase in the frequency of fatigue processes, plastic deformations, and the degree of wear. When a certain level of entropy is reached, the operation of the machine is limited, and a major overhaul is performed, which helps to reduce the entropy of the machine operation.

In the process of targeted management of the operational reliability of the machine, the accuracy of the incoming information about the state of the system is very important. Such information should contain the actual, time-varying reliability (failure-free operation and maintainability) of all the components of the machine — units and parts.

Obviously, achieving zero entropy of a machine as a complex system is possible not only by analyzing quantitative indicators of component reliability, but also through identifying the causes of failures. Then, the volume of information under study when studying a sample lot of objects (parts, units, machines), obtained under operation, increases significantly. Conducting a special analysis allows us to determine the causes of component failures and provide clear recommendations for their elimination.

Thus, the authors have proven that the method of monitoring the reliability of technical systems by identifying the entropy of the causes of failures considered in the research provides for effective control of the reliability of complex systems, taking into account not only the operational causes of failures, but also design features, materials, dimensions, and manufacturing of parts. The application of this method of reliability control of complex systems will make it possible to develop a reliability management system with identification of failure causes. This will make it possible to consider the machine not as a probabilistic system, but as a deterministic system, where the change in reliability is precalculated. Although the need for reliability management is decreasing, reliability control will probably remain an important requirement to prevent possible errors in machine design.

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Claimed Contributorship:
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Conflict of Interest Statement: **the authors declare no conflict of interest.**

All authors have read and approved the final manuscript.

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Заявленный вклад авторов:
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А.В. Ольшевская: валидация результатов, курирование данных.
А.С. Пруцков: написание черновика рукописи, написание рукописи – рецензирование и редактирование.

Конфликт интересов: **авторы заявляют об отсутствии конфликта интересов.**

Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 21.03.2025
Reviewed / Поступила после рецензирования 12.04.2025
Accepted / Принята к публикации 16.04.2025