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DIAGNOSTICS OF THE STATE AND PREDICTION OF THE RESIDUAL RESOURCE OF PARTS IN EXTREME OPERATING CONDITIONS

A methodology has been developed to assess the performance and determine the residual resources of the equipment during its operation. Based on the analysis of the physical essence and the synthesis of the main principles of building models for determining the residual resource of equipment operating in complex, including extreme operating conditions, the advantages, disadvantages and prospects of using criteria based on mathematical and probabilistic methods are determined. The classification and systematization of the main criteria for evaluating the performance and residual resources of the equipment has been carried out. Their formalized description of changes in the technical condition of objects during their operation is given. It is noted that the criterion of an ideal observer should be used when the cost of assessing the condition of materials at the early and empty stages of its degradation is equal; the criterion of the minimum average risk should be used when the costs of incorrect assessment of the condition of the material are high. The maximum likelihood criterion has the advantage of not requiring knowledge of the a priori probability of costs. The criterion of root mean square error estimations involves assigning the parameters of the customary laws of the distribution of estimation characteristics. The criterion of achieving a given level of reliability is recommended to be used when the consequences of equipment shutdowns are more significant than preventive measures. The minimum posterior probability criterion is used in cases where the loss matrix is known. Practical recommendations are given for their use in systems of technical diagnostics and non-destructive testing when assessing the condition of equipment operating in difficult operating conditions. An example of the methodology implementation is given.
Keywords: residual resource, performance, uncertainty, external environment, evaluation criteria, diagnostics, forecasting, operation, transport.

INTRODUCTION

The equipment's residual resource is the material's total working time from the moment of control and diagnostics of the technical condition to the transition to the limit state, at which its further operation is impossible. The transition to the limit state occurs gradually as physical wear and tear is reached. However, the operating conditions of the equipment are not always stable in terms of time due to sharp changes in temperature, pressure, humidity of the environment, and loads on the working parts of the mechanisms.

When the limit state is reached, the equipment is disabled. It needs to be more accurate in making conclusions about reaching the limited state of the equipment when assessing the residual resource at the early stage of material degradation, leading to unjustified shutdowns and decommissioning of the equipment. However, its operation is safe. Errors in estimating the limit state at later stages lead to disasters and harm not only the equipment but also the health of the personnel. Therefore, accounting for the standard service life for assessing the equipment resource is a determining parameter of the suitability of the products. Calculation of the residual resource of the equipment is included in the examination of the operation of any complex equipment.

At the same time, peak loads on the parts and components of the mechanisms reduce the quality of the residual resource assessment and complicate its quantitative interpretation. There is a state of uncertainty and risk to equipment operation safety. Therefore, the problem of estimating the residual resource is multifaceted. Developing methods for assessing the residual resource of equipment operated in challenging production conditions is an urgent and urgent task.

DATA ANALYSIS AND PROBLEM STATEMENT

Analysis of existing models for assessing the condition of technical objects, diagnostics, predicting performance and residual resources shows the existence of correlational dependencies between changes in physical and mechanical characteristics and operational properties of materials [1-4].

Diagnostic information, which includes:

- information about periods between repair cycles,
- data on the latest conclusions of operational control,
- operating conditions and environmental parameters,
- data on the load on the object,
- information about zones of possible destruction.

When identifying the operational state and determining the value of the residual resource of equipment operating in difficult operating conditions, mathematical models are used that describe in detail the internal and external processes of the object of diagnosis. According to their structure, such models are stochastic, statistical and deterministic. Stochastic models are built on the basis of probabilistic concepts. The probability distribution functions of the estimated variables, which are the basis of the investigated process and operating conditions, are calculated. Statistical models are built on the basis of experimental data on the relationship between input and output variables. Deterministic models are means of interconnection of measured and calculated values.

For short-cycle loads, deterministic and statistical models of residual resource estimation are used, taking into account standardized parameters, conditions and criteria for determining the limit state, limitations and duration of effects [5, 6]. The following mathematical processing of a priori information excludes the presence of the human factor and is an objective assessment of material degradation during its operation, caused by fatigue damage and defects such as cracks, shells, corrosion damage [7-9].

The most common method of assessing the residual resource under multi-cycle loading is the method of expert assessments, based on the analysis of the causes and mechanisms of damage, establishing the actual loading, forecasting the parameters of the technical condition, establishing regularities and trends, making decisions about extending the service life of the tested equipment [10, 11]. Despite the large share of subjectivity associated with the composition, qualifications, experience and other components that determine the quality of the examination, this method of control is widely used in practice.

The diagnosis of the residual resource consists in monitoring the characteristics that reflect the process of changing the parameters of the technical condition at different moments of the equipment's operation in relation to the limit value [12, 13]. Although this method can be attributed to express methods, the scope of its rational use extends to those objects of forecasting in which changes in the controlled characteristics at the time of control are at least half of the maximum values.

Extreme, complex and uncertain operating conditions of the equipment sharply reduce and limit the possibilities of mathematical and expert methods, since it is necessary to know the determining parameters of the technical condition of the equipment, the criteria for determining this condition and the possibility of failures, for which probabilistic estimates should be used.

THE PURPOSE AND TASKS OF THE RESEARCH

The purpose of the study is to develop a methodology for determining the serviceability and residual resource of equipment operating in difficult operating conditions.

Tasks of the research:

1 Analysis of the physical essence and basic principles of using criteria for diagnosing the quality of materials, mechanisms and structures.

2. Assessment of the applicability of diagnostic criteria and non-destructive testing to conclusions about the performance and value of the residual resource of the equipment operating in difficult operating conditions.

3. Development of procedures for determining the serviceability and residual resource of equipment under extreme and difficult conditions of technical operation.

THE RESULTS

Due to the lack of information about the manifestations of the external environment that affect the functioning of production facilities, the degree of impact, the duration and magnitude of the load, the types of deformation, when assessing the performance of structures and the residual resource, it is necessary to use a number of criteria that differ in their physical essence and nature of origin.

The physical essence and semantic content of the criteria are based on regulatory documents based on the principles of fracture mechanics, tear test methods, bending and tensile tests, and strength calculation methods for structures. Based on the result of identifying the condition of the construction material and the criteria for evaluating the suitability of the products for further operation, a conclusion is given about the further operability and residual resource of the equipment.

The classification of the composition of the performance criteria and the residual resource of products in difficult operating conditions includes:

- the criterion of an ideal observer, in the form of non-degradation and re-degradation at the early and late stages of material degradation,
- the criterion of the minimum average risk from both non-finishing and failure to operate technical objects with limited or exhausted residual resources,

- the criterion for normal recognition of the technical condition of diagnostic objects, which consists in choosing the optimal decision rule between the two extreme states of non-docking and over-docking,
- criterion of maximum plausibility, which consists in probabilistic assignment of the object of diagnosis to one or another state,
- criterion of the maximum posterior probability, based on assigning the object of diagnosis to classes whose posterior probabilities exceed others,
- the Neyman-Pearson test, which is based on the given permissible probabilities of correct and false identification,
- the criterion for achieving a given level of reliability, when the consequences of decommissioning are incomparable with the costs of scrapping,
- the Harrington interval desirability function criterion, based on an artificial metric of correspondence with standard analogues,
- the criterion is based on the estimation of the root mean square error during diagnostic measurements.

The presented classification of criteria and the recommended sequence of their use are shown in fig. 1.

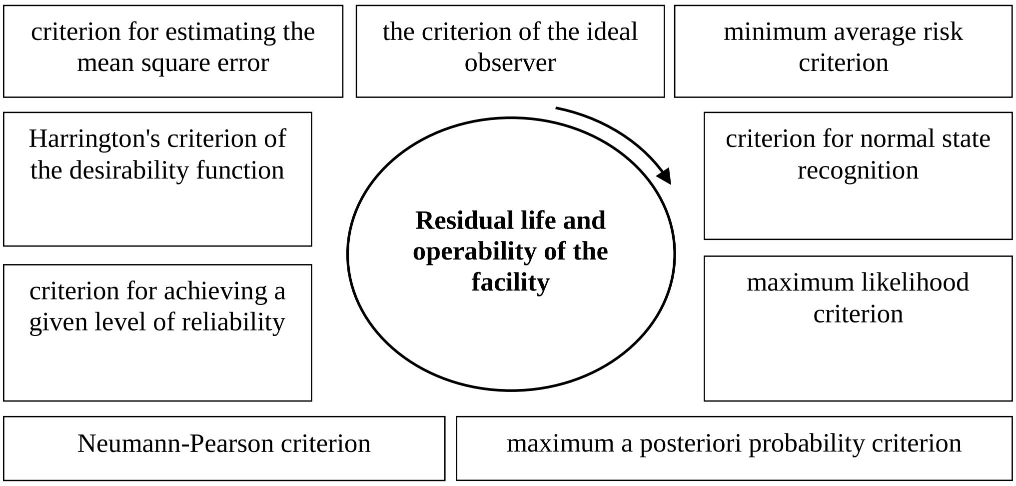

Fig. 1. Criteria for assessing serviceability and residual life

The ideal observer criterion, which is widely used in defect inspection, in its content, is expressed by the probability of missing existing defects by the non-destructive control system and the probability of false rejection of suitable products, which is equally unacceptable and unacceptable. As for the assessment of the residual resource, the transformation of this criterion of incompleteness will look like an unreasonable need to perform an assessment of the performance of the equipment and the residual resource at the stage when no structural changes in the material occur during operation, because everything is stable and stable and the diagnosis of changes is not appropriate. This moment can be attributed to lack of touch. A shortcoming will be the omission of the beginning of changes in the material structure and its degradation, when diagnostics are necessary due to emergency effects of the operating environment, but according to the plan of the inter-repair cycle, it is not yet foreseen. This is the worst situation.

From the point of view of preserving the commonality of concepts during the study of the criteria for evaluating the residual resource and working capacity, the concepts of under-handling and over-handling will be preserved

For the criterion of the perfect observer of reject cost C_1 and rejects C_2 are considered equal and a quantitative indicator of reliability G can be seen as

$$G = 1 - (F + \beta)$$

where F – probability of rejects; β – probability of rejects.

The consequences of rejects and overstocks are different, so the criteria for solving the problems of optimising the control system are also different. The most cautious criterion is the minimum average risk criterion R.

The criteria of the minimum average risk in the case of a false assessment of the residual resource are used in cases where large losses are expected due to the omission of low-quality products, and the criteria of an ideal observer in cases where large losses are due to the incorrect classification of the state of quality products.

The criterion of normal recognition of the technical condition of objects of diagnosis is the task of statistical recognition of correct and incorrect assessments of the condition of objects of diagnosis in the form of a set of observations recorded in the form of a matrix.

$$X = \begin{bmatrix} x_{11} \cdot x_{12} \cdots x_{1n} \\ x_{21} \cdot x_{22} \cdots x_{2n} \\ \vdots \cdot \vdots \\ x_{p1} \cdot x_{p2} \cdots x_{pn} \end{bmatrix}$$

Each column of the matrix represents a vector of the states of diagnostic objects. In the theory of statistical decisions, all types of decision rules are based on the formation of a probability ratio L and its comparison with a certain threshold c

$$L = \frac{f_n\left(x_1,\ldots,x_n \middle| \ a_2\right)}{f_n\left(x_1,\ldots,x_n \middle| \ a_1\right)} \geq c$$

where $f_n\left(x_1,\ldots,x_n \middle| a_j\right)$ – probability density of values $x_1,\ldots,x_n$ provided they belong to a class a_j. The decisive rule for k = 2 looks like

$$L = \frac{f\left(x_1,\ldots,x_n \middle| \ a_2\right) \geq}{f\left(x_1,\ldots,x_n \middle| \ a_1\right) \angle} \frac{\varPi_{12} - \varPi_{11} P(a_1)}{\varPi_{21} - \varPi_{22} P(a_2)}$$

where $\varPi = \begin{bmatrix} \varPi_{11} \varPi_{12} \\ \varPi_{21} \varPi_{22} \end{bmatrix}$ – loss matrix, element $\varPi_{ki}$ which quantifies the losses from a wrong decision $P(a_j)$ – a priori probabilities of classes.

The criteria for maximum plausibility of conclusions about serviceability and residual life do not require knowledge of the a priori probabilities of classes and loss functions.

$$a = \begin{cases} a_2, \text{if } L\left(x_n\right) \geq 1 \\ a_1, \text{if } L\left(x_n\right) < 1 \end{cases}$$

Cognisable through α_k – the probability of correctly assigning the state of objects to the appropriate class and through β_k the probability of assignment to a class to which it does not belong. Assigning an object state to a class other than the one it actually belongs to is a type 1 error. Assigning the state of objects to a certain class to which it does not actually belong is a type 2 error. With two classes, the following equality holds $\alpha_1 = \beta_2$ and $\alpha_2 = \beta_1$ and probability α_1 and β_1 coincide with the possibilities of errors of the 1st and 2nd kind (Fig. 2).

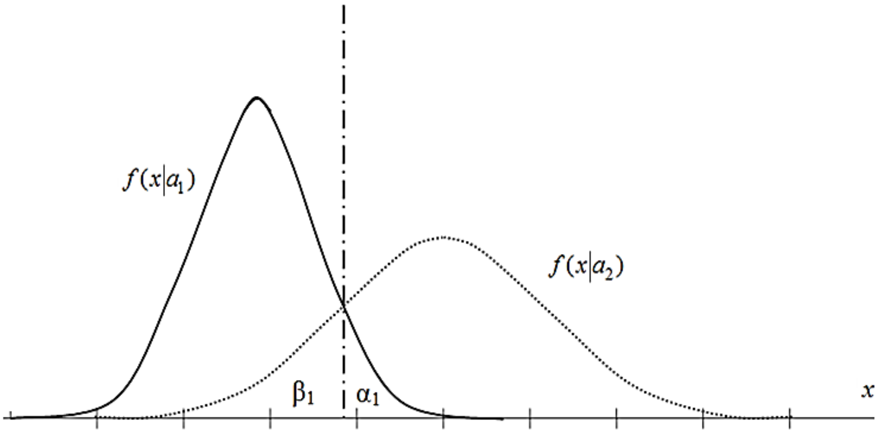

Fig. 2 Probability densities of assessments of the state of serviceability of structures

The maximum a posteriori probability criterion is used when the loss matrix is unknown, according to which the observation x_n belongs to the class a_1, whose a posteriori probability is equal to $P\left(a_j \middle| x_n\right)$ and exceeds the a posteriori probabilities of other classes:

$$a = \begin{cases} a_2, \text{if } L(x_n) \geq P(a_1)/P(a_2) \\ a_1, \text{if } L(x_n) < P(a_1)/P(a_2) \end{cases}$$

$$P(a_j|x_n) = \frac{P(a_j) f(x_n| a_j)}{\sum_{k=1}^{K} P(a_k) f(x_n| a_k)}$$

To build a classification based on the maximum likelihood criterion, it is necessary to determine the intersection points of the probability density plots

$$L(x) = \frac{f(x, m_1, \sigma_1)}{f(x, m_2, \sigma_2)} = 1$$

The Neumann-Pearson test should be used if we have difficulties in estimating losses. In this case, they proceed from the given permissible probabilities of correct and false identification of the operational state of the diagnostic objects.

The criterion of achieving a given level of reliability of assessments of the technical condition of workability is used in the control of particularly responsible products, when the consequences of failure are not commensurate with the costs of handling.

$$G_0 = 1 - F$$

The Harrington interval desirability function criterion is used as an indicator of the reliability of serviceability and residual life estimates. For this purpose, an artificial metric is introduced, in which the set of reviews is put in line with the standard analogue, i.e., the partial desirability of the function is calculated d_i.

$$d_i = \exp[-\exp(-y_i)] = e^{-e^{-y_i}}$$

Where y_i – value i – of that partial response, translated into a dimensionless scale of desirability $d_u (u = 1, 2, \ldots, n)$ (Fig. 3).

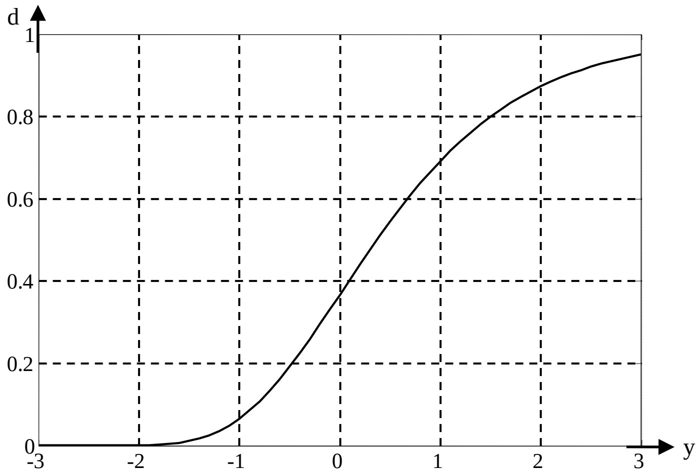

Fig. 3 Harrington's desirability function

The desirability scale has an interval from 0 to 1. Values $d_u = 0$ corresponds to a completely unacceptable level of quality, and the value of $d_u = 1$ the best value (Table 1).

The generalized desirability function is calculated as the geometric mean of the partial desirabilities

$$D = \sqrt[n]{\prod_{i=1}^{n} d_i}$$

where n – the number of analyzed indicators of the diagnostic objects' performance status.

Table 1 Interval scale of quality of indicators of the state of health of diagnostic objects

Rank	Quality	Interval of numerical values
1	Very good	0,8-1,0

2	good	0,63-0,80
3	Satisfactory	0,37-0,63
4	bad	0,20-0,37
5	Very bad	0

This method requires the involvement of a priori information about the contribution of this parameter to the overall desirability of determining the indicators of the state of health of the diagnosed objects.

A special place among the criteria of the technical condition of objects should be given to the criterion of the root mean square estimation of measurements, where for given values of the parameters of normal distribution laws (m_1, σ_1) i (m_2, σ_2), characterize two classes of diagnostic objects a_1 and a_2, are defined as the probability density of the observation results $f(x|a_1) = f(x,m_1,\sigma_1)$ and $f(x|a_2) = f(x,m_2,\sigma_2)$. The measured values of the features of the object x are realizations of a random variable with a distribution density $f(x,m,\sigma)$ equal

$$f\left(x,m,\sigma\right)=\frac{1}{\sqrt{2\pi}\cdot\sigma}exp\left(\frac{-\left(x-m\right)^2}{2\sigma^2}\right)$$

The numerical characteristic of reliability is the correctness of assigning the mathematical expectation of the measured parameter of the state of the diagnostic object to the category of worthy m_A defective m_B states with standard deviations S_A and S_B. The amount of risk from making an incorrect decision on the suitability of the diagnostic object for further operation is determined by the ratio of the standard deviation to the mathematical expectation.

DISCUSSION OF THE RESULTS

The obtained results of using the criteria for the correct assessment of the states of operability and residual life of equipment operating in difficult operating conditions are summarized in Table 2.

Table 2. Criteria for the technical condition of the facilities' equipment and residual service life

Name of the criterion	Advantages	Disadvantages
The criterion of the ideal observer	The total risk of extreme material condition assessments is taken into account	The cost of an incorrect assessment of the material condition at the early and late stages of its degradation is considered equal
Minimum medium risk criterion	The average risk of extreme estimates is taken into account	Used when losses due to incorrect assessment of the material condition are high
Criterion for normal state recognition	Determine the optimal decision rule between the extreme states of the equipment	The need to specify statistical distributions of the state characteristics of diagnostic objects
Maximum plausibility criterion	Comparison of state estimation probabilities with the selected estimation quality threshold	The use of the criterion does not require knowledge of the a priori probability of losses
Minimum a posteriori probability criterion	Use of a posteriori information	Used in cases where the loss matrix is known
Criterion for achieving a given level of reliability	Assessment of the health of critical products	It is used in cases where the consequences of equipment shutdowns are greater than reinsurance
Harrington's interval desirability function criterion	Ability to assess the reliability of the diagnostic object	The need to introduce a metric for standardized assessments
The Neumann-Pearson criterion	Possibility of probabilistic estimates	Knowledge of correct and incorrect identification probabilities is required
Criteria for estimating standard errors and errors	Use of mathematical statistics	The need to specify the parameters of normal laws of distribution of evaluation characteristics

The analysis of the information presented in Table 2 made it possible to outline a number of ways to improve the quality of performance assessments and the residual resource of equipment operating in difficult operating conditions.

One way to improve the reliability of determining the technical condition of diagnostic objects is to reduce the errors in the estimation of the diagnostic parameter *X*. Another way to improve the quality of estimates of equipment performance and residual life is to increase the search sensitivity. But at the same time, when determining the technical condition of diagnostic objects at the level of $X \geq X_0$, rejects are on the rise. If such cases are detected, diagnostics are carried out using other quality criteria for statistical significance assessments.

As a practical example, we consider a structural element made of St3sp steel subjected to simultaneous longitudinal tensile and transverse bending forces. The construction of the limit curve of the bearing capacity of the structure in the load space was performed according to [14, 15].

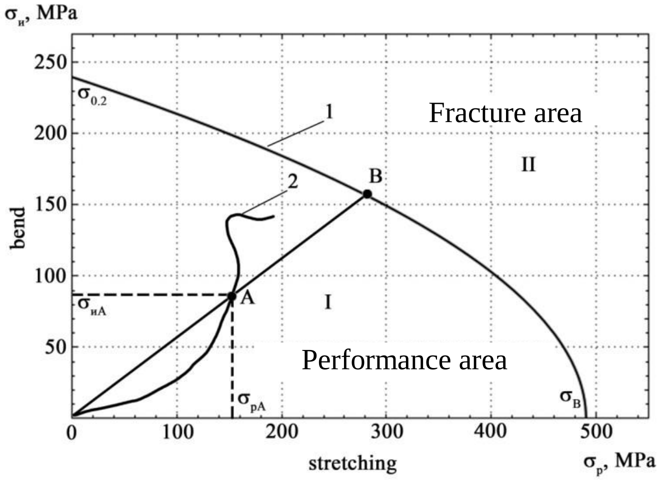

Fig. 4 Graphical interpretation of the safety margin in terms of mechanical stress:
1 – limit curve, 2 – load trajectory

The equation of the limit curve is as follows:

$$\left(\frac{\sigma_{и}}{\sigma_{0.2}}\right)^2 + \frac{\sigma_{р}}{\sigma_{в}} = 1$$

When an element is loaded with a single load, the limit curve degenerates to a point. If one of the coordinates of the point is zero, the load-bearing capacity means that the equilibrium is no longer stable.

Let's consider a scheme for calculating the safety margin for an arbitrary point A located on the load trajectory. For point A, the condition of static stability is as follows:

$$\left(\frac{\sigma_{иA}}{\sigma_{0.2}}\right)^2 + \frac{\sigma_{рA}}{\sigma_{в}} \leq 1$$

Let's multiply both terms of this equation by a certain coefficient λ, whose value is chosen so that the inequality turns into equality:

$$\left(\lambda\frac{\sigma_{иA}}{\sigma_{0,2}}\right)^2 + \lambda\frac{\sigma_{рA}}{\sigma_{В}} = 1$$

Coefficient λ is the safety margin at the time when the load corresponds to point A. Geometrically, the safety margin is equal to the ratio of the segment OB to the segment OA. Therefore, the condition of serviceability can be formulated as follows:

$$\lambda = \frac{OB}{OA} \geq 1$$

Analytical safety margin λ is the positive root of this equation:

$$\lambda = \frac{\sigma_{0.2}}{\sigma_{иA}}\left[-\frac{1}{2}\frac{\sigma_{0.2}\sigma_{рA}}{\sigma_{В}\sigma_{иA}} + \sqrt{\frac{1}{4}\left(\frac{\sigma_{0.2}\sigma_{рA}}{\sigma_{В}\sigma_{иA}}\right)^2 + 1}\right]$$

Approximations of mechanical stress for tensile deformation are obtained σ_o and bending σ_b make it possible to represent these curves in the coordinates of the evaluation characteristics.

CONCLUSIONS

1. A developed methodology for assessing the performance and residual resource of equipment operating in difficult conditions. It is shown that the uncertainty in assessing the degree of influence of the external environment and extreme load conditions can be reduced with the introduction of statistical and mathematical criteria.

2. The analysis of the quality criteria of the technical condition of the objects based on the examination of the physical essence of the main features and the mathematical presentation of operations for determining the states of working capacity and residual resource made it possible to make a systematic classification of the areas of rational use, advantages and disadvantages. It is shown that the scope of application of classical mathematical criteria related to the quality of evaluations requires the introduction of associative relations, while statistical criteria related to the evaluation of parameters and distribution laws of evaluation characteristics require the processing of experimental information.

3. Ways to increase the reliability of performance estimates and residual resource of equipment operating in difficult conditions are outlined. It is shown that the main one of them is an increase in sensitivity to the border between the state of operability and the area of damage of the diagnosed products. Another way is to reduce errors when measuring evaluation characteristics and change the sequence of using criteria.

REFERENCES

1.Mygal V., Arhun S., Hnatov A., Ulianets O., Kunicina N., Ribickis, L. (2022, May). Diagnostics of Tractor Transmissions by Vibration Levels. In 2022 IEEE 7th International Energy Conference (ENERGYCON) (pp. 1-4). IEEE. DOI: 10.1109/ENERGYCON53164.2022.9830506

2.Perederyi V., Borchik Eu., Lytvynenko V., Ohnieva O. Information Technology for Performance Assessment of Complex Multilevel Systems in Managing Technogenic Objects.CEUR Workshop Proceedings, 2020, vol. 2805, pp. 175-188. http://ceur-ws.org/Vol-2805/paper13.pdf.

3.Korniejenko K. , Łach M., Chou S.-Y. , Lin W.-T. , Cheng A. , Hebdowska-Krupa M. , Gadek S. , Mikuła J. Mechanical properties of short fiber-reinforced geopolymers made by casted and 3D printing methods: A comparative study. Materials, 2020, 13 (3), art. no. 57

4.Li S., Li M., Liu Z., Li M. A Data-Driven Residual Life Prediction Method for Rolling Bearings (2023) Proceedings of 2023 IEEE 12th Data Driven Control and Learning Systems Conference, DDCLS 2023, pp. 1629-1633. DOI: 10.1109/DDCLS58216.2023.10166951

5.Xu J. , Guo L. , Zhang R. , H. Hu, F. Wang, Z. Pei, QoS-aware Service Composition Using Fuzzy Set Theory and Genetic Algorithm. Wireless Personal Communications, 2018, 102 (2), pp. 1009-1028

6.Zhao, L., Zhang, S., Zhang, X., Li, Y. Locating and sizing method for energy interconnection oriented active distribution networks based on stochastic chance constrained programming (2020) Dianli Xitong Baohu yu Kongzhi/Power System Protection and Control, 48 (14), pp. 121-129. DOI: 10.19783/j.cnki.pspc.191118

7.Levin V.M., Yahya A.A. Adaptive management of technical condition of power transformers. International Journal of Electrical and Computer Engineering. 2020. 10 (4), P. 3862-3868.

8.Liangxing Lin, Guozheng Ma, Jianfang Sun, Cuihong Han, Qingsong Yong, Fenghua Su, Haidou Wang. (2023) Remaining Useful Life Prediction Method of Coated Spherical Plain Bearing Based on VMD-EEMD-LSTM. Jixie Gongcheng Xuebao/Journal of Mechanical Engineering. 59(9), c. 125-136 DOI: 10.3901/JME.2023.09.125

9.Liu W., Jiao S., Wen T., Zhu J. Remaining Life Prediction Method of Relay Protection Equipment Based on Digital Twin (2023) 2023 4th International Conference on Computer Engineering and Application, ICCEA 2023, pp. 243-247. DOI: 10.1109/ICCEA58433.2023.10135436

10.Havruk V. O. Static simulation modeling of inventory management, Scientific and technical collection Bulletin of the National TransportUniversity, (2017), issue 2. P. 80–87

11.Jin Y., Xin G., Antoni J. Towards automated, integrated and unsupervised diagnosis of rolling element bearings (2023) Mechanical Systems and Signal Processing, 203, art. no. 110691.

12. Li N., Wang X., Yang T., Han Q. Research on Micro-Turbine Operating State Characterization Based on Bearing Vibration Signals Analysis (2023) International Journal of Acoustics and Vibrations, 28 (4), pp. 435-450.

13.Momenzadeh M., Sehhati M., Rabbani H. A novel feature selection method for microarray data classification based on hidden Markov model. Journal of Biomedical Informatics, 95(2019), art. no. 103213.

14.Marasanov V., Stepanchikov D., Sharko A., Sharko O. Technology for determining the residual life of metal structures under conditions of combined loading according to acoustic emission measurements. Communications in Computer and Information Science, 2020, 1158, pp. 202–217

15.Polyvoda O., Rudakova H., Kondratieva I., Yuriy Rozov Y., Lebedenko Y. Digital acoustic signal processing methods for diagnosing electromechanical systems. Lecture Notes in Computational Intelligence and Decision Making: Proceedings of the XV International Scientific Conference "Intellectual Systems of Decision Making and Problems of Computational Intelligence"(ISDMCI'2019), Ukraine, May 21–25, 2019, pp. 97-109

Передерій В.І., Нужний С.М., Лебеденко Ю.О. Діагностика стану та прогнозування залишкового ресурсу деталей в екстремальних умовах експлуатації.

Розроблено методологію оцінки працездатності та визначення залишкового ресурсу обладнання в процесі його експлуатації. На основі аналізу фізичної сутності та синтезу основних принципів побудови моделей визначення залишкового ресурсу обладнання, що працює у складних, у тому числі екстремальних умовах експлуатації, визначені переваги, недоліки та перспективи використання критеріїв, покладених в основу математичних та ймовірнісних методів. Виконано класифікацію та систематизацію основних критеріїв оцінки працездатності та залишкового ресурсу обладнання. Дається їх формалізоване опис стосовно зміни технічного стану об'єктів за її експлуатації. Зазначено, що критерій ідеального спостерігача слід використовувати у разі коли вартість оцінки стану матеріалів на ранній та пусті стадії його деградації рівні, критерій мінімума середнього ризику слід використовувати, коли великі витрати від неправильної оцінки стану матеріалу. Критерій максимальної правдоподібності має перевагу, оскільки не вимагає знань апріорної ймовірності витрат. Критерій оцінок середньоквадратичних помилок потребує завдання параметрів нормальних законів розподілу оціночних характеристик. Критерій досягнення заданого рівня надійності рекомендується використовувати, коли наслідки в зупинках обладнання більше ніж перестрахувальні заходи. Критерій мінімума апостеріорної ймовірності використовується у випадках коли матриця втрат відома. Наводяться практичні рекомендації щодо їх використання у системах технічної діагностики та неруйнівного контролю при оцінці станів обладнання, що працює у складних умовах експлуатації. Наводиться приклад реалізації методології.

Ключові слова: залишковий ресурс, працездатність, невизначеність, зовнішнє середовище, критерії оцінки, діагностика, прогнозування, експлуатація, транспорт.

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