JOURNAL OF MARITIME RESEARCH

Vol XXII. No. I (2025) pp 25–34

ISSN: 1697-4840, www.jmr.unican.es

Analysis Of the Methods Used to Assess the Reliability Of Marine Navigation Equipment and Systems

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ARTICLE INFO

Article history:
Received 22 Mar 2024;
in revised from 17 Apr 2024;
accepted 05 Jun 2024.

Keywords:
shipping, maritime transport, ocean transportation, ship navigation process, ship handling, bridge equipment, devices, operational readiness, system reliability, redundancy, duplication, emergencies, navigation safety, incident prevention, technical condition, accident risk.

ABSTRACT

The growth of shipping intensity and the increase in the size and speed of ships lead to increased maritime traffic density and require stricter operational safety requirements. The article discusses the problem of the decreasing reliability of marine navigation systems caused by the constant complexity of their technical infrastructure. Despite the high reliability of individual components, the overall complexity of the systems leads to an increased risk of failure, especially under specific operating conditions. Given the remoteness of ships from repair bases, failure of critical equipment can lead to emergencies with severe consequences. The study focuses on improving technical means' reliability by introducing structural redundancy (duplication) and applying comprehensive evaluation approaches, including a priori, a posteriori, and hybrid methods. Mathematical models of degradation processes are presented, based on which probabilistic-physical models for estimating the time to failure are built. The article aims to form a systematic approach to ensuring the continuous operability of marine navigation systems at all life cycle stages, which is critical for improving the reliability of maritime transportation and reducing the risk of accidents.

1. Introduction.

The growing number, size, and speed of vessels underscore the importance of heightened maritime safety measures. Ensuring the reliability of marine technical systems is essential for safe navigation. Nevertheless, the increasing complexity of Technical equipment challenges the overall reliability of the system. While individual components may be reliable, the continuous advancement of technical systems can reduce their overall reliability. This decline poses a risk of emergencies, jeopardizing maritime safety. Addressing this challenge is crucial to guaranteeing the smooth operation of vessels and elevating safety standards in marine navigation.

The basic standards and classical approaches to assessing system reliability are laid down in [1-3], which contain a regulatory and methodological framework for determining the residual life, forecasting, and statistical analysis of failures. Papers [4-6] demonstrate the application of reliability models in related high-risk industries (nuclear power, drilling systems, wind power) using stochastic processes and diffusion modeling.

Probabilistic physical models, including DN-distributions, estimates of degradation of mechanical components and computer equipment, are presented in [7-10]. Paper [11] extends the control range to cases of complex nonlinear systems, which is relevant for adaptive control in maritime navigation. Theoretical estimation models (inverse distributions, wear functions) and application examples to medical and industrial equipment are presented in [12-16].

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Modern methods for estimating the residual life, considering the variability of degradation and the Bayesian approach, are disclosed in [17-20]. Environmental sustainability, risk management, and information security in the transport environment are covered in [21-24].

Estimates of thermal efficiency and heat transfer processes in non-standard environments are considered in [25-26], which is helpful for engineering support of ship life support systems. Papers [27-28] focus on maneuverability, decision-making, and the impact of bulky cargo, which is key to assessing operational safety.

Developments in energy saving and automation of ship systems, including electric drives and combined engines, are described in [29-30]. Predicting the instability of compressors and digital twins of diesel systems is covered in [31-32].

Multi-criteria optimization of marine terminals and modeling of infrastructure projects are discussed in [33-34], while the influence of hull geometry on maneuverability is described in [35]. Papers [36-39] go beyond ship systems but provide support in energy audits, cooling, and materials science.

A study [40] substantiates the effectiveness of acquiring unfocused ships, which is essential for operational decisions. Sources [41-42] supplement the engineering part with load calculations and structural reliability. Digital modeling, intelligent solutions, and robotic control systems are described in [43-44]. The topics of energy efficiency, pollution, alternative energy, and wind impact forecasting are presented in [45-47].

The issues of maritime security, cyber threats, and vulnerability of ship systems are raised in [48-50], where maritime situational awareness is also assessed. The environmental aspects of ballast water and charter contracts are discussed in [51-52].

The concepts of sustainable energy in the fleet are discussed in [53], and improving the energy efficiency of electric motors is discussed in [54]. Geopolitical influence and regional risks are covered in [55-56].

The ship-to-windmill dynamic, which combines engineering and energy components, is analyzed in [57]. The reliability of bearing supports and the prediction of braking efficiency are discussed in [58]-[59], and [60] presented a methodology for expert risk assessment of ship operations, which summarizes the concept of a comprehensive analysis of operational reliability.

The literature review reveals a broad spectrum of research modelling technical and organizational systems. It underscores the significance of simulation modeling in attaining elevated reliability standards. The analyzed topics encompass diverse issues and their implications for system performance. The research emphasizes the necessity of an integrated approach to enhance the reliability and safety of technical systems. The article explores the challenge of diminished reliability in marine navigation systems and proposes strategies to mitigate it, aiming to ensure seamless vessel operation and bolster navigation safety. The primary focus lies in implementing equipment redundancy (duplication) as an approach to guarantee continuous vessel operation and mitigate the risk of emergencies. The objective is to offer technical solutions and recommendations that augment the reliability of marine navigation systems and ensure navigation safety amidst escalating transportation traffic and intricate vessel operating conditions.

2. Objetives.

Equipment reliability is one of the fundamental indicators of the operational process. Reliability, by definition, refers to an object's ability to maintain specified parameter values over time within established limits. This characteristic encompasses the capacity to perform required functions under designated operational modes and conditions, considering aspects such as technical servicing, repairs, storage, and transportation. As known, reliability is a multifaceted property that, depending on the object's purpose and operational conditions, comprises a combination of traits: faultlessness, durability, repairability, and preservability. This necessitates a quantitative assessment of reliability levels and the determination of the dependency of reliability on usage regimes and operating conditions.

2.1. Methods.

The electronic component base designed for maritime applications significantly differs from general-purpose electronics. The distinctions are outlined in Table 1:

Table 1: Characteristics a comparison between general-purpose electronics and marine electronics.

Characteristic	General-Purpose Electronics	Marine Electronics
Specific Environmental Needs	Typically standard conditions	Specialized maritime conditions
Operational Durability	Standard requirements	Enhanced durability for maritime use
Reliability Expectations	High reliability expectations	Extremely high reliability expectations
Resistance to Harsh Elements	Moderate resilience	High resistance to marine elements

Source: Authors.

The problem of reliability is becoming especially relevant in the field of marine vehicles, as said the growing number of ships, their size and speed leads to an increase in traffic and increases the requirements for navigation safety. Reliability of shipboard equipment is becoming a crucial aspect of ensuring navigation safety, which requires a comprehensive approach to assessing and ensuring their effectiveness in harsh marine environments.

In such circumstances, the electronic component base intended for use on ships must possess not only the traditional properties of electronic components, but also high resistance to aggressive marine environments, significant reliability, and optimal durability in conditions of constant exposure to humidity, corrosion, and other external factors.

Thus, the problem of ensuring the reliability and efficiency of ship systems and their electronic component base is the subject of in-depth analysis and consideration in this article.

The electronic component base for maritime applications significantly differs from its general-purpose industrial counterpart. Table 2 outlines key aspects of this distinction, comparing the functional nomenclature, serial production characteristics, reliability requirements, temperature ranges, and service life between maritime and general-purpose electronic component bases.

Table 2: Aspects of differentiation between marine and general-purpose electronic component bases.

Aspect	Marine Electronic Component Base	General-Purpose Electronic Component Base
Functional Nomenclature	Up to 1500 items	Less than 1500 items
Serial Production Throughout Lifecycle	Low serial production	High serial production
Reliability Requirements	Operating hours until failure: 109 hours and more	Operating hours until failure: 410,000 and less hours
Temperature Range	From minus 60 to plus 125 °C	From 0 to plus 45 °C
Service Life	Not less than 15 years	From 10,000 to 100,000 hours

Source: Authors.

Table 3: Requirements and Reliability Assessment Methods at Different Stages.

Stage	Processes and Actions
Design Stage (A priori Methods)	Input Data: Initial parameters and characteristics of the designed system.
	Theoretical Modeling: Utilizing theoretical models for analysis and prediction of reliability.
	Assessment: Establishing a priori reliability estimates based on preliminary data and model calculations.
Experimental Evaluation Stage (A posteriori Methods)	Experiments and Testing: Conducting experiments and tests for actual verification of system performance.
	Experience Data: Collecting data on system operation under real operational conditions.
	Comparison with Design Parameters: Comparing actual results with a priori reliability estimates.
Optimization Tasks (Reliability Level)	Maintenance Strategies: Developing optimal strategies for technical maintenance and risk management.
	Reserving: Implementing redundancy and duplication to enhance system continuity.
	Inventory and Spare Parts Management: Optimizing inventory and inventory management for prompt response to failures.

Source: Authors.

This complex set of rigorous requirements necessitates a comprehensive consideration of the impact of degradation processes over time on the parameters of electronic components concerning quantitative assessments of the stability of long-term functioning electronic equipment.

The assurance of conformity of the electronic component base to specified requirements can only be guaranteed through direct testing of electronic components and functional blocks for reliability. On one hand, the probability of failure-free operation of such devices and systems approaches unity, necessitating significantly larger sample sizes for testing. On the other hand, the time during which this probability is guaranteed is substantial, and even with direct testing, the obtained information lags behind the pace of the delivery of devices and systems to the end user. Thus, the practical feasibility of verifying compliance with stringent requirements for the installation of components and blocks in equipment often becomes problematic.

In summary, reliability studies encompass a comprehensive approach, involving upfront theoretical assessments, empirical validations, and ongoing optimization strategies to ensure and improve the reliability of instruments and systems.

The desire to obtain information on the reliability of devices and systems in a shorter period and, preferably, with fewer test samples has stimulated the development of accelerated assessment methods. These methods include a combination of a priori (computational), a posteriori (experimental), and hybrid approaches. Reliable criteria are essential for interpreting the results of proliferation studies.

Such criteria can be derived from the theory describing degradation processes in devices and systems. However, theoretical work in accelerated reliability assessment is often based either on the prediction theory or on laws and physical postulates describing certain aspects of degradation and failure processes.

Such an approach does not take into account that the research objects are products that undergo changes in the course of testing, becoming sources of unreliability inherent in production technology.

All of this necessitates the development of probabilistic and physical foundations for accelerated reliability assessment and solving urgent problems in the field of reliability.

Solving this issue is an integral part of meeting the reliability requirements for parts and assemblies dictated by transportation needs.

The reliability problem can be divided into two areas: ensuring reliability and its calculation (control). The former is based on solving traditional design and technological problems to create high-quality devices and systems and ensure their proper functioning. The second is mainly related to the use of specialized mathematical methods. Since the existing systems under development are designed for long-term operation, special preventive measures are taken to ensure their reliability, which are integrated into a system of scheduled preventive maintenance.

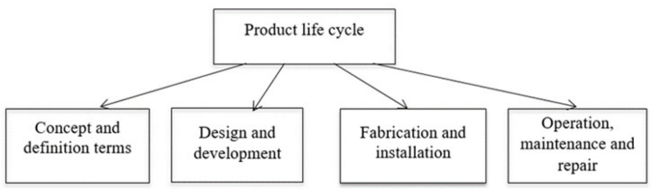
Until now, the reliability theory and practice field has predominantly advanced along a trajectory rooted solely in probabilistic concepts, specifically the theory of probability. In this context, failures are regarded as abstract random events, and the various physical states of instruments and systems are simplified into operational and non-operational. During system operation, errors may be identified and rectified. If correcting errors does not introduce new errors or fewer errors than those rectified, the system's reliability continuously improves during operation. The more intensively the system is operated, the more errors are detected, increasing reliability.

The methodology for obtaining final reliability results for instruments and systems, based on probabilistic (statistical) theory, involves gathering failure statistics from tests or operations.

Subsequently, the most suitable probability distribution model developed in probability theory (exponential, normal, Weibull, log-normally distributed, etc.) is selected using established statistical goodness-of-fit criteria. This chosen model is accepted as the theoretical probability distribution model for failure-free operation (reliability models). From this model, the necessary quantitative reliability indicators are determined.

System reliability assessment (calculation) is carried out by computing the probabilities of elements' operational states (Fig. 1).

Figure 1: Product life cycle stages.



Source: Authors.

A reliability assurance program is developed for an object's entire lifecycle. It serves as a document that establishes a set of interconnected organizational and technical requirements and measures to be implemented at specific stages of the object's lifecycle. The program aims to ensure the specified reliability requirements and enhance reliability. It can be developed as a single document or as separate documents during the design, production, and operation stages.

Reliability assurance programs are essential documents that provide a comprehensive approach to addressing reliability-related tasks, considering the interests of all stakeholders (suppliers, consumers) throughout the objects' life cycle.

The reliability assurance program involves analyzing, verifying, controlling, and maintaining the specified reliability level, as established in normative and technical documents. It depends on project decisions, specific constraints, and requirements. An important factor is the identification of accurate reliability requirements since, typically, there is no precise information about the reliability of the components of the developed product. Therefore, for accelerated reliability assessment at the design stage, simulation modeling methods (based on information about analogs and prototypes of the object and their components), statistical modeling, and approximate a priori calculation are recommended.

This approach is particularly relevant for navigation equipment, ensuring that the system's reliability is thoroughly addressed and maintained throughout its lifecycle.

Ensuring the object's faultlessness, durability, and repairability is particularly important. The testing strategy should assess the reliability risks for both the supplier and the consumer. During the object's manufacturing stage, accelerated forced testing methods (deterministic and control) are employed, and forecasting methods are also utilized.

At the stage of operation, maintenance, and repair, the object is used as intended, serviced, and repaired. Measures to ensure reliability should focus on collecting operational information, evaluating and analyzing data on malfunctions and failures, maintenance and repair strategies, and spare parts provision, including calculations and accelerated testing.

The classification of reliability assessment methods, formally divided based on how initial information about the object is obtained, includes a posteriori (accelerated testing methods, forecasting methods), a priori (modeling methods and calculation methods), and a priori-a posteriori (combined methods), which combine features of both a priori and a posteriori methods (calculation and experimental methods), as shown in Fig. 2. The prediction of reliability involves observing direct (defining) or indirect predictive parameters. It is possible to forecast based on the results of completed observations of device and system samples or by studying the reliability of a product during its operation. This aspect is particularly significant for devices and systems produced in small quantities or as unique specimens that perform critical functions. For such cases, estimating reliability based on failure statistics is unacceptable, especially for highly reliable devices and systems with redundancy structures.

2.2. Results.

Within the classification of reliability prediction methods, the following approaches exist: direct prediction, backward prediction, forward prediction, present prediction, back prediction, individual prediction, group prediction.

Table 4: Classification of Reliability Assessment Methods.

Category	Methods
A priori methods	- Theoretical Modeling
	- Expert Judgments
A posteriori methods	- Experiments and Testing
	- Comparison with Design Parameters
Accelerated assessment	- A priori methods
	- A posteriori methods
Optimization methods	- Maintenance Strategies
	- Inventory Management and Reserving
Prognostic methods	- Degradation Modeling
	- State Data Analysis

Source: Authors.

The first group is most commonly used to address reliability tasks. To justify the choice of a particular forecasting method, its quality must be assessed quantitatively. Each technique should have a specific quality indicator accompanying it.

Mathematical modeling can, in some cases, allow for predicting a product's reliability in a very short period. Methods of mathematical reliability modeling can be divided into two main groups: statistical and simulation modeling.

Statistical modeling methods are employed to study the behavior of a sample of devices and systems during reliability testing. These methods rely on a random number generator distributed according to a specified probability distribution. The most commonly chosen random variable is the time until the product fails. Statistical modeling allows for simulating any testing plan and obtaining all statistical estimates of the examined sample of devices and systems that have ”failed.” Transitioning to quantitative reliability indicators is achieved either directly through statistical estimates in non-parametric reliability estimation methods or by computing the parameters of theoretical failure distributions.

Simulation modeling methods, also known as machine experiments, study the behavior of complex devices and systems within a specified, sometimes scaled, time frame. Based on the simulation results of a product's performance, statistical analysis is conducted to obtain reliability indicators, as in the following example:

- Exponential Distribution Reliability Function, describes the reliability function for the exponential distribution. It tells us the probability that a system will function without failure until time t;
- Mean Time To Failure (MTTF) calculates the Mean Time To Failure. This metric represents the average time a system is expected to operate before encountering a failure, with λ being the failure rate;
- General System Reliability Formula, expresses the reliability of a system over time, considering variations in the failure rate;
- Binomial Reliability Model calculates the probability of n systems failing out of a total of m systems using binomial coefficients and the basic reliability function $R(t)$, Table 5.

Figure 2: Basic tools for analysing the reliability of system.

Metric	Description
Exponential Distribution Reliability Function $R(t)=e^{-\lambda t}$	Describes the probability that a system will function without failure until time t, based on the reliability function for the exponential distribution
Mean Time To Failure (MTTF) $MTTF=1/\lambda$	Calculates the average time a system is expected to operate before encountering a failure, with λ being the failure rate
General System Reliability Formula $R(t)=e^{-\int_0^t \lambda(u)du}$	Expresses the reliability of a system over time, considering variations in the failure rate
Binomial Reliability Model $P(n,m)=\binom{m}{n}R(t)^n[1-R(t)]^{m-n}$	Calculates the probability of n systems failing out of a total of m systems using binomial coefficients and the basic reliability function $R(t)$

Note: λ represents the failure rate, t denotes time, and R(t) is the reliability function.

Source: Authors.

Reliability assessment involves using a priori calculation methods during a product's design or modernization stages. These methods rely on prior information about the research object, such as the structural scheme, composition, operational modes, and conditions. A priori calculations serve the purpose of comparative analysis, preliminary reliability assessment, and justifying reliability requirements. Additionally, calculation-experimental methods are employed to evaluate identical elements and refine estimates obtained through a priori calculations. This integrated approach accelerates the acquisition of reliable information about the product.

The presented approach to reliability assessment methods enables the application of a systematic methodology grounded in the basic theoretical reliability model, the distribution of time to failure. It integrates existing and newly developed a priori, a posteriori, and combined methods to expedite the acquisition of reliable information about the product. Recently, there has been a growing prevalence of probability-physical reliability models, which can effectively replace the current apparatus for studying and predicting reliability.

The probability-physical approach uses failure distribution laws (reliability models) derived from the analysis of physical degradation processes leading to failure. In this approach, degradation processes are considered random processes. This probability-physical approach directly establishes the connection between the probability of reaching a critical level and a physically deterministic parameter, linking the probability of failure and the physical parameter causing failure.

In electronic devices like integrated circuits, it is practically impossible to identify all deterministic parameters causing failures in numerous components, let alone measure them.

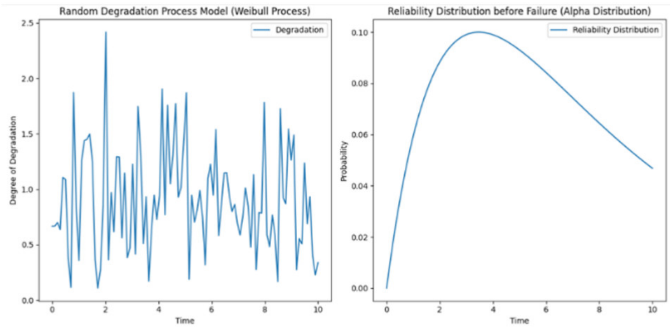
In such cases, statistical estimation of the average rate of the generalized degradation process of the product remains possible. However, it is undisputable that these products undergo physical degradations, determining the corresponding probability of failure. Therefore, these products correspond to a specific probability-physical reliability model.

Experimentally, it has been proven that the discrepancy in estimating the reliability indicators of devices and systems depends on the adopted theoretical model and can vary by several orders of magnitude.

Thus, the correct choice of the theoretical failure distribution model for high-reliability integrated circuits, semiconductor devices, etc., proves to be challenging. Obtaining complete failure samples for electronic components, even in forced modes, is impossible. The choice of the theoretical failure distribution model is mainly made considering physical reasoning.

Several formalization schemes of failure models are based on analyzing the dynamics of deterministic parameters leading to failure. One of the early attempts to conceptualize the behavior of a deterministic parameter in the formalization of the model of parametric failures was to represent the change in the deterministic parameter as a linear law.tic parameters leading to failure. One of the early attempts to conceptualize the behaviour of a deterministic parameter in the formalization of the model of parametric failures was the representation of the change in the deterministic parameter as a linear law.

Figure 3: Model of a random degradation process (fan process) and a scheme for forming the distribution of time to failure (alpha distribution).



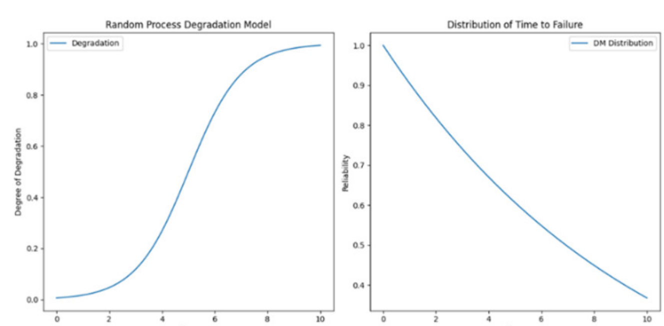
Source: Authors.

The hypothesis of vigorous mixing of the stationary wear process is also adopted in this consideration. This assumes that the change in variance is proportional to time and that the distribution of working time becomes asymptotically normal for large wear values (see Figure 4).

Analyzing various degradation processes, it is notable that they exhibit a random nature, and their values can display both monotonic and non-monotonic characteristics. Complex electronic devices such as integrated circuits are simultaneously susceptible to the influence of many processes. All these processes, whether uncorrelated or weakly correlated, contribute to the overall degradation of the device.

Figures 5 and 6 qualitatively represent typical degradations. The processes shown with countless realizations may correspond to a complex electronic device, like an integrated circuit with numerous electronic components. The degradation process of electronic devices, alongside monotonic realizations (mechanical failure), is also due to electrical phenomena.

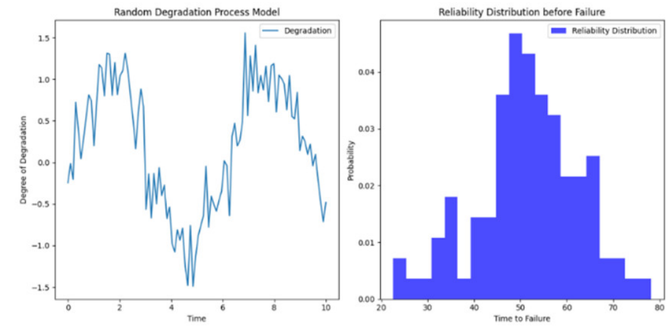
Figure 4: The model of a random degradation process (a highly "mixed" Gaussian process) and the scheme of forming the distribution of time to failure (a normal parametric distribution) have non-monotonic realizations. Therefore, in the general case, these devices' degradation is considered a process with non-monotonic realizations.



Source: Authors.

This figure presents two subplots illustrating key aspects of reliability analysis. Model of a Random Degradation Process

Figure 5: Model of a random degradation process (non-monotonic) and scheme of reliability distribution formation (DN distribution).



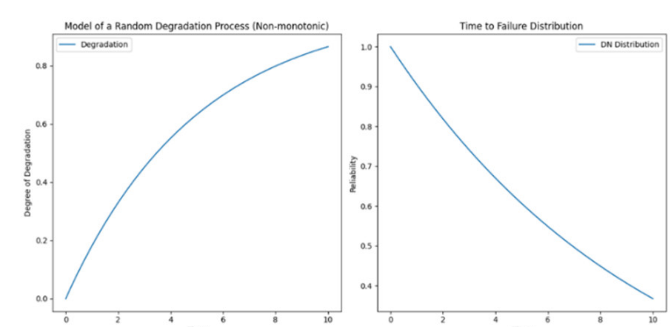
Source: Authors.

(Non-monotonic):

- The left subplot depicts a non-monotonic degradation model over time.
- The degradation model is characterized by the formula 1−e−0.2·time, displaying the degree of degradation as time progresses.
- Scheme of Reliability Distribution Formation (DN Distribution):
- The right subplot highlights the formation scheme of the time to failure distribution.
- The time to failure distribution is represented by the formula e−0.1·time, providing insights into the reliability trends over time.

The subplots are arranged side by side for ease of comparison. Both visualizations contribute to a comprehensive understanding of the non-monotonic degradation process and the contribution of time to failure, offering valuable insights into the reliability characteristics of the analyzed system.

Figure 6: Model of a random degradation process (Markov monotonic process) and scheme of forming the distribution of time to failure (DM distribution).



Source: Authors.

The four types of two-parameter probabilistic-physical failure models (alpha distribution, normal parametric, DN distribution, DM distribution) are based on the analysis of a kind of degradation process - stationary wear (fracture)- and share parameters with the same physical interpretation. However, due to differing formalization schemes, the expressions for the laws of failure distribution and the formal characteristics of these models can vary significantly. Let's provide a comparative assessment of these probabilistic-physical failure models.

As can be seen visually, the mathematical models of the degradation processes differ markedly (see Fig. 3-6), and the analytical expressions for the laws of the time-to-failure distribution are di*ff*erent accordingly. The models of the analyzed processes differ significantly from the physical point of view. An idealized random process (see Fig. 3) indicates that its characteristics are entirely determined by the initial state (quality of sample manufacturing) and do not depend on the mechanical, physical, and chemical degradation processes occurring inside the objects under the influence of external conditions and time. The model in Fig. 3. A process with strongly "mixed" realizations has a rapidly damped correlation function, i.e., it does not depend much on the initial state. The Markov models (see Figs. 5-6) have, as it were, generalizing physical properties that are partially inherent in the first (Fig. 1) and second (Fig. 3) models.

Thus, the analysis of the main curves of probabilistic-physical failure models shows that the compared models have significantly different patterns that determine the quantitative reliability indicators. The accepted idealization of changing the defining parameter (degradation process) and its realizations is the foundation on which the predicted process is built - the time distribution to reach the threshold level of the defining parameter.

The adequacy of mathematical models for random and real degradation processes determines how well the predicted distribution (time to failure of the investigated objects) aligns with the actual scattering of failures in the general population. In cases of adequacy, the probability-physical model of failures can be evaluated from two perspectives: first, by examining the initial ideal and real degradation processes, and second, by comparing the predicted theoretical distribution with observed failure data.

The second approach appears more realistic and significant from a practical standpoint. The visual assessment of the presented mathematical models of the defining parameter behavior during operation and their physical foundation mentioned earlier suggests that the models in Figures 3-4 more accurately reflect the real process of changing the defining parameter than others. Alignment with experimental failure data is essential for a more thorough verification of the adequacy of failure models.

When investigating the issues of ensuring the continuous operational state of a vessel with insufficient reliability of its equipment, one proposed approach to solving this problem is equipment redundancy (duplication). This strategy involves having additional copies of equipment or systems that can be activated in case of failure of primary components. Equipment redundancy guarantees the vessel's continuous operation, even if some of its components fail. This helps mitigate the risk of accidents and ensures safe navigation. Upon detection of a primary equipment failure, the backup equipment can be activated automatically or by the operator to ensure that the system continues to operate without interruption. Therefore, this approach is one of the methods to enhance the reliability of marine systems and reduce the risk of emergencies. This strategy is widely utilized in shipbuilding and the maritime industry to ensure the reliability of technical means and the uninterrupted operation of vessels.

3. Discussion.

The study of reliability engineering has emphasized the importance of ensuring the continuous operating state of technical objects throughout their life cycle. Probabilistic-physical models, such as those based on failure distributions, have laid the foundation for understanding and predicting the reliability of complex electronic systems, considering both mono- tonic and non-monotonic degradation processes.

Life-cycle considerations have revealed the need for an integrated approach to reliability, involving the development of reliability programs at different stages of an object's life. These programs are the most critical documents in forming organizational and technical requirements to achieve reliability objectives. Reliability assessment methods are considered, including a priori calculations and design - experimental approaches.

These methods help evaluate and compare different design and circuit options during the design phase, providing essential insight for decision-making.

The effects of degradation on various electronic and mechanical components have been considered. It has been shown that degradation processes have both monotonic and non - monotonic characteristics, and the adequacy of mathematical models for these processes has been discussed. Furthermore, the conclusion emphasizes the importance of equipment redundancy in improving reliability, especially in offshore systems. Redundancy, which involves duplicating equipment or systems, has become a practical strategy to ensure uninterrupted operation and reduce the risk of accidents.

The study of reliability and degradation design processes has provided valuable insights into methods, models, and strategies to improve technical systems' reliability and continuous operation throughout their life cycles. The versatility of these considerations emphasizes the complexity and importance of reliability engineering in various technical fields.

Conclusion.

The study found that ensuring the reliability of maritime navigation systems is a multidimensional engineering and organizational task that covers the entire life cycle of a technical object. The increasing complexity of ship electronic systems requires new approaches to modeling degradation processes, including monitoring physical parameters and statistical processing of failure data. The probabilistic physical models proposed in this paper allow us to predict the moment of reaching a critical state more accurately and formulate adaptive maintenance strategies. It has been determined that the effective use of equipment duplication (redundancy) is an effective mechanism for maintaining the operational readiness of a ship in conditions of limited repair availability.

The results demonstrated the feasibility of implementing comprehensive reliability programs during the design stage, including a priori assessments, simulation modeling, accelerated testing, and risk calculation. The findings from this work can serve as a theoretical and methodological foundation for developing standards and regulations concerning the technical operation of marine systems in challenging navigation conditions.

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