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Formal and mathematical basis of the aircraft reliability management system

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Abstract. Continuous monitoring of the current technical condition of the aircraft fleet of the Armed Forces of Ukraine and forecasting trends in its change showed that recently the reliability of combat aircraft has been ensured mainly by extending their service life. Further extension of the life cycle without performing the necessary amount of restoration work is impossible, and the cost of such work is quite high. The availability of information from developers regarding the maximum service life of the main types of combat aircraft and the safety margins of their design is an objective prerequisite for working out appropriate measures to maintain the serviceability of aviation equipment in service with the Armed Forces of Ukraine. The relevance of the study is due to the need to systematize methodological approaches to the issues of admission to further operation, formalize existing methods and methods of maintaining the serviceability and airworthiness of the aircraft fleet. The purpose of the work is to form methodological foundations for creating a system for making management decisions on admission to further operation of aircraft with exhausted resource indicators. The article structurally considers the composition of a mathematical bionic model of experimental data processing, which, according to the results of expert assessment, simulates the mechanisms of making management decisions. An algorithm for solving the problem of preparing a

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decision on extending the service life, taking into account the aging of the airframe structure in operating conditions, is presented. In practice, the proposed mathematical model is the basis of an intelligent decision-making support system for extending the service life of aircraft. The materials of the article are of practical value for military experts, specialists in the application, operation and repair of military aviation equipment. The article has practical significance for increasing the efficiency of reliability management systems of the aviation fleet of the Armed Forces of Ukraine by increasing the validity of decisions made.

Keywords: technical condition, power elements, aircraft operation, control systems, decision support system.

Introduction

Objectively, the resources and service life of aircraft are related to the technical condition of the power elements (hereinafter referred to as PE) airframes structure. The possibilities of increasing the resource indicators of aging aircraft are implemented on the basis of resource calculations using the hypothesis of linear summation of fatigue damage when processing data from on-board flight parameter control devices, which is comprehensively investigated in [2].

The continuous growth in the amount of information and the constant complication of tasks performed by the aging fleet of aviation equipment (hereinafter referred to as AE) indicate the need to improve existing and create new innovative systems for making and approving management decisions. It is precisely intelligent decision support systems that are capable of implementing a continuous controlled decision-making process in real time in complex situations that have many components and are characterized by uncertainty and unstable structuring.

Problematic issues of decision-making on extending the service life of aging aircraft have only partially been studied in the works on technical diagnostics, so there is a need to develop methods that allow to increase the reliability of decisions made by an official (decision-maker – hereinafter referred to as DM) for a specific situation of extending the service life of aircraft based on the results of troubleshooting of the airframe design during its inspections in the conditions of operating units and aviation enterprises.

In the processes of aircraft operation, where the term "management decision systems" is more often used, DSS (hereinafter referred to as Decision Support System) is an interactive application system that provides end-users of aircraft, who make decisions about its further operation, easy and convenient access to data and models of serviceability maintenance, in which the appropriate decision-making algorithms in semi-structured and unstructured situations with various input data have been worked out. The complex of appropriate methods of serviceability maintenance in DSS is a component of the reliability management system of the aircraft fleet. At the same time, DSS supports and enhances (but does not replace or cancel) the reasoning and assessments of the decision-maker. The essence and importance of expert assessments do not decrease, control over decision-making remains with the person [1].

Therefore, the purpose of this study is to consider and analyze the structure of the bionic mathematical model in the reliability management system as the basis of an intelligent decision-making support system for extending the service life of aircraft with exhausted resource indicators.

Methodological Framework

During the preparation of the article, a comprehensive methodological approach was applied, and systems analysis methods were used to classify and rank the current technical condition of the aircraft fleet. Changes in the technical condition of aircraft over time occur as a result of aging processes, negative impact of environmental factors, and operational factors, which is quite naturally reflected in the values of the technical condition parameters. The presence of these patterns and their

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familiarity make it possible, using probabilistic methods, to predict possible values of these parameters for the future, if their values are known at a certain time interval in the past.

To assess operational reliability and plan the further operation mode, new methods and models for determining and predicting changes in the technical condition of an aircraft product are required. The specified tasks are weakly formalizable and unstructured. To perform them, it is advisable to combine fuzzy logic, statistical and probabilistic methods, neural networks, genetic networks, etc. The article uses methods of fuzzy logic analysis to form management decision options.

The principles of vector information processing by a universal mathematical model for biological systems, as well as the principles of logical information transformations performed by a person when solving intellectual tasks, were used.

Task statement

Analysis of data obtained using non-destructive testing of the airframe structure allows dividing the studied aircraft into separate groups (classes) depending on the operating methods and, accordingly, predicting the probability of failure-free operation during the operation of the airframe structure:

technical condition of the airframe during the operation system according to the resource;

technical condition of the airframe according to the results of the control and technical inspection during operation according to the technical condition of the aircraft;

technical condition of the airframe according to the results of control and restoration work during transfer to operation according to the technical condition;

technical condition of the airframe according to the results of work performed at an aircraft repair enterprise [3].

Fig. 1 shows the qualitative dependence of the predicted changes in the probability of failures of the PE of the P_{PH} (t) airframe design depending on the calendar service life of the aircraft. Changes in the technical condition are shown for the airframe design after repair work at an aviation repair enterprise.

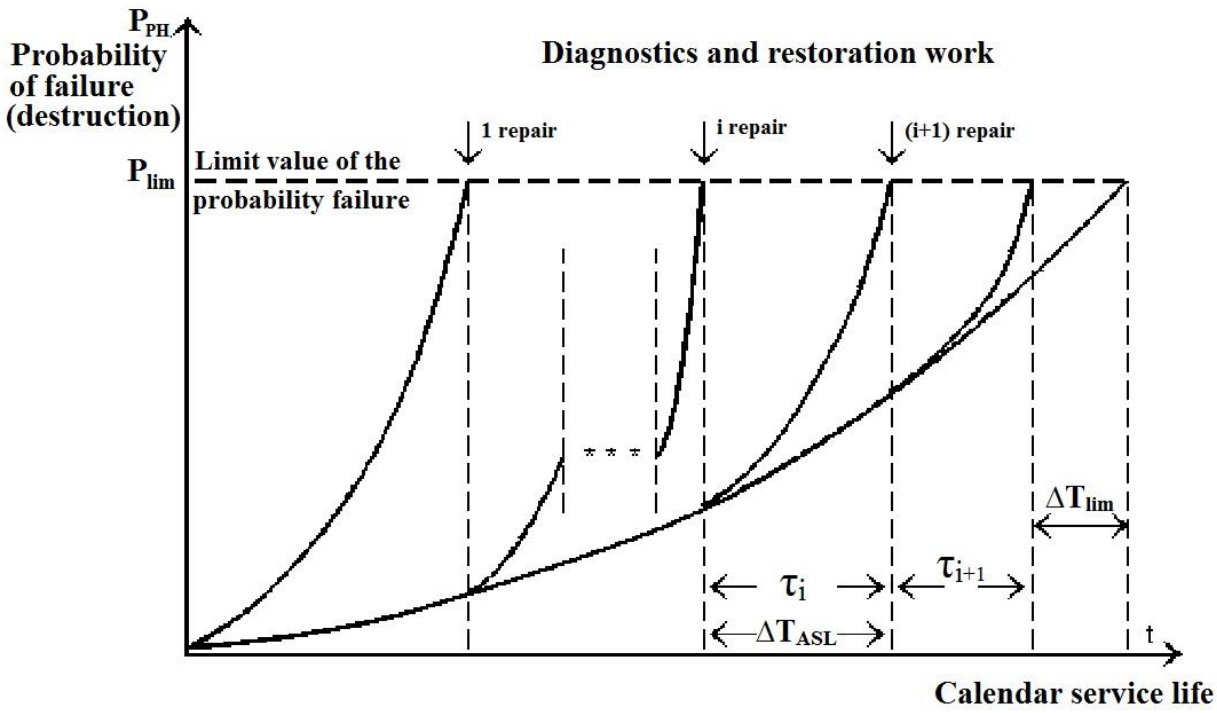


Figure 1. Functional dependencies of changes in the probability of failures of power elements of the airframe structure

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Fulfillment of the requirements for ensuring flight safety during the extension of service life is determined by time intervals during which the conditions for maintaining strength are observed. Fig. 1 schematically shows the time intervals τ_i , τ_{i+1}, within which it is possible to extend the calendar service life of the aircraft for the period ΔT_{ASL}.

The peculiarity of the aging aircraft fleet is the gradual degradation of the mechanical characteristics of the alloys used in the design, their fatigue resistance and crack resistance [4]. As a result of the action of the above circumstances

$$\tau_{l+1} \leq \tau_l,$$

which leads to the need to make decisions to correct the value of ΔT_{ASL}, by which it is planned to increase the service life after each stage of work on diagnostics of the airframe design.

The probability of destruction of $P_{PH}(t)$ can be determined by the formula [3]:

$$P_{\text{рн}}(t) = e^{-\gamma(t)((\alpha_{\text{cr}}(t)-\alpha_{\text{in}})},$$

where is $\gamma(t)$ – the defect coefficient of the structure, is $\propto_{\text{cr}}(t)$ i $\propto_{\text{in}}$ – the size of the defect critical and initial.

Today, most decisions on the further operation of aircraft are made based on the results of expert assessments, based on the base of expert knowledge, skills and abilities of relevant specialists and decision-makers. At the same time, the criteria field is not structured and systematized for decision-making, input data on the technical condition of the AE, the relationship between them, operational limitations, etc. may not be sufficiently taken into account, which may lead to insufficient justification of the decision being made. To increase the reliability of air traffic control decision-making, it is necessary to develop a mathematical model that will simulate the thinking process of experts, taking into account the results of the analysis of the reliability of the aging aircraft fleet.

Results and Discussions

Structure of the mathematical bionic model

One of the directions of development of methods for preparing decision-making for aging aircraft is the development of a mathematical model of experimental data processing, which simulates decision-making mechanisms in the functioning of biological systems and allows the DM to understand the validity and feasibility of various decision options [5].

Fig. 2 shows the structure of the mathematical model, which includes bionic model modules that reflect in a formal form the transformations carried out by the DM when generalizing the results of the action of operational factors and forming multidimensional control data into images of the psychosemantic space of the subject area [6].

In the bionic mathematical model, it is proposed to consider three vector spaces $\hat{O}_1, \hat{O}_2, \hat{O}_3$, the dimensionality of which is determined by the number of parameters of the PE control domain of the aircraft airframe.

The first space $\hat{O}_1$ is formed by estimates of the PE strength loss indicators based on the processing of data from the control means of each individual PE of the aircraft airframe and the determination of the list of discrete surface elements of damaged PE.

The use of fuzzy cluster analysis methods allows you to determine the image of the technical condition of the airframe depending on the number and parameters of the loss of strength of damaged PE.

In the second space $\hat{O}_2$, based on algorithms of fuzzy logical analysis of decision-making, the results of analytical calculations and stochastic modeling of the rate of strength changes are corrected depending on the assessment of the aging of the structure.

In the space $\hat{O}_3$, in addition to the results of strength control of individual PEs, of the same type for the aircraft fleet, multidimensional scaling methods are used, followed by the determination of factors that affect the durability of the structure and allow predicting durability.

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The use of estimates of the compliance of experimental data with mathematical models of changes in the strength of the PE makes it possible to form options for DM to extend the intended service life of the aircraft airframe structure.

Mathematical model for estimating the service life of the airframe structure

The condition for the destruction of the structural integrity of the aircraft airframe according to the hypothesis of linear summation of damage is formulated as follows: the sum of relative fatigue damage ζrez is equal to unity [7]:

$$\zeta_{\text{rez}} = \sum_{i=1}^{\nu} \frac{m_i}{N_i} = 1 ,$$

N_i - number of load cycles to failure at stress level σ_i ;

m_i - current number of load cycles $(i = 1, \dots, \nu)$;

ν – number of load levels.

For aging structures, the actual stress level σ_j increases due to the accumulation of damage in the surface and internal layers of the material.

Internal damage, as is known, is caused by the evolution of dislocation structures. The damageability of the surface layer is associated with the formation of a defect structure – a deformation relief.

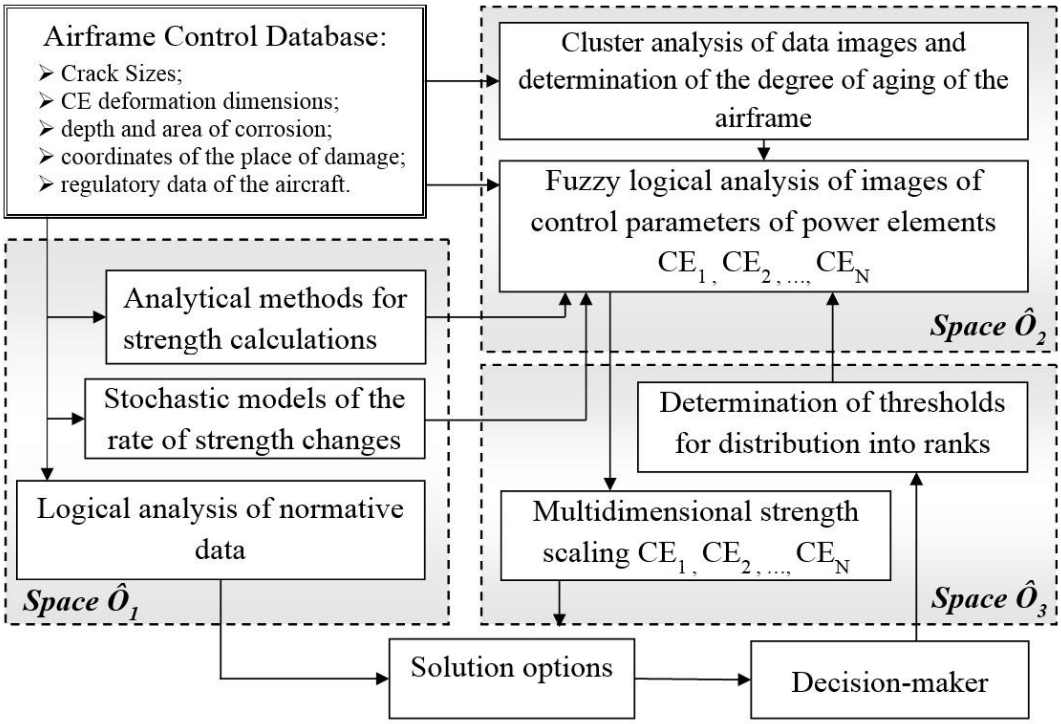


Figure 2. Modules of the structure of the mathematical model of data analysis in the preparation of decisions on extending the life of the airframe structure

Recently, a methodology for quantitative assessment of the deformation relief and the corresponding fatigue damage has been developed [6].

Fig. 3 shows changes in the position of the fatigue strength curve of the PE material of the aging structure and the presence of a corresponding ratio of the change in the number of cycles of permissible loads ($N_{C1} < N_{C0}$).

Therefore, when making a decision on extending the service life of aircraft, it is necessary to simultaneously solve the problematic issues of reducing the established service life of aircraft. In

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order to determine for aging structures the functional dependence of the fatigue strength curve on the surface disturbances of the PE material recorded during the inspection, it is necessary to first perform surface sampling and describe the damage using discrete elements.

The result of aging of the structural material is a decrease in the "safe" resource [4]:

$T_{SF1} < T_{SF0}$

The list of damaged PEs by the number N is the set $SE = \{PE_1, \dots, PE_j\}$, $(j = 1,2, \dots, N)$. The strength of the airframe depends on the PE, which has its minimum level. To assess the value of strength, appropriate analytical calculation methods have been developed [8].

Based on the results of non-destructive testing of the PE structure and analysis of the general technical condition of a particular aircraft, experts can adjust the assessment of the structural strength obtained by the calculation method.

Mathematical model of decision-making regarding the terms of extension of the service life of the aircraft airframe design

The mathematical method of fuzzy logical analysis of weakly formalized parameters for assessing the technical condition of the PE allows obtaining an adjusted assessment of the airframe strength. At the same time, it is advisable to take as parameters quantitative assessments of cracks, places of corrosion damage, bruises, dents, places of friction on the surface and weakening, loss of rivets.

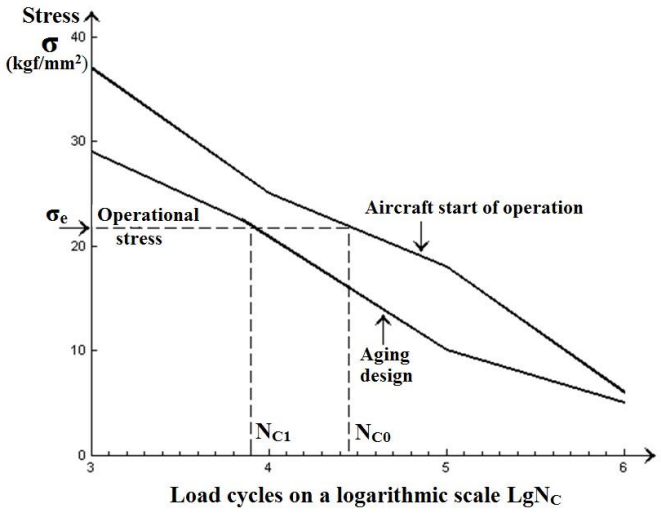


Figure 3. Reducing the number of cycles of permissible loads due to aging of the airframe structure material

The mathematical model provides for the presence of structural blocks of the fuzzifier, basic rules (knowledge base), the formation of a conclusion and a defuzzifier [9].

Multidimensional scaling of the experts' adjusted estimates for the established population of the aircraft fleet allows you to determine the maximum resource of the structure, taking into account the maximum service life.

To obtain variants of draft decisions, a vague algorithmic approach was applied to the problem of ensuring the reliability of the airframe design by choosing a linear algorithm B in the structure, which carries out DM when making decisions on the required number of R measures for the control and restoration of damaged PE [8].

The functional form of the linear algorithm with when restoring the j-th power element assumes

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$$B(X) = A_1 R_1^{x_1} A_2 R_2^{x_2} \dots A_j R_j^{x_j} \dots A_N R_N^{x_N},$$

where is Aj – the working operator, depending on the parameter ζ_{rez}, ; x_j – operator Aj control frequency; Rj – operator of control and restoration works PEj, which functionally depends on the parameter of the quality of work performance r_j (r=1 – low, r=3 – medium, r=5 – high); $X = (x_1, x_2, \dots, x_N)^{\square}$ – vector of multiplicity of control and restoration.

The problem of finding the optimal solution is formed in the form: find a vector $X = (x_1, x_2, \dots, x_N)^{\square}$ that provides $C_B(X) \to min$ with restrictions: $P_{\text{рн}}(\zeta_{\text{rez}}, X) \le P_{\text{рн}}^{\text{lim}}$,

where is $C_B(X)$ – vector of costs for control and restoration work; $P_{\text{рн}}^{\text{lim}}$ – destruction probability limit.

To determine the vector $X = (x_1, x_2, \dots, x_N)^{\square}$, it is necessary to apply an algorithm for finding the optimal value of the function, which takes into account the nonlinear features of the target function $C_B(X)$.

Thus, expert evaluation procedures were applied in the structure of a bionic mathematical model to solve the multi-criteria problem of making a management decision under conditions of stochastic uncertainty. The proposed mathematical apparatus involves the use of various methodological approaches and application options.

Conclusion

The implementation and application of the DSS in the operation of the AE will improve the processing of relevant information and knowledge on the state of the AE in real time, improve the efficiency and validity of decisions on the further operation and use for its intended purpose, will provide an opportunity for the decision-maker to solve problems and tasks related to the technical operation and combat use of the AE.

Recommendations

1. To comply with flight safety requirements, it is necessary, when extending the service life of the airframe structure of an aging aircraft, to consider separately the issue of reducing the resource indicators of its main power elements.
2. The algorithm proposed in the work, after its further development to the level of a working calculation computer program and its appropriate testing and approbation, can be a reliable tool for solving the problem of extending the service life of the aircraft airframe design.
3. The use of a set of methods and algorithms, similar to the one proposed, and aimed at increasing the reliability and validity of ATS decisions for a specific situation, will create and establish an effective and effective system of intelligent support for decision-making on the operation of aircraft.

Conflict of Interest

The author declares that he has no competing interests related to the subject of the article.

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Формально-математична основа системи управління надійністю літальних апаратів

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Анотація. У результаті проведення постійного моніторингу поточного технічного стану парку авіаційної техніки Збройних Сил України та прогнозування тенденцій його зміни виявлено, що останнім часом забезпечення надійності літальних апаратів бойового складу здійснювалось переважно шляхом продовження строків служби. Подальше продовження життєвого циклу без виконання необхідного обсягу відновлювальних робіт неможливо, а вартість таких робіт досить висока. Наявність інформації розробників щодо граничних

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термінів експлуатації основних типів літальних апаратів бойового складу та запаси міцності їх конструкції є об’єктивною передумовою для відпрацювання відповідних заходів з підтримання справності авіаційної техніки, що знаходиться на озброєнні Збройних Сил України. Актуальність дослідження обумовлена необхідністю систематизації методичних підходів до питань допуску до подальшої експлуатації, формалізацією існуючих методів та способів підтримання справності та льотної придатності парку літальних апаратів. Метою роботи є формування методологічних основ створення системи прийняття управлінських рішень про допуск до подальшої експлуатації літальних апаратів з вичерпаними ресурсними показниками. У статті структурно розглянуто склад математичної біонічної моделі оброблення експериментальних даних, яка, за результатами експертного оцінювання, імітує механізми прийняття управлінських рішень. Наведено алгоритм вирішення задачі підготовки прийняття рішення щодо продовження строку служби з урахуванням старіння конструкції планера в умовах експлуатації. Запропонована математична модель є основою інтелектуальної системи підтримки прийняття рішень щодо продовження строків експлуатації літальних апаратів. Матеріали статті становлять практичну цінність для військових експертів, фахівців з питань застосування, експлуатації та ремонту військової авіаційної техніки. Стаття має практичне значення для збільшення ефективності систем управління процесами експлуатації парку авіаційної техніки Збройних Сил України шляхом підвищення обґрунтованості рішень, що приймаються.

Ключові слова: технічний стан, силові елементи, експлуатація літака, системи керування, система підтримки рішень.