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Mathematical model of the process for diagnosing defects in aircraft structure elements made of composite materials

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Abstract: The scientific article is the result of a study aimed at creating a mathematical model for diagnosing defects in aircraft structural elements made of composite materials. Its feature is an innovative approach to assessing the probability of defects and their characteristics, based on the analysis of the material properties and technical parameters of the structure. The developed model combines methods of statistics, mathematical modeling and data analysis, which provides more accurate and reliable results. The findings obtained from the study may be of great value in improving diagnostic and quality control methods in aircraft manufacturing and operation. This in turn helps to improve the safety and reliability of aircraft, which is one of the main priorities of the aviation industry. The use of mathematical modeling can significantly increase the efficiency of diagnostics and quality control, which in turn has a positive effect on the technical operation of aircraft as a whole. Comprehensive analysis of defects in aircraft composite structures is effective in improving detection accuracy and optimizing maintenance. In modern aviation, where safety and reliability are crucial, the use of mathematical modeling provides the opportunity not only to identify defects, but also to predict their further development, providing preventative measures. This approach also improves aircraft productivity by reducing maintenance and repair time, which can ultimately increase airline revenues. Standardization of diagnostic processes and the introduction of new technologies in the field of defect detection represent important directions for future research. However, it is also necessary to consider the cost-effectiveness and practical applicability of the developed models and methods.

Key words: composite materials, aviation, defect diagnosis, operation of air transport, maintenance, mathematical model.

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Математическая модель процесса диагностирования дефектов элементов конструкции воздушных судов, выполненных из композиционных материалов

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Аннотация. Научная статья является результатом исследования, направленного на создание математической модели для диагностики дефектов элементов конструкции воздушных судов, изготовленных из композиционных материалов. Исследование отличается новаторским подходом к оценке вероятности возникновения дефектов и их характеристик на основе анализа материальных свойств и технических параметров конструкции. Разработанная модель объединяет в себе методы статистики, математического моделирования и анализа данных, что позволяет получить более точные и надежные результаты. Полученные в ходе исследования выводы могут быть весьма ценными для улучшения методов диагностики и контроля качества в процессе производства и эксплуатации воздушных судов. Повышение уровня безопасности и надежности воздушных судов является одним из главных приоритетов авиационной отрасли, и разработанная математическая модель способствует достижению этой цели. Применение математического моделирования может значительно повысить эффективность диагностики и контроля качества, что в свою очередь положительно влияет на техническую эксплуатацию авиационной техники в целом. Обсуждаются методы анализа и моделирования, направленные на обнаружение и классификацию дефектов, а также их влияние на безопасность и надежность воздушных судов. Рассматриваются современные подходы к контролю качества и техническому обслуживанию, а также предлагаются рекомендации по улучшению процессов диагностики и превентивного обслуживания воздушных судов для обеспечения их безопасной эксплуатации. Стандартизация процессов диагностики и внедрение новых технологий с целью обнаружения дефектов важны для дальнейших исследований. Однако необходимо также учитывать факторы, влияющие на экономическую эффективность и практическую применимость разработанных моделей и методов.

Ключевые слова: композиционные материалы, авиация, диагностирование дефектов, эксплуатация воздушного транспорта, техническое обслуживание, математическая модель.

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Introduction

Nowadays composite materials play the key role in lightweight, sustainable and efficient aircraft structures [1]. Nevertheless, the crucial aspect of their application is the high level of safety and technical reliability provision. Diagnosis of composite structural element defects is of particular importance in these terms. The given article focuses on mathematical model development of the defect analysis [2, 3].

The purpose of the given paper is to make a universal tool, able to predict defect occurrence probability and to estimate their characteristics basing on the technical parameters of the structure and its material properties. The new approach, based on statistics, mathematical modelling and data analysis methods complex application is proposed to achieve the goal.

The research results are expected to have a significant impact on diagnosis and quality control methods in aircraft structure and operation. Aircraft reliability and safety increase is an important problem, and efficient defect diagnosis tools development will contribute to meet the purpose.

Research methods

One faces several problems (fig. 1) during composite material defect diagnosis. Defect invisibility or insignificant impact on aircraft outward, including inner defects, for instance, blisters and delimitations are the main detection complications. Besides that, material inhomogeneity makes it difficult to detect exactly defect distribution and impact on structure sustainability and reliability.

Diagnosis methods, such as visual inspection, ultrasonic control, X-ray, are limited, which also affects defect detection efficiency due to composite material features. Expensive equipment and necessity of process and its record standardization make the diagnosis more complicated and costly. Thus, the efficient composite material defect diagnosis requires the development of new approaches, methods and models, and wider industry standards adoption.

It is necessary to describe a mathematical model considering the complex approach for aircraft composite material defect detection.

Research results

Complex approach for defect detection can be described with mathematical modelling including diverse methods, as there is a defect detection function $F_j(D_i)$ for each of them, determining detection veracity E_i using the given method [4–8].

Then defect detection veracity in aircraft S area can be determined as a sum of veracities using every method, considering their weight or efficiency:

$$P(D_s) = \sum_{j=1}^{m} w_j \cdot F_j(D_i), \qquad (1)$$

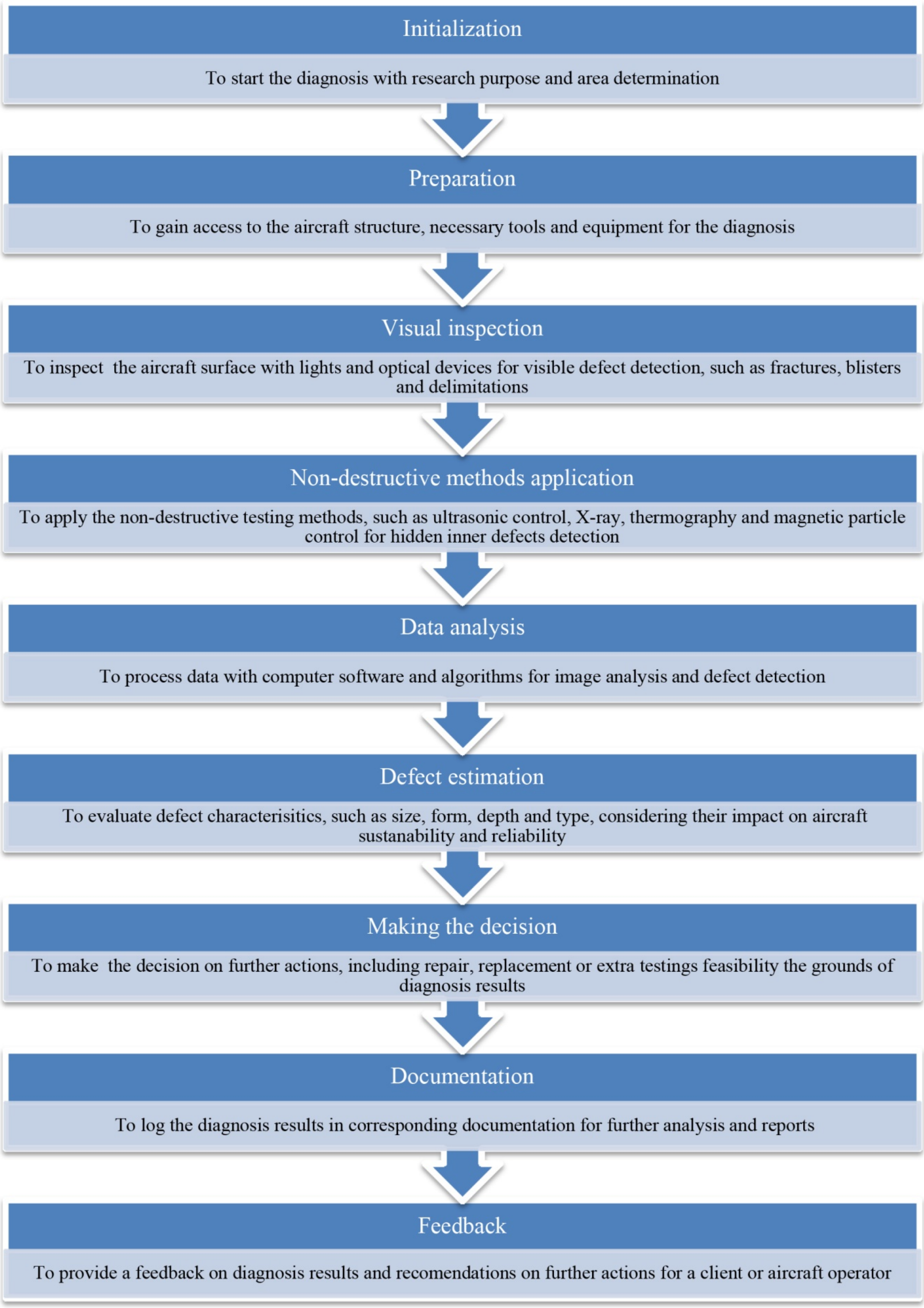

Fig. 1. Algorithm for a general approach to the process of diagnosing defects in composite aircraft structures

where m – diagnosis methods quantity, w_j – j^{th} diagnosis method weight or efficiency. Thus, the given model considers the diagnosis complexity, allowing to estimate defect detection in aircraft area using its different methods. Model practical relevance is its ability to consider different diagnosis methods (visual inspection, ultrasonic control, X-ray, etc.), and to estimate defect detection veracity with each of them. It is possible to enhance detection processes for defects harder to identify visually. Detection veracity is determined by $F_j(D_i)$) detection function which integrates all the methods data. This function allows to run a complex analysis and increase diagnosis accuracy.

It is necessary to implement a range of indicators for aircraft composite material defects detection mathematical modelling based on certain elements defect veracity statistics. Let there be an aircraft made of composite elements, marked as E_i, where i – is the element index. Let D_i be the E_i defect parameter vector, which may include such characteristics, as defect size, form, depth and type.

Then it is possible to determine $P(D_i)$ veracity of both defect occurrence and absence basing on statistics.

With all the elements, defect detection veracity in certain aircraft area is a multiplication of all the defect veracities in this area.

Thus, the mathematical model may be recorded as

$$P(D_i) = 1 - \Pi_{i=1}^{n} \mathrm{P}\overline{(D_i)}, \qquad (2)$$

where n – is a number of elements in S area.

The model allows to estimate defect occurrence veracity in certain aircraft areas basing on certain element defect veracity statistics, considering the aircraft features and parameters. This allows to predict defect veracity and implement preventive measures.

Mathematical model based on finite elements method for aircraft composite material structure defect detection:

Let u be the nodal displacements vector, f – external forces vector, K – stiffness matrix, d – defect vector, r – reaction vector.

Then element dynamic linear equation can be written as

$$\mathrm{Ku} - \mathrm{f} - \mathrm{d} = \mathrm{r}, \qquad (3)$$

where Ku is the inner nodal forces sum, r is vector of reactions, compensating external effects.

The solution of individual equations for finite elements, their further integration in terms of the whole aircraft allows to estimate voltage, deformation and reaction distribution, which provides the opportunity of defect detection and analysis and aircraft elements technical condition [7–10].

Application of fuzzy sets in a mathematical algorithm for defect diagnosis in composite aircraft structures [11, 12]. Let us assume that each step of the algorithm (see Figure 1) is represented by a fuzzy set, where W is the ordinal number of the step. This fuzzy set can be described by the membership function F_{w_i} *(x)*, which characterizes the degree of membership of an element x to the setW_i. Let x denote the vector of data or parameters obtained at a given step of the diagnosis [12–15]. At each step i of the algorithm, where $i = 1, 2, \ldots, n$, we can estimate the degree of membership of each element x to the set K_i using the membership function F_{w_i}(x). This approach takes into account the uncertainty and various aspects of information at each step of the diagnostic process. Further, for each step of the diagnostic process, a weighting coefficient K_i can be determined, which reflects its importance or weight in the overall diagnostic process. Weighting coefficients are established expertly and calculated on the basis of statistical data. To combine the outputs of different phases of an algorithm using fuzzy sets and weighting factors, it is possible to use aggregation operations such as the arithmetic mean or weighted mean [16, 17]. For example, to estimate the overall degree of membership of an element x in a set of defects [18], we can apply the following equation:

$$F_{defect}(\mathrm{x}) = \sum_{i=1}^{n} K_i \cdot F_{w_i}(\mathrm{x}). \qquad (4)$$

Therefore, we can combine the results of all diagnosis stages, taking into account their

Table 1

Weighting coefficient based on expert assessments and statistical data from Rossiya Airlines

Diagnosis data	**Weighting coefficient 1**	**Weighting coefficient 2**	**Weighting coefficient 3**	**Weighting coefficient 4**	**Weighting coefficient 5**	**Weighting coefficient 6**	**Weighting coefficient 7**
Initialization	0.12	0.15	0.18	0.1	0.14	0.1	0.11
Preparation	0.1	0.17	0.12	0.15	0.11	0.14	0.21
Visual inspection	0.25	0.21	0.18	0.27	0.23	0.22	0.19
Non-destructive testing	0.18	0.2	0.22	0.19	0.16	0.21	0.25
Data analysis	0.15	0.14	0.16	0.12	0.19	0.17	0.15
Defect estimation	0.1	0.11	0.13	0.11	0.1	0.13	0.1
Making a decision	0.1	0.08	0.1	0.07	0.1	0.08	0.1
Documentation	0.1	0.14	0.11	0.09	0.08	0.15	0.08

weighting factors, to calculate the overall degree of element belonging [19]. The weighting factors (see Table 1) are determined based on the analysis of statistical data collected during the diagnostics of aircraft at Rossiya Airlines. The determination of the weighting factors includes expert assessments, where specialists evaluate the importance of each diagnostic stage based on their experience and knowledge. The use of statistical analysis methods allows us to objectively determine the weighting factors, taking into account the frequency and importance of defect detection at each diagnostic stage.

During the scientific research, data on the importance of each diagnosis stage, such as the number of detected defects, frequency of method use, accuracy of the method, and costs of its implementation was collected. Expert assessments of the importance of each diagnosis stage were obtained. Basing on the collected data and expert assessments, each stage was assigned with S_j significance criteria. The significance assessments were transformed into weighting coefficients W_j with normalization:

$$w_j = \frac{S_j}{\sum_{k=1}^{m} S_k}, \quad (5)$$

where S_j is the significance score for each j^{th} diagnostic step, m is the total number of diagnostic steps. These weighting factors w_j are then used in the overall defect detection probability function. This approach allows for an objective assessment of the contribution of each diagnostic method and optimization of diagnostic and maintenance processes.

The study of the table of weighting factors for each stage of aircraft composite structure defect diagnostics reveals several important aspects [20–23]. The visual inspection and non-destructive testing stages acquire the highest weight, which emphasizes their importance in the overall diagnostics process. Significant weighting factors for the visual inspection and non-destructive testing stages (the average value for all weighting factors is 0.22 and 0.2, respectively) indicate the key importance of these stages in defect detection and assessment. The data analysis and defect evaluation stages are also significant, as evidenced by their weighting factors (average value) of 0.15 and 0.11, respectively, emphasizing the importance of thorough information analysis and objective defect assessment. The preparation and documentation stages have lower, but still significant weighting factors

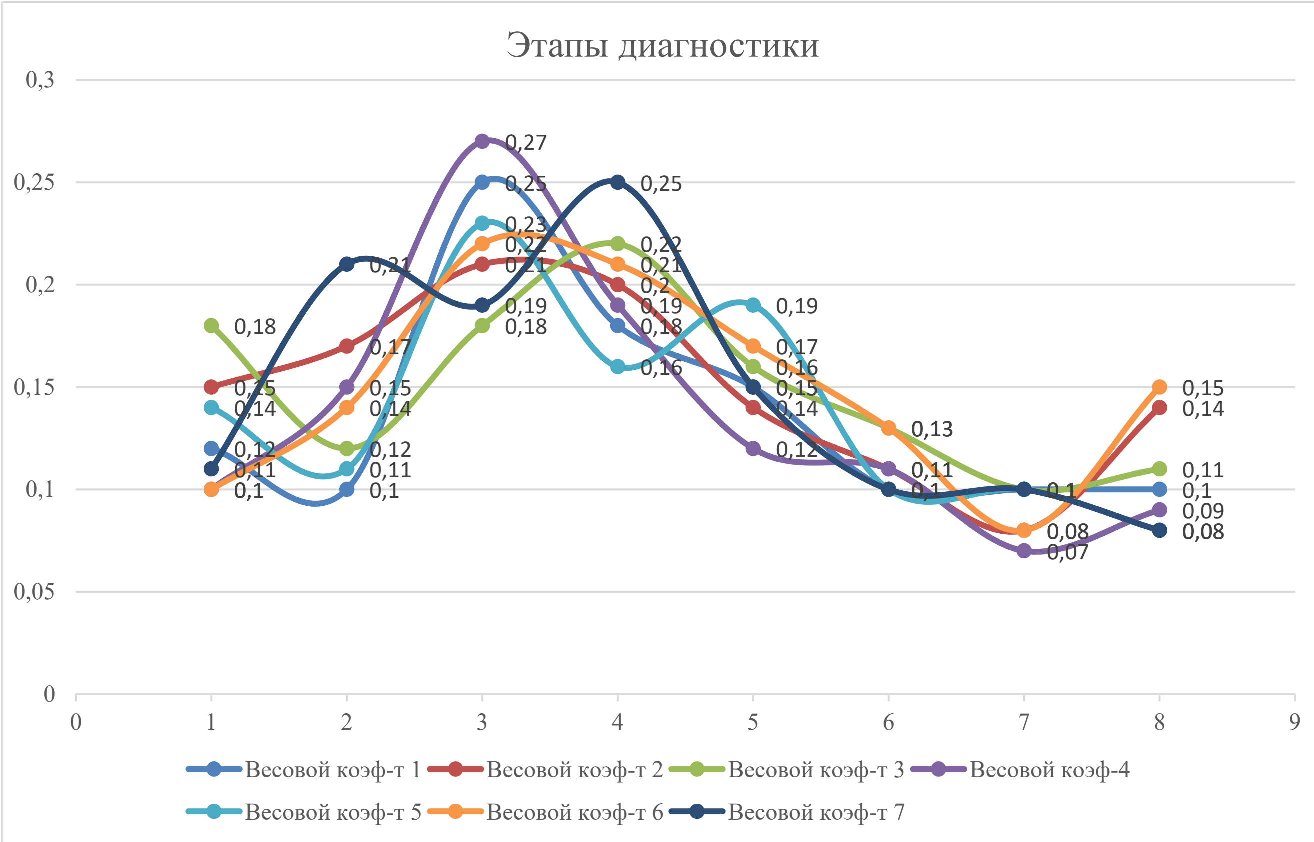

Fig. 2. Diagram of diagnostic stages with a weighting coefficient based on statistical data from Rossiya Airlines

(the average value is 0.14 and 0.11, respectively), which confirms their importance for organizing and documenting the diagnostics process. This analysis (see Figure 2) confirms the need for a global approach to the diagnostics of defects in aircraft composite structures in order to ensure their safety and reliability.

In this case, each stage has its own weighting factor in relation to various aspects that can be taken into account when diagnosing defects in composite structures of aircraft. This table helps to take into account various factors and their importance at each stage of the diagnostic process. The use of an integrated approach and mathematical modeling in detecting defects in composite structures brings significant economic benefits. This method ensures more precise and effective detection of defects, which reduces the likelihood of incidents and reduces the need for expensive repair measures. When using an integrated approach, prompt detection of defects at early stages and preliminary planning of repair work can reduce downtime and reduce fleet maintenance costs. This helps to improve flight safety and reduce operating costs of airlines, which ultimately increases the overall economic efficiency of air transport. The following equation can be used to assess the economic efficiency of an integrated approach to diagnostics:

$$\mathrm{EE} = \sum_{i=1}^{n} \mathrm{K}_i \cdot \mathrm{E}_i, \qquad (6)$$

where *EE* is the economic efficiency, n is the number of diagnostic methods, $\mathrm{K}_i$is the weighting coefficient for the i^{th} method, $\mathrm{E}_i$is the efficiency indicator for the i^{th} method.

Naturally, the combined approach to detecting defects in composite structures of aircraft not only improves the accuracy of defect detection, but also helps to optimize the costs of maintenance and repair work. This is crucial in the current aviation industry, where safety and reliability are put in the first place. Mathematical modelling makes it possible not only to detect defects more efficiently, but also to predict their development, which allows for preventive measures to prevent emergency situations. This method also helps to increase the efficiency of aircraft by reducing the time required for maintenance and repair, which can ultimately lead to an increase in airline profits.

Conclusion

Aircraft composite material defect detection mathematical model is a significant progress in aircraft safety and reliability improvement. Complex approach, which includes different diagnosis methods, increases the defect detection precision and efficiency, and eventually decreases emergency occurrence. The conclusions may become a ground for more efficient aircraft quality and operation control strategies, which as a result will provide greater level of aviation safety. Diagnosis process standardization and new defect detection technology implementation are the further research key objectives. Nevertheless, it is also necessary to take into consideration the factors, affecting the given model and methods efficiency and implementation. In general, aircraft composite material defect detection mathematical model development provides aircraft safety together with operation and maintenance enhancing prospects.

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