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DEFECTS OF AIRCRAFT STRUCTURAL ELEMENTS BASED ON POLYMERIC-COMPOSITE AND THEIR DIAGNOSTICS BY NONDESTRODUCTIVE CONTROL METHODS

Abstract. *This article examines the application of non-destructive testing (NDT) methods for assessing the structural integrity of aircraft components made from polymer-based composite materials. Composite materials are widely used in aviation due to their high strength-to-weight ratio, corrosion resistance, and durability. However, these materials are subject to various defects caused by manufacturing processes, operational loads, and environmental factors such as temperature and humidity fluctuations. Traditional NDT methods, including ultrasonic, radiographic, optical-visual, capillary, and thermal testing, each have specific advantages and limitations. Ultrasonic testing, for example, does not provide comprehensive volumetric analysis, while radiographic methods require complex safety measures. Optical-visual techniques fail to detect internal defects, and capillary methods suffer from low productivity. To address these challenges, the study proposes improvements to existing diagnostic techniques, the development of new automated models, and the optimization of parametric indicators. The research also explores an integrated "human-machine-environment" system to enhance the reliability of defect detection and assessment. Advancements in NDT technologies will not only increase the accuracy and efficiency of aircraft inspections but also improve safety, extend service life, and reduce maintenance costs. The findings of this study contribute to the development of modern diagnostic complexes that ensure higher operational reliability of aircraft structures.*

Key words: *composite materials, defect, non-destructive testing method, loaded parts, diagnostic models, dynamic correlation.*

Introduction.

Aircraft have a complex structure. During the long-term operation of aircraft mechanisms and components, defects that occur during their service life lead to an increase in accidents. Ensuring safety is the responsibility of modern technical diagnostics, which are closely related to automatic monitoring systems. Technical diagnostics is the science of determining the state of a technical system and solving a wide range of problems such as obtaining and evaluating diagnostic information. Currently, aircraft monitoring systems are limited in scope, making it impossible to predict the technical state of all aircraft elements and assemblies over a long period of time during their dynamic motion. Recently, one of the most pressing issues is the creation of combined systems for diagnostics and forecasting of the technical condition of aircraft. Such combined systems make it possible to timely monitor defects in polymer composite-based structural elements, assemblies and nodes, accurately obtain information through modern sensors installed in the composition of composite materials, study their dynamic and static characteristics and process them on board, automatically compare information within permissible limits and transmit it to a ground station, and also control various physical parameters. Namely, the creation of modern automated monitoring systems in this direction, as well as the complex design of the “human - machine - environment” system are considered one of the most pressing issues [1].

The purpose of the work is to conduct a comparative analysis of diagnostic methods (models) for the control of polymer composite-based structural elements of the HG and to identify directions for improving existing diagnostic methods.

Materials and methods of the study.

In aviation technology, the replacement of structural parts of aircraft with high-modulus polymer composite materials (PKM) is considered one of the important and strategic issues. Composite materials are considered multicomponent materials. Typically, a composite material consists of a plastic base (matrix) and various reinforcing fillers. According to the structure of the filler, composite materials (KM) are divided into fibrous, layered and dispersed solid materials. The matrix of the composite material ensures the monolithicity of the material, and the filler provides stress transfer and distribution.

Depending on the composition and properties of the matrix and filler, their proportions and the choice of placement, materials are divided into operational and technological types. Many composite materials surpass traditional materials and alloys in terms of their mechanical properties (specific strength, hardness, wear resistance, fatigue limit, thermal and vibration resistance, sound absorption, impact viscosity, etc.). The impact strength and elastic modulus of composites are 2...5 times higher than those of conventional structural alloys. Studies show that during the operation of structures made of composite materials, mechanical, impact, corrosion, etc. type damage leads to the formation of cracks, and the effect of periodic fluctuations in temperature and humidity leads to an increase in their size. Thus, diagnostics of structures and their periodic repair prevent breakdowns and increase operational safety.

Currently, a number of non-destructive inspection methods have been developed in scientific research centers in many countries of the world for the control of materials and products, where the development of damage from the initial stage to complete destruction (wearing out) of materials is monitored. Defects formed in materials, the study of their informative parameters, as well as the calculation of defects in structures fall under the responsibility of non-destructive inspection methods. However, non-destructive inspection methods used in the control of composite materials have shortcomings. Namely, in order to eliminate these shortcomings, research is being conducted in the leading scientific research centers in the field of non-destructive inspection to improve the most effective diagnostic methods and develop new methods. It is known that composite materials are widely used in aviation, rocket, automotive, mechanical engineering, metallurgy, etc. industries. Over the past decade, the use of composite materials in aircraft structures has increased significantly, which is 50-55% in Boeing 787, Airbus A350 aircraft, 80-85% in small aircraft, and 100% in unmanned aerial vehicles. Figure 1 shows the replacement of the entire fuselage section of a Boeing 787 aircraft with aerospace composite materials, and Figure 2 shows the replacement of individual parts of an A-380 aircraft with aerospace composite materials.

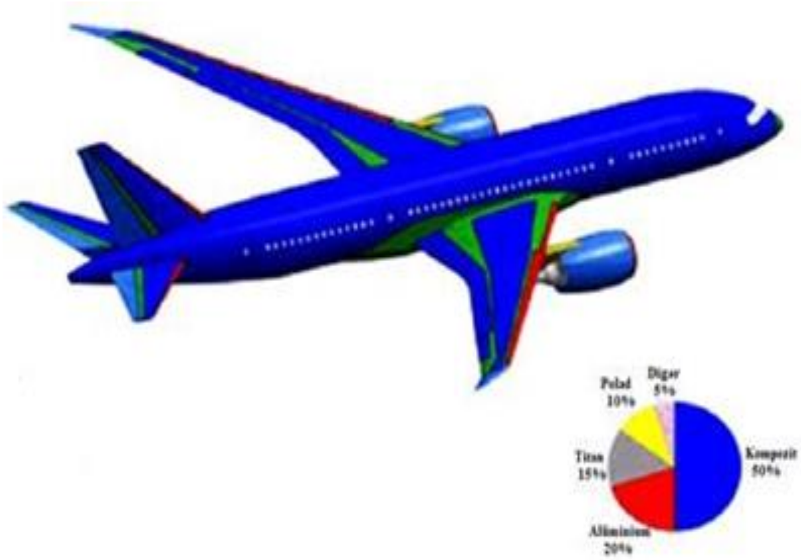

Figure 1 – Replacing an entire Boeing 787 HG fuselage section with composite materials

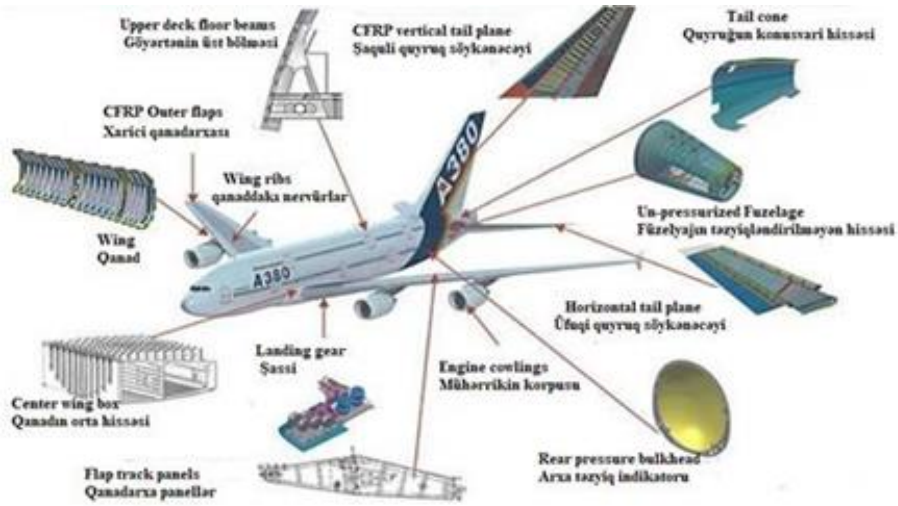

Figure 2 – Replacement of Airbus A-380 HG with aerospace composite materials [1]

Unlike metal, composite materials are considered non-monolithic materials and are considered the main part of the structure in terms of quality.

Defects found in composite materials are divided into two classes: production and operational defects. Defects are divided into three groups: micro-, mini- and macro-defects [3].

Micro-defects are defects that occur in reinforcing fibers (microcracks, microparticles, microvoids, fractures, bends, etc.), between elementary fibers in the matrix (micropores, microcracks, microparticles, etc.) and on the fiber-matrix surface.

Mini-defects are bends, fiber breakage, small scratches, dents, fractures in groups or individual parts of elementary fibers.

Macro defects are cracks, voids, depressions on the surface of the composite material, impact defects, cracking, delamination, blistering, air macroparticles, non-adherent parts, and other defects.

During the polymerization process of composites [3], the irregular distribution of internal stresses, bonds, and other technological factors leads to delamination, detachment of individual layers, brittleness, crack formation, and separation of fibers and reinforcement strands (Fig. 3 and

Fig. 4).

Unlike metallic materials, composite material defects can increase during operation, which reduces the reliability of the structure. Here, liquid penetrates into the composite through a crack on the matrix surface, damaging it and reducing its elastic modulus. Even with a typical delamination defect, the bond strength weakens, fibers break, and tensile strength decreases.

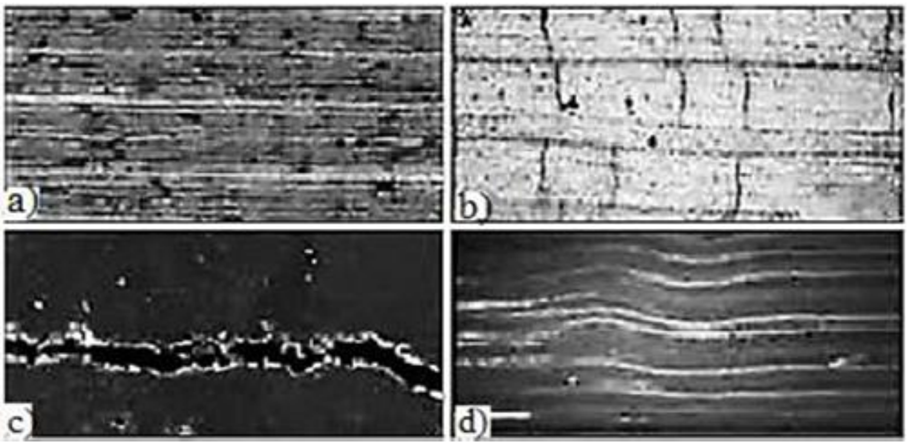

Figure 3 – Defects in composite materials: a) pores (black); b) cracks; c) delamination; d) wave-like defects [3]

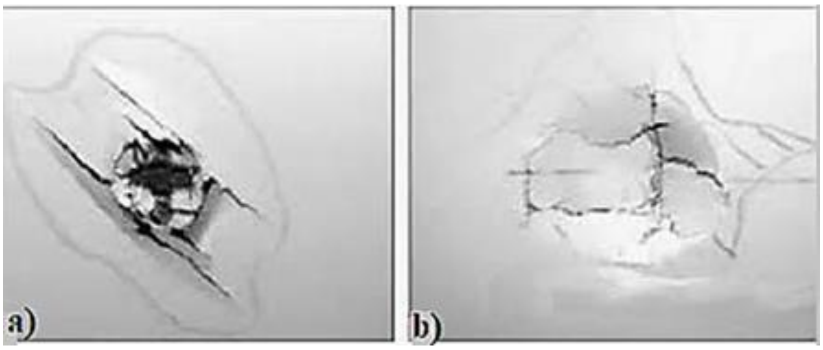

Figure 4 – External damage of composite materials: a) on the surface of the wing; b) in the fuselage [3]

Composite-based objects are very difficult to control because they have a heterogeneous structure, anisotropic properties, many different types of reinforcement (unidirectional, transverse-longitudinal, combined, etc.), specific physical properties (high electrical insulation quality, low thermal conductivity, sound absorption, many physical and mechanical characteristics, low density (0.02- q/sm^3). It is very difficult to keep the situation under control. Therefore, testing composite materials by physical methods compared to homogeneous structures (metals) is characterized by low sensitivity, transmittance and signal-to-noise ratio.

Depending on the nature of the filler used in many types of composite materials, they are usually dielectric or poorly conductive. Practically all composite materials are non-magnetic materials, which is why many non-destructive testing methods used for metals are considered unsuitable for composite-based products. The main non-destructive testing methods used for composite materials are given in Table 1 [1,3]. Let us consider the main characteristics of the methods used. Testing composite materials by high-frequency ultrasonic methods is considered ineffective, since the power of ultrasonic waves with a frequency of 1...5 MHz is scattered in the matrix, fibers and other particles and weakens. Thus, the control becomes difficult depending on the thickness range of composite materials. Some types of composite materials are very sensitive to moisture, and non-destructive testing methods are not applicable here.

In the nondestructive ultrasonic method, a powerful laser excites waves, making it essential for personnel to handle the technology with care and work under controlled conditions for a limited time. Among the various acoustic nondestructive testing methods, the low-frequency approach is particularly effective for riveted joints in multilayer polymer composite materials. This method enables the inspection of multilayer riveted construction joints composed of carbon, boron, and organic glass-type fibers, including non-metallic coatings and riveted joints between frames.

A key distinction of the low-frequency nondestructive testing method for multilayer riveted constructions based on polymer composites lies in its unique capabilities. It allows for the detection of structural non-dampness in gyroscopic materials, ensuring the integrity of details and assemblies. Additionally, it facilitates the assessment of surface curvatures, accommodating both concave and convex components. Furthermore, this method proves effective in evaluating uneven surfaces of anisotropic materials, enhancing the reliability of structural inspections.

Table 1 – Basic methods of non-destructive testing used for composite materials [1,3]

Area of application	Control methods used for KM	Information parameter	Control production, m^2/hour	Sizes of detected defects, mm	
				Minimum scan	Minimum length
Damage to smoothness	Active thermal control	Temperature, heat area	0.6	0.15	10
Crack (open defect)	Surface wave ultrasound method	The time duration of the ultrasonic signal between the receiver and transmitter of the ultrasonic transducer	2.1	0.1	15
Revealed defects	Ultrasonic sound and thermography method	Acoustic radiation and thermal area	0.6	0.001	5...7
Various defects and cracks	Radiography Radioscopy Radiometry	Conversion of X-ray intensity into optical beam	4...5	0.15	3
Cracks	Radio wave	Radiation characteristics	0.5	0.1	15
Foreign particles, roughness	X-ray television	Comparison of X-ray and video images	7	0.2	0.2
The unevenness of multi-layer construction in rotating bodies	Tangential lighting	Size change and depth detection	3	0.2	10

In non-gyroscopic composite materials, the acoustic contact between the transmitter and the object is established through a viscous liquid. Typically, the free oscillation method is employed for testing composite materials, analyzing the characteristics of free oscillations that occur after a vibration shock. This method, in combination with appropriate electronic equipment, enables the detection of various defects, including layered and air-bubble cavities, as well as non-adherent parts. Compared to other low-frequency acoustic methods such as impedance, velocimetric, and acoustic-topographic techniques, the free oscillation method offers distinct advantages. It allows for the detection of defects located at significant depths, facilitates the control of structural materials with a low elastic modulus, and ensures effective monitoring of materials characterized by a high damping coefficient of elastic oscillations.

One of the most common methods is the radiation control method [3]. This method allows the detection of various voids, individual particulate foreign materials, as well as non-uniform structures (fractures of reinforcing elements, voids, etc.). It has been established that, as in metals, if the illumination has a weak effect on defects (cracks perpendicular to the radiation flux, delamination), depending on the change in the total thickness of composite materials, then the application of the X-ray method becomes impossible.

For this type of materials, the capillary-radiation inspection method is used, in which the contrast of the elements of the illuminated object is increased by the penetration of a liquid X-ray contrast penetrant. For this purpose, a wide range of organic and inorganic penetrants with a high absorption coefficient of X-rays are produced. One of the most common penetrants is considered to be a solution of ZnI2 (zinc iodide). It is opaque and has high radiation compared to other substances. With this method, it is possible to detect surface or intermediate damage as a result of the penetration of capillary penetrants into cracks or interlayer gaps. The high achievements of radiation defectoscopy in the last decade have also had an impact on the development of digital X-ray television inspection.

Here, the X-ray beam is converted into an optical beam by passing through the object with the help of optical converters and is reflected on the monitor screen by the telephoto method. Here, inexpensive X-ray optical scintillation crystals are used and the optical image is read by a small-sized charge-coupled device (CCD) with high sensitivity (Fig. 5). The digital radioscopy method provides instant digital X-ray imaging, improves visual imaging, and determines the measurement of geometric parameters controlled by the images. Here, a database (flash radiography) provides for the input, storage, selection, display of images, and the extraction of results, as well as data transmission to local and external networks [3].

Figure 6a shows low-contrast images of a fiber with a width of a few pixels inside a composite material using the digital X-ray method. In this case, it is difficult to examine the structure of the fiber. Here, specialized digital filters are used for image processing, which improves the X-ray image of the fibers in given directions in the composite material (Figures 6b, c and d).

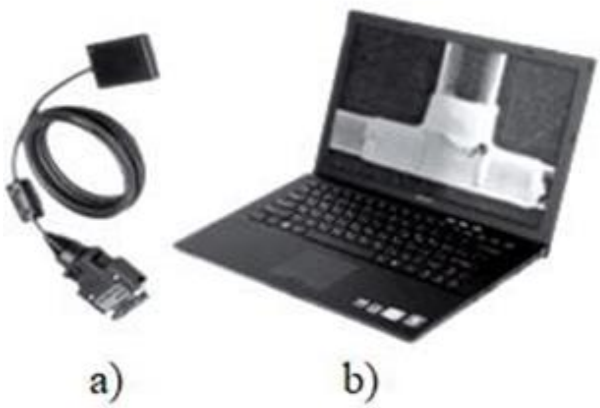

Figure 5 – X-ray flash radiography method of HCC matrix: a) YCC sensor; b) X-ray image of a trident made of composite material [3]

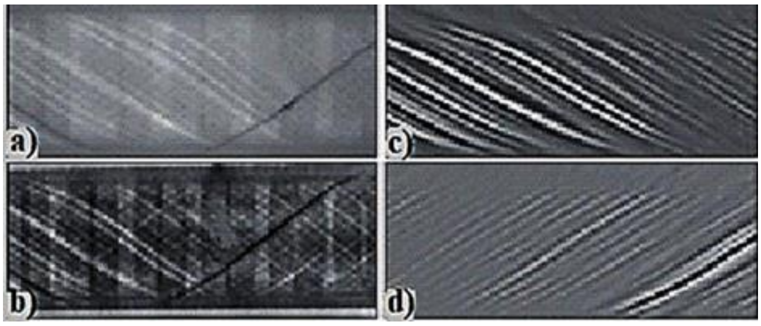

Figure 6 – X-ray image of a composite sample: a) real; b), c), d) images after digital contrasting

Figure 7 shows images of carbon fibers and their fractures. Here, the effective use of computed tomography depends on the geometric dimensions of the object. Such an expensive technology can be considered unique for the study of volumetric internal structures. Its resolution is several microns and is determined by computed microtomography.

Figure 7 – Visualization of cracks in the internal structure of composite material using tomography [5]

It is difficult to diagnose large-sized composite materials using the tomography method, when 360...720-pixel images are rotated at an angle of 360 degrees. This method makes it possible to obtain 6, 12, 24 projections with small angles. However, exposure deficiencies are encountered here. In this case, the error in the reconstruction of geometric parameters increases sharply.

Thermography (thermal) method is the most promising non-destructive inspection method for composite material-type structures [2, 6]. The basis of this method is infrared technology (thermal imager or pyrometer) and determines the presence of a defect as a result of changes in temperature fields. Thermography records temperature changes at 0.01°C. Thus, during mechanical loads, energy concentration sites are recorded, where energy is released as a result of plastic deformation. By recording temperature fields on the surface, it is possible to determine the location of the energy concentrator relative to the surface of the product. Here, taking into account the issues of non-stationary heat transfer, it is also possible to determine its dimensions and location. Figure 8 and Figure 9 show images of the distribution of heat fields (thermograms) in composite-based objects [6].

Figure 8 – Thermogram of the defect of the composite panel of the aircraft [2]

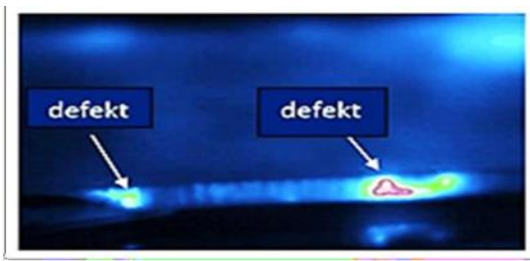

Figure 9 – Thermogram of the defect found on the honeycomb panel of the wing of the Super Jet-100 aircraft [2]

The main advantages of thermographic control are universality, high evaluation of temperature signals, efficiency, high productivity and remote measurement. The disadvantages of this method are the presence of specific noise generated by the object (fluctuations in optical properties), as well as by an external heat source.

It has been established that the active thermography method is one of the new, highly effective and informative methods of non-destructive control and is widely used in the aerospace industry. Due to a number of advantages of the active thermal control method, it is more expedient to inspect composite materials using this method (Fig. 10 and Fig. 11).

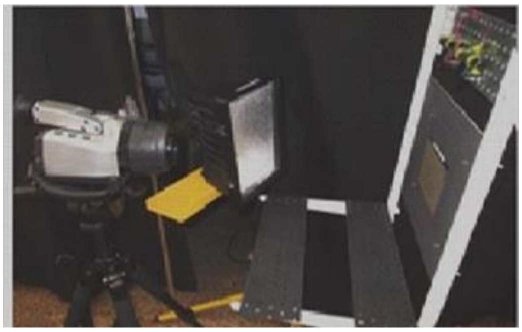

Figure 10 – Active temperature control method applied to composite materials [2]

Figure 11 – The device of the active temperature method for the study of airplanes (Automation Technology, Germany) [2]

However, recently, automated diagnostic monitoring systems of leading organizations such as Boeing, Airbus, AgustaWestland (AW), Northrop Grumman, NASA have been designed based on modern sensors. The application of such sensors has been widely used in conducting scientific research and measuring many different physical parameters (deformation, temperature and magnetic field). Studies show that further improvement of modern sensors based on the fiber-optic method in the future will give impetus to the development of a number of areas. For example, modern sensors will allow for full monitoring of the internal structure of composite material parts, rivet joints, and airframes, as well as for operational monitoring of the resources of individual elements of the structure and uneven areas in a short time. Figure 12 and Figure 13 show the installation of modern sensors in the internal structure of composite materials [5].

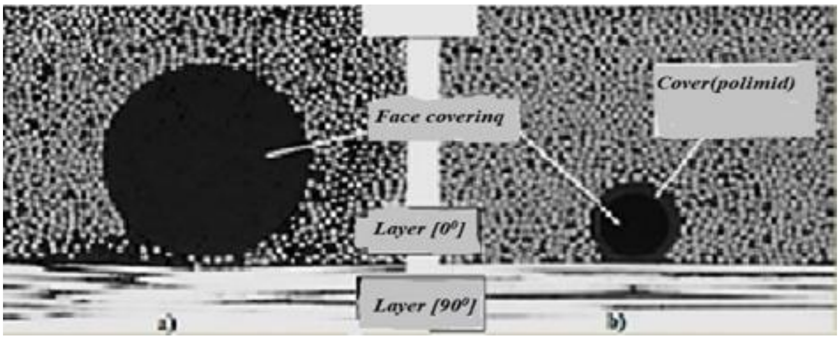

Figure 12 – Placement of conventional optical fiber (a) and small diameter fiber (b) in the internal structure of carbon fiber [4,5]

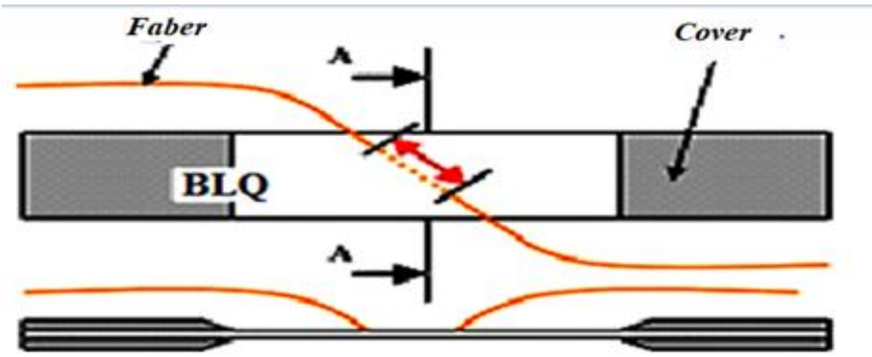

Figure 13 – The sensor installed on PCM [4,5]

Conclusion.

Thus, the above methods of non-destructive testing have their advantages and disadvantages for the diagnosis of composite materials. The ultrasonic method does not allow volume control of composite materials, as it is necessary to take into account the requirements for the material of the controlled object, as well as its surface. The radiation method limits the complexity of the technical execution, used to ensure the requirements of radiation safety, as well as specific defects of composite materials. The disadvantage of the optical-visual method is that hidden defects are not detected, and the disadvantage of the capillary method is its contact and low productivity. The disadvantage of the heating method is a one-sided check, dependence of surface temperature signals on the depth of defects, as well as a high level of detection of additive and multiplicative sounds when using an optical stimulator. It also makes it difficult to control the quality of composite materials.

And with this connection, the improvement of diagnostic methods in recent years, the creation of new automated diagnostic models using non-destructive control methods, the study of new methods and tools, as well as the optimization of parametric indicators are considered as one of the most important issues of creating new modern diagnostic complexes.

The creation of such control systems will not only increase the safety of aircraft operation, increase its resource, increase the accuracy of measurements, make it economically efficient and affordable, but also open the way for a complex and convenient study of the "human - machine - environment" system.

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ПОЛИМЕРЛІ-КОМПОЗИТТІК НЕГІЗДЕГІ ӘУЕ КЕМЕЛЕРІНІҢ КОНСТРУКТИВТІК ЭЛЕМЕНТТЕРІНІҢ АҚАУЛАРЫ ЖӘНЕ ОЛАРДЫ БҰЗБАЙТЫН БАҚЫЛАУ ӘДІСТЕРІМЕН ДИАГНОСТИКАЛАУ

Аңдатпа: *Жобалау үшін бұзылмайтын сынау әдістерінің салыстырмалы талдауы жүргізілді. Бұл мақалада полимер негізіндегі композициялық материалдардан жасалған ұшақ компоненттерінің құрылымдық тұтастығын бағалау үшін бұзылмайтын бақылау (ББ) әдістерін пайдалану қарастырылады. Композиттік материалдар жоғары беріктік пен салмақ қатынасына, коррозияға төзімділігіне және беріктігіне байланысты авиацияда кеңінен қолданылады. Дегенмен, бұл материалдар өндірістік процестерден, жұмыс кернеуінен және температура мен ылғалдылықтағы өзгерістер сияқты қоршаған орта факторларынан туындаған әртүрлі ақауларға сезімтал. Дәстүрлі бұзылмайтын бақылау әдістері, соның ішінде ультрадыбыстық, радиографиялық, оптикалық-визуалды, капиллярлық және термиялық, олардың артықшылықтары мен шектеулері бар. Ультрадыбыстық тексеру, мысалы, кешенді көлемдік талдауды қамтамасыз етпейді, ал радиографиялық әдістер күрделі қауіпсіздік шараларын талап етеді. Оптикалық-визуалды әдістер ішкі ақауларды анықтай алмайды, ал капиллярлық әдістер төмен өнімділіктен зардап шегеді. Осы мәселелерді шешу үшін зерттеу қолданыстағы диагностикалық әдістерді жетілдіруді, жаңа автоматтандырылған модельдерді әзірлеуді және параметрлік көрсеткіштерді оңтайландыруды ұсынады. Зерттеу сонымен қатар ақауларды анықтау және бағалау сенімділігін арттыру үшін адам-машина-қоршаған ортаның біріктірілген жүйесін қарастырады. Бұзбайтын сынақ технологияларын дамыту әуе кемелерін тексерудің дәлдігі мен тиімділігін арттырып қана қоймайды, сонымен қатар қауіпсіздікті жақсартады, қызмет ету мерзімін ұзартады және техникалық қызмет көрсету шығындарын азайтады. Бұл зерттеудің нәтижелері әуе кемелері құрылымдарының пайдалану сенімділігін арттыратын заманауи диагностикалық жүйелерді дамытуға ықпал етеді.*

Түйін сөздер: *композициялық материалдар, ақаулық, бұзылмайтын бақылау әдістері, жүктелген бөлшектер, диагностикалық модельдер, динамикалық корреляция.*

ДЕФЕКТЫ КОНСТРУКТИВНЫХ ЭЛЕМЕНТОВ ВОЗДУШНЫХ СУДОВ НА ПОЛИМЕРНО- КОМПОЗИТНОЙ ОСНОВЕ И ИХ ДИАГНОСТИКА МЕТОДАМИ НЕРАЗРУШАЮЩЕГО КОНТРОЛЯ

Аннотация: *Проведен сравнительный анализ методов неразрушающего контроля для конструкции. В данной статье рассматривается применение методов неразрушающего контроля (НК) для оценки структурной целостности компонентов летательных аппаратов, изготовленных из композиционных материалов на основе полимеров. Композитные материалы широко используются в авиации благодаря высокому соотношению прочности и веса, коррозионной стойкости и долговечности. Однако эти материалы подвержены различным дефектам, вызванным производственными процессами, эксплуатационными нагрузками и факторами окружающей среды, такими как перепады температуры и влажности. Традиционные методы неразрушающего контроля, включая ультразвуковой, радиографический, оптико-визуальный, капиллярный и тепловой, имеют свои преимущества и ограничения. Ультразвуковой контроль, например, не обеспечивает всестороннего объемного анализа, а радиографические методы требуют сложных мер безопасности. Оптико-визуальные методы не позволяют обнаружить внутренние дефекты, а капиллярные методы страдают от низкой производительности. Для решения этих проблем в исследовании предлагается усовершенствовать* *существующие методы диагностики, разработать новые автоматизированные модели и оптимизировать параметрические показатели. В исследовании также рассматривается интегрированная система «человек-машина-среда» для повышения надежности обнаружения и оценки дефектов. Развитие технологий неразрушающего контроля позволит не только повысить точность и эффективность проверок воздушных судов, но и улучшить безопасность, продлить срок службы и снизить затраты на обслуживание. Результаты данного исследования способствуют разработке современных диагностических комплексов, обеспечивающих повышение эксплуатационной надежности авиационных конструкций.*

Ключевые слова: *композитные материалы, дефект, методы неразрушающего контроля, нагруженные части, диагностические модели, динамическая корреляция.*

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