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Method of continuous non-destructive observation of profiles made of polymer fibre composite materials for the registration of crack formation

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ABSTRACT

The relevance of the study is conditioned by the absence of the necessary devices and structures made of composite materials such as stingers with holes for registering cracks. The purpose of the study is to develop the design and manufacturing technology of stringer-type profiles made of composite materials with micro-holes in the cross-section or inside which hollow polymer fibres are laid, while the holes did not significantly affect the strength of the product and the specified strength properties of the product are preserved. The task of manufacturing products from a polymer composite material is solved by a method that includes pre-laying hollow longitudinal fibres or introducing bundles coated with anti-adhesive lubricant at specified cross-section points of stringers with subsequent pressing when laying pre-cut layers of composite material in a mould (polymerisation of the binder). After cooling, decompressing, removing the bundles with anti-adhesive grease (the second option) and stripping the product, special sensors are installed, a vacuum is created inside the holes or pressure is applied within 0.1-0.2 atm. At the same time, the holes do not significantly affect the strength of the product and the specified properties of the product are preserved. The study suggests a method for continuous and autonomous monitoring of the integrity of profiles made of polymer fibre composite materials for registering the formation of cracks based on the introduction of longitudinal micro-holes or hollow fibres under pressure or vacuum into their structure, followed by recording changes in the pressure value. The advantage of the proposed method is that it allows making a product from composite materials with increased physical and mechanical properties, increasing operational safety, increasing service life, and reducing the cost of routine inspections due to continuous monitoring of the occurrence and development of damage in real time. At the same time, the reliability of the design significantly increases, which leads to an improvement in the quality of the product.

Keywords: Micro-holes, Damages, Pressure, Vacuum, Stingers, Polymers.

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1. Introduction

In light structures, monitoring and timely detection of damage play a significant role in ensuring the desired reliability. Additional advantages can be provided by monitoring using methods based on the control elements built into the system (Structure Health Monitoring (SHM)) when designing structures of minimum weight to reduce operating costs and reduce the weight of the product [1-22]. Both goals play a crucial role in aircraft construction. The necessary technologies have been partially developed, but they are still not used on production aircraft. With the help of recording devices built into the structure, it is possible to partially replace the design inspection programmes that are still based on conventional methods. Embedded control methods are designed for continuous and autonomous monitoring of damages, stresses, deformations by means of sensor systems permanently applied to the structure or integrated into it, while ensuring structural integrity. At the same time, the data is not only saved, but also interpreted and acted upon by taking the appropriate action.

Many embedded control technologies are based on principles that are already used in aircraft inspections and maintenance, such as ultrasound or eddy currents. But these technologies differ from conventional methods of non-destructive testing in that the sensors remain on the structure and, thus, repeated access to the observed point is not required. The measurement results can either be evaluated online, during the flight, or processed during maintenance. Sensors can be installed on the surface of the structure, embedded in the material or integrated between two parts. The proposed method of integrated control relates to the design of products made of composite materials used in the aerospace industry, shipbuilding, automotive, sports equipment, medical industry, which have increased physical and mechanical characteristics and reliability of operation. [23-30] Since composite materials are expensive, any damage resulting in cracks can lead to catastrophic consequences and large financial losses.

Timely determination of the beginning, place of occurrence, and speed of crack propagation allow more accurately determining the intervals of inspections and increase the service life of the product. There are similar examples of the construction of aluminium alloy profiles of the stringer type, which have special holes into which pressure is applied or a vacuum is created. Loading the holes through pressure or vacuum allows simply and effectively observing the integrity of the stringers. If small cracks can be detected long before reaching the critical length, then continuous monitoring allows managing the problem during operation. The task becomes more complicated when observing structures made of composite materials. To reliably detect and monitor the development of cracks, it is necessary to use improved non-destructive testing technologies, one of which is considered in this paper. The relevance of the study is conditioned by the absence of the necessary devices and structures made of composite materials such as stingers with holes for registering cracks. The purpose of the study is to develop the design and manufacturing technology of stringer-type profiles made of composite materials with micro-holes in the cross-section or inside which hollow polymer fibres are laid, while the holes did not significantly affect the strength of the product and the specified strength properties of the product are preserved

2. Material and methods

The design of the profile (stringer type) made of a fibre composite material with longitudinal micro-holes or hollow fibres located at the most loaded points of the cross-section is used to determine the appearance and propagation of cracks in real time, by recording changes in the pressure or vacuum created inside the hole or hollow fibre. The profile is made either by removing the bundle from the fibres treated with an anti-adhesive composition, or by laying hollow fibres inside the composite material, then placing the assembled package in a mould and then impregnating the assembled package with a binder under pressure or by infusion of the assembled package and polymerisation of the assembled package to obtain a product (stringer or stringer panel) that has the ability to simply and effectively register the integrity of the product. When a crack is formed, the pressure or vacuum value changes, thereby, through measuring this pressure drop, it is possible to determine the presence and moment of the crack occurrence. When a crack in the stringer has reached the longitudinal hole, the pressure or vacuum value changes, thereby, through the measurement of this change, the presence of a crack is determined by special sensors (Figure 1). This method was used in design and experiments to observe damage in inaccessible metal layers [31-44]. At the same time, the holes do not significantly affect the strength of the product and the specified properties of the product are preserved.

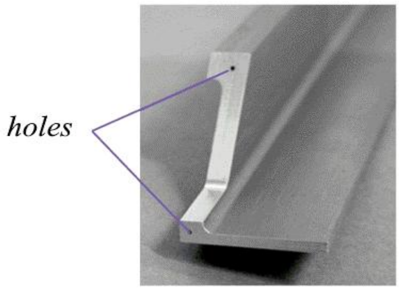

Figure 1. Holes in the stringer

Composite materials in which glass, basalt, carbon, organic, boron fibres are used as fillers, and polyester, epoxy, phenolic-formaldehyde resins are widely used as a binder in the production of various technical products [45-62]. It is known that products made of composite materials have a number of disadvantages, which primarily include low interlayer strength, low impact strength, a tendency to crack when damaged, etc. [63; 64; 65]. To eliminate these disadvantages, various methods were used – growing whiskers made of sapphire, silicon oxides, etc., which turned out to be very expensive and were not widely distributed and introduced into industry. In addition, it was proposed to introduce titanium or stainless-steel foil layers between the layers of the composite material, which also has disadvantages in the form of layering due to the difference in the coefficients of linear thermal expansion of the foil and the composite material, transversal reinforcement in the form of cross-linking layers of the composite package was also proposed [66-79].
However, these technological methods do not register damage in the form of cracks that occur during the operation of products. The task of manufacturing products from a polymer composite material is solved by a method that includes pre-laying hollow longitudinal fibres or introducing bundles coated with anti-adhesive lubricant at specified cross-section points of stringers with subsequent pressing when laying pre-cut layers of composite material in a mould (polymerisation of the binder). After cooling, decompressing, removing the bundles with anti-adhesive grease (the second option) and stripping the product, special sensors are installed, a vacuum is created inside the holes or pressure is applied within 0.1-0.2 atm. At the same time, the holes do not significantly affect the strength of the product and the specified properties of the product are preserved.

3. Results and discussion

Aircraft lifecycle management is the most topical issue in their creation, operation, and certification. All possible measures are taken to ensure reliable operation near or beyond the estimated service life. An important role, in this case, is played by the assessment of the appearance of multiple scattered fatigue damage in one part or in identical neighbouring parts, which are cracks of such magnitude and frequency that the structure can no longer meet the requirements for permissible damage.

One of the characteristic features of the aircraft life cycle is the qualitative satisfaction of the requirements for increasing the period of its accident-free and general operation. Ensuring the safe life of the aircraft has long been accepted as a mandatory method of creating an aircraft. This method assumes strict maintenance of the period of trouble-free operation for a full fleet of aircraft of the specified type under certain equal conditions without the presence of a real danger of its catastrophic or fatigue failure. The accumulated experience in the construction of aircraft of different classes indicates that, if it is necessary to increase the resource, it is advisable to use the operational survivability method, which includes the principles of permissible deformation and systematic destruction.

To determine the coefficient of total fatigue failure, the equation is proposed:

$$Kff = Kf \times \beta sl, \tag{1}$$

where: Kf – fatigue failure coefficient for one stage of the test programme; βsl – service life of the aircraft structure materials until cracks occurs.
The value of the parameter βsl depends on the change in the values of a number of interrelated quantities, such as Ks – the strength coefficient of the aircraft structure materials, τe — the average operating time of the aircraft between the scheduled repair of structural elements, ƚ – the total number of cycles of the aircraft structural strength test programme.

In general, the considered dependence can be represented as:

$$\beta sl = f(Ks, \tau e, ƚ) \tag{2}$$

Figure 1 shows the dependence of the change in the values of the strength coefficient of the aircraft structure materials on the number of cycles of the flight test programme.

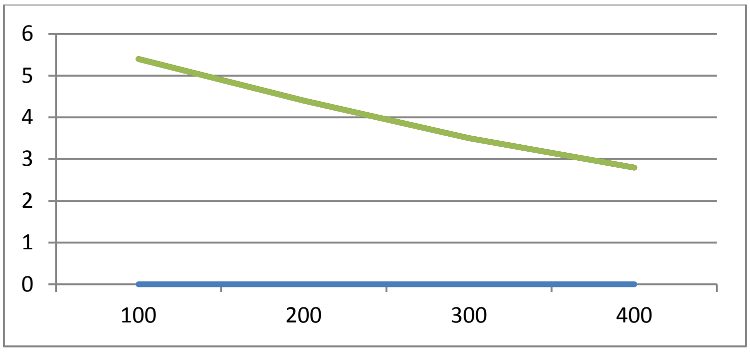

Figure 2. The dependence of the change in the values of the strength coefficient of the aircraft construction materials on the number of cycles of the flight test programme

The calculated values of the parameter ŧ are plotted along the abscissa axis, and the values of the strength coefficient of materials Ks are plotted along the ordinate axis.

As can be seen from the data presented in Figure 1, an increase in the cycles of the flight test programme, in other words, an increase in the number of flight hours of an aircraft has an inverse relationship with the value of the strength coefficient of its construction materials. Fatigue stresses accumulating in the materials of the aircraft structure gradually led to the appearance of cracks in its structure, which causes its premature destruction and the failure of the aircraft.

The methods of continuous non-destructive observation of profiles made of polymer fibre composite materials used in modern aircraft operation conditions for registering the formation of cracks differ into several main groups, depending on the observation goals pursued and the expected results:

1. A method of flaw detection used to detect microscopic defects in the surface of the aircraft structure, small cracks, shells, delaminations, and rejections of the upper layers of the surface when performing their mechanical processing. Methods of free, pulsed, and resonant vibrations, and methods of echo-pulse analysis of surface quality are used to detect surface defects.
2. The method of flaw detection, which is used to detect large structural defects of an aircraft, mainly on the surface, and deep chips, creases and other damages that gradually manifest themselves on the surface of profiles made of polymer fibre composite materials. The use of profilometers and profilography contributes to a more accurate determination of irregularities that occur on the surface, including deep damage to the aircraft structure.
3. A method for analysing changes in the internal structure of the structural material to determine the physical and chemical properties and predict the service life of aircraft parts.
4. A diagnostic method, which allows tracking changes in the physical and chemical properties of aircraft construction materials and predict the life of the main components of the aircraft.

A detailed differentiation of the varieties of the method of continuous non-destructive observation of profiles made of polymer fibre composite materials for registering the formation of cracks that are significant from the standpoint of integrated use to increase the overall efficiency of crack detection operations in the aircraft structure made of materials of this kind is presented in Table 1.

Table 1. Varieties of the method of continuous non-destructive observation of profiles made of polymer fibre composite materials for registering the formation of cracks in the structure

Method name	Variations used	Scope of application
Mechanical impedance method	Method of quality control of adhesive joints, a method of quality control of parts installed with tension in structural units	Control of connections with several adhesive layers and the quality of placement of pins, studs, and other structural elements
The method of using natural vibrations	The method of using forced oscillations, the method of using free oscillations	Control of the occurrence of defects in the elements of the multilayer structure of the aircraft, with an assessment of the quality of the connections of non-metallic and metallic layers
Passing method	Shadow passing method, a method of using bicycle symmetry when	Monitoring the condition of cellular and layered structures created using polyamide paper, and in

Method name	Variations used	Scope of application
	passing	the presence of one-way and two-way access to it
Reflection method	The method of reflection is reverberation and the method of echolocation	Control of the joints of metallic and non-metallic layers, using light fillers, and tracking the occurrence of defects between the adhesive joints of thin-walled structures

The varieties of the method of continuous non-destructive observation of profiles made of polymer fibre composite materials for registering the formation of cracks presented in Table 1 cover almost all aspects of monitoring the condition of aircraft structural elements made using materials of this type. At the same time, the specific situation in which the practical use of any of these varieties is advisable is important, since the technical difficulties that arise during the operation of the aircraft structure determine the final choice of the type of method for observing profiles made of polymer fibre composite materials and the expected results.

The reliability of profiles made of polymer fibre composite materials is essential from the standpoint of ensuring the safety of the operation of aircraft of all types [80-94]. In this context, the use of modern methods of continuous non-destructive observation of profiles prevents fatigue damage to the structure and preserves the duration of aircraft operation.

The use of quality control methods for profiles made of polymer fibre composite contributes to the development of the industry for the production of modern aircraft structures, the search for new ways to improve the reliability of the operational use of materials used in the field of aircraft construction [95]. At the same time, the design problems detected in a timely manner can be effectively and efficiently eliminated using modern developments through the use of modern polymer composite materials, the use of which is aimed at improving the aircraft design.

Varieties of the method of quality control of polymer fibre profiles perform the functions of complementing the quality studies of these structural materials, to form a better picture of control and identify additional opportunities to improve the quality of modern aircraft structures. At the same time, the choice of a specific type of the method used is determined both by the design features of polymer fibre composite materials and the nature of possible damage. Improving the quality of the product and increasing the durability of the operation of the aircraft structure require constant monitoring of its current condition to timely identify possible changes in design features and deterioration in the quality of the material [96-110]. The issues of the operational use of polymer fibre profiles in the design of modern aircraft require constant quality control of the current state of these structures and timely operations to make the necessary structural changes.

Acoustic methods of monitoring the state of polymer fibre profiles in a number of situations can be successfully replaced by radiological control methods, in particular, one of these is radiographic. The correct choice of modes with the specified control parameters contributes to achieving high quality of monitoring operations, which is caused by obtaining high-quality and high-resolution X-rays [111-124]. At the same time, this method also has significant disadvantages, in particular, due to its labour intensity, the significant cost of the film components necessary for X-ray examination, and the impossibility of its practical application in a number of situations that occur during the aircraft operation. In addition, acoustic methods for monitoring profiles made of polymer fibre composite for registering the formation of cracks are effective from the standpoint of practical application of the results obtained, since it is much easier to apply in real operating conditions, as a result of which they have found wider practical application in aviation.

In some cases, the method of continuous non-destructive observation of profiles made of polymer fibre composite materials for registering the formation of cracks turns out to be insufficiently reliable if two-way access to the controlled structure is required [125]. In the actual operating conditions of the aircraft, this is not always possible, which necessitates the use of other methods. At the same time, the use of the reflection method allows sending an ultrasonic pulse to the controlled area, which allows monitoring the state of the surface under study without direct two-way access. In this case, the reflected signal contains data about the state of the controlled surface and the presence of possible integrity violations on it, which determines the type of subsequent changes.

Various profiles made of polymer fibre composite materials are found not only in aviation technology, which allows choosing methods for controlling the formation of cracks on their surface. In any case, the quality of control determines both the need for repair of certain profile, and the duration of subsequent operation after repair.

The method of continuous non-destructive observation of profiles made of polymer fibre composite materials for registering the formation of cracks allows monitoring without causing any mechanical damage, which both preserves the profile itself and extends its operation time as much as possible. The use of composite materials in the manufacture of a product contributes to an increase in its physical and mechanical characteristics, increase of the service life, which is important from the standpoint of subsequent use. The high reliability of the design in this case will be conditioned by the high-performance characteristics of the profile, which generally indicates high standards of quality of its manufacture and reliability of further practical use.

4. Conclusion

Monitoring and timely detection of damage play a significant role in ensuring the desired reliability. The necessary technologies have been partially developed, but they are still not used on production aircraft. With the help of recording devices built into the structure, it is possible to partially replace the design inspection programmes that are still based on conventional methods. Embedded control methods are designed for continuous and autonomous monitoring of damages, stresses, deformations by means of sensor systems permanently applied to the structure or integrated into it, while ensuring structural integrity. At the same time, the data is not only saved, but also interpreted and acted upon by taking the appropriate action.

The advantage of the proposed method is that it allows making a product from composite materials with increased physical and mechanical properties, increasing operational safety, increasing service life, and reducing the cost of routine inspections due to continuous monitoring of the occurrence and development of damage in real time. At the same time, the reliability of the design significantly increases, which leads to an improvement in the quality of the product.

The results obtained in the course of this study indicate that there are significant prospects for further scientific research in the field of practical application of polymer fibre composite materials in aviation technology, as a way to increase the structural strength of aircraft. The reliability of the aircraft design is directly related to the duration and safety of its practical operation, which is extremely important from the standpoint of compliance with the tasks for which it was designed. In addition, this study can serve as a starting point for further research in this line, since it contains practical recommendations for improving the quality of profiles made of polymer fibre composite materials, which is extremely important for finding ways to further practical use.

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