The study of the possibility of X-ray inspection of fiber-optic sensors embedded into the structure of a polymer composite material

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\textbf{Annotation.} Currently, during the operation of structures, it is important to use the so-called systems for monitoring the state of structures, which in real time allow you to monitor changes in temperature and deformation fields. To diagnose the condition in such systems, various sensors are used, for example, strain gauges, fiber-optic, piezoluminescent. Most modern monitoring systems use fiber-optic sensors because they have more advantages and fewer disadvantages than other sensors. When monitoring the state of a structure, fiber sensors are mounted on the surface of the structure, however, when monitoring structures made of composite materials, it is possible to introduce fiber lines directly into the structure of the composite material at the stage of manufacturing the structure. When fiber lines are introduced into the structure of a composite material, a number of difficulties arise, namely, due to the fragility of fiber lines, breaks are possible both at the exit from the structure and inside. When considering polymer composite materials, the problem of the location of fiber sensors arises due to the resin flow during the process of forming structures. The solution to the problems described above can be the creation of the so-called Smart-layer, in which the fiber lines will be rigidly fixed, which will protect the fiber from breaking, and limit the movement of the fiber during the formation of structures. Thus, within the framework of this work, we investigate the issue associated with the assessment of the location of fiber sensors in the Smart layer after the formation mode. The location of the sensors after the structure is formed is investigated by radiation methods of non-destructive testing.

\section{1. Introduction}

At present, during the operation of structures, special attention in the literature is paid to the creation and implementation of the so-called Smart-structures [1-3], which in real time record the change and evolution of deformation and temperature fields, as well as the origin and evolution of defects of various types. Strain gauges, fiber-optic and piezoluminescent are used as sensors in such monitoring systems. Most modern monitoring systems use fiber-optic sensors, since they have a number of advantages: small size, flexibility, heat resistance, ease of implementation in multilayer composites, the ability to integrate into a single development network.

The Sandia National Laboratories in collaboration with Structural Monitoring System, Sykorsky, Boeing, AEM, Acellent and others, which use fiber-optic sensors and strain gauges as sensors, are implementing systems for monitoring the state of structures in carbon fiber reinforced plastic (CFRP) [4]. Sandia National Laboratories are embedding sensors in commercial aircraft to detect incipient defects since 2001, in mining equipment since 2005, and since 2016 are embedding fiber lines to US bridges to detect cracks, corrosion, and structural health monitoring. However, Sandia National Laboratories are currently using Acellent technology for embedded monitoring. Acellent has developed a monitoring system based on strain gauges imprinted in plastic. This technology makes it possible to protect sensors at the stage of implementation,
however, the issue related to the location of sensors in structures made of carbon fiber reinforced plastic (CFRP) remains open (due to the increased temperatures of molding products).

As part of the implementation of the state assignment «Development of a system for monitoring the state of structures made of polymer composite materials for modern aircraft engines based on built-in fiber-optic sensors», the team of PNRPU developed a prototype of a system for monitoring the state of a structure, which includes: the object of monitoring; fiber-optic sensors (FOS); interrogator required to obtain data on the deformation of the monitoring object; software that processes data from FOS. When the developed monitoring system was introduced into the outlet guide vane by radiation methods of non-destructive testing, it was found that the fiber lines change their location relative to the initial one during the molding process. This is due to the fact that the vane pen is curvilinear and different in thickness, and during the molding process, due to the movement of the resin, the fiber-optic lines are displaced (Figure 1). It should be noted that the introduction of FOS into the structure was difficult due to the fragility of the fiber during the insertion process, as a result of which one of the ends of the fiber lines broke off.

![Figure 1. Initial FOS placement (a), FOS placement after forming mode (b).](image)

Thus, it was established that it is necessary to control the location and protection of fiber sensors when introduced into a CFRP structure. When solving the described problems, prototypes of Smart-layers of various configurations were created, which make it possible to protect the optical fiber and outputs during the laying of the fiber into the structure. Within the framework of this work, the question of the location of the Smart-layer with fiber lines after the mode of forming the structure from CFRP was investigated. A plate with the curvature of the corresponding outlet guide vane was chosen as the object of research.

2. Making a curved plate

To conduct research to identify the location of fiber lines in the CFRP, two Smart-layers were made. The first configuration included a polyurethane-based Smart layer (melting point 200 °C) into which a fiber line was embedded. The second layer consisted of polyamide (with a melting point of 220 °C). When choosing materials, it was taken into account that the molding temperature of CFRP structures is 180 °C, therefore, the material from which the Smart layer is made should have a melting point above this mark.

It should be noted that at this stage, the Smart layer manufacturing technology has a significant drawback - the displacement of the optical fiber relative to the central position inside the layer, which is associated with insufficient tension and fixation of the fiber during the formation of the layer. Insufficient tension and fixation of the fiber in the tooling contribute to the longitudinal displacement of the fiber during the movement of the melt (in the case of using polyamide and polyurethane) during the formation of the layer,
which leads to a wave-like deformation of the optical fiber. It is planned to solve this problem by modifying the technological equipment, a system of pre-tensioning of the fiber-optic line.

A curved plate with a curvature corresponding to the feather outlet guide vane was made of carbon fiber on the basis of a unique scientific installation «research complex for scientific and technological research in the field of creating products from polymer composite materials». At the manufacturing stage, Smart-layers were laid between layers 5 and 6, as shown in Figure 2a. Such stacking of Smart-layers is justified by the area of greatest curvature, in which the maximum displacement of fiber lines in the vane was recorded. The plate after the forming mode is shown in Figure 2b.

![Figure 2](image1.png)

**Figure 2.** Making a curved plate: (a) - embedding Smart-layers, (b) - plate after the molding mode.

The next stage of the study was to conduct radiation non-destructive testing in order to identify the location of fiber lines after the forming mode.

### 3. X-ray non-destructive testing

Radiation non-destructive testing was carried out on a portable microfocus X-ray unit. The X-ray source is made in a monoblock design with a focal spot size not exceeding 50 microns. A flat-panel indirect conversion detector with a pixel size of 140 μm was used as an X-ray image detector. The detector consists of a matrix of thin-film transistors and a scintillator (phosphor) layer based on cesium iodide with a thickness of 500 μm. Figure 3 shows a general view of the X-ray unit with the investigated curved plate.

![Figure 3](image2.png)

**Figure 3.** General view of the X-ray unit with the studied plate.
Figure 4 shows an X-ray image of the investigated curved plate with embedded Smart layers.

Thus, in the course of X-ray non-destructive testing, it was found that the developed Smart layers make it possible to solve issues related to the location of optical fibers when they are introduced into a curved structure directly in the Smart layer. It should be noted that the displacement of the optical fiber relative to the central position inside the layer is associated with insufficient tension and fixation of the fiber during the formation of the layer, which will be eliminated in the near future.

4. Reference
As part of the study, Smart-layers were manufactured and embedded in a CFRP sample, radiation non-destructive testing of a curved CFRP plate with embedded fiber optic sensors, with a curvature that corresponds to the outlet guide vane pen, was carried out. Within the framework of radiation monitoring, it was found that the embedded Smart layers do not change their position relative to the original packing in a curved plate. The next stage of the study is the refinement and implementation of the Smart-layer directly into the outlet guide vane structure made of CFRP.

Thus, when introducing FOS into a structure, it is recommended to use Smart-layers, since they allow safe (without fiber damage) implementation and ensure the required location of sensors in the structure to control the area under study.

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