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Versions of Fiber-Optic Sensors for Monitoring the Technical Condition of Aircraft Structures

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Abstract

It is necessary to monitor the technical condition of various equipment due to the increased requirements for the safe operation of complex technical objects, such as bridges, structures, aircraft, cars and others. Monitoring systems based on the use of fiber-optic sensors measuring various physical quantities (temperature, deformation, pressure, vibration, etc.) are increasingly used for these purposes, since they have significant advantages over electrical sensors. The aim of the study is to compare the various options for the implementation of fiber-optic strain sensors to monitor the stress-strain state of the monitored object. A theoretical and experimental comparison of three types of fiber-optic sensors was carried out: on a mechanical fastener, sensors glued to the surface of a monitored design, and sensors embedded in a polymeric composite material at the stage of its manufacture. The requirements for the elements of the onboard systems of the aircraft according to the document “Environmental conditions and test procedures for airborne equipment QR-160D” are selected as comparison parameters. To assess the characteristics of various types of fiber-optic strain sensors, comparative bench mechanical and environmental tests were carried out. According to the test results, it was concluded that each type of sensor has its own advantages and disadvantages in comparison with each other, and in general, each of them can be used to create new standard systems for structural health monitoring of various units and structures of the aircraft (SHM systems). Also, the article proposed a new method of gluing a fiber-optic sensor to a controlled structure. This method - the use of specialized equipment, providing convenience and stability of gluing.

Keywords: Helicopter; HUMS; SHM; FBG; Fiber-Optic Deformation Sensor; Composite Material; Deformation.

1. Introduction

At the stage of testing the structures of the aircraft in order to determine their physico-mechanical characteristics, various methods of destructive and non-destructive testing are used, such as ultrasonic, acoustic, thermal, optical and other methods [1].

Measurements of individual parameters of the structure, such as stress-strain state, temperature, acoustic density of the material, changes in the linear dimensions of the structure and others, during the tests allow to determine the technical condition of the structure and assess the stability and susceptibility of the structure to external influencing factors (load, temperature, pressure, vibration, etc.). This information is necessary both when developing a new design and when confirming the characteristics of existing structures during their operation (qualification, type tests, etc.).

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1.1. Evaluation

The main idea of structural health monitoring (SHM) is to use Nondestructive Evalation and Testing (NDE / NDT) methods to study the state of the supporting structural elements for a long period of time, primarily to increase safety. The actual choice of components for an SHM system depends on the monitoring task and scope, as these aspects set the boundary conditions for what to track, at what level of accuracy and resolution over time, and so on. Although the overall goal of SHM is to track the structural state of a technical system, this information can be used in several different ways. The implementation of SHM technology differs depending on the application [2]. Thus, the book "Structural Health Monitoring (SHM) in Aerospace Structures" [3] presents various implementation options for SHM technology for monitoring the state of structures in the aerospace industry, which include contact and contactless methods for retrieving information about the state of a structure, and using various types of sensors, based on fiber optic, piezoelectric and flexoelectric technologies.

Currently, an example of SHM technologies are the HUMS (Health and Usage monitoring system) type systems used in helicopters. These systems are based on the use of vibration sensors to monitor the technical condition of the engine, transmission and gearboxes of the helicopter [4].

One of the options for monitoring the technical condition of highly loaded aircraft parts (for example, a helicopter) is a strain gauge control method that allow to determine the stress-strain state and the loads acting on the monitored parts. Using this control method, it becomes possible to estimate the residual life of the monitored structure and proceed to the operation of the aircraft on the actual state [5].

At present, electrical strain gauges and fiber optic strain gauges based on a Bragg grating (FBG) are used as sensors for measuring loads, [6]. It is worth noting that in order to use these types of sensors when creating a standard system for monitoring the technical condition of high-loaded parts as part of a helicopter, it is necessary to meet a number of technical requirements for sensors, including resistance to temperature, vibration and climatic influences, ensuring the maintainability of sensors.

Unlike electrical strain gauges, fiber optic sensors have several advantages, including:

- Absence of electromagnetic pickups.
- High sensitivity to the measured value.
- No restrictions on the length of the signal supply fiber-optic cable.
- Miniature sizes.
- Lack of electrical power to fiber-optic sensors.

The use of new measuring instruments in the composition of the aircraft (helicopter / aircraft), such as fiber-optic sensors, will allow to proceed to the operation according to the actual condition of individual machinery units due to the possibility of continuous monitoring.

In the article, various versions of fiber-optic strain sensors designed to measure the stress-strain state of an object were analyzed to assess the possibility of using fiber-optic sensors when creating new full-time monitoring systems for the technical condition of various aircraft units and structures. A new method of gluing a fiber-optic sensor to a controlled structure was also developed, consisting in the use of specialized tooling providing convenience and stability of gluing.

2. Research Methodology

The following activities were carried out to conduct research in this area:

- Review and analysis of existing fiber-optic strain sensors used to monitor the stress-strain state of aerospace engineering designs.
- Analysis of the technical requirements for the sensors used in the composition of the standard SHM systems in the aerospace industry.
- Carrying out comparative tests of various versions of the implementation of fiber-optic strain sensors.
- Analysis of the results for compliance with the sensors to their technical requirements.

2.1. Options for Fiber Optic Sensors

Fiber optic deformation sensor based on FBG is a section of optical fiber with a periodic structure of a change in the refractive index applied [7]. The outer diameter of the sensor is about 250 μm with a length of 5-10 mm. The principle of fiber optic deformation sensor is based on the reflection of a narrowband part of the optical spectrum when optical radiation passes through it from a broadband light source. At the same time, the central wavelength of the reflected narrow-band part of the optical spectrum, the so-called Bragg wavelength, depends on external factors, such as temperature and deformation, acting on the sensitive part of the sensor (Figure 1).

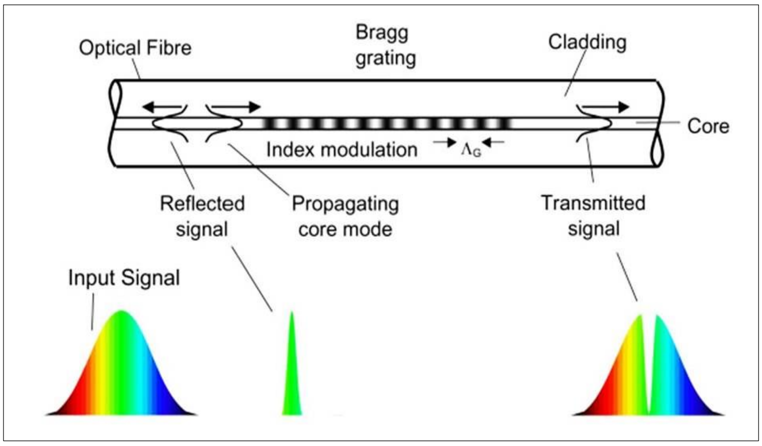


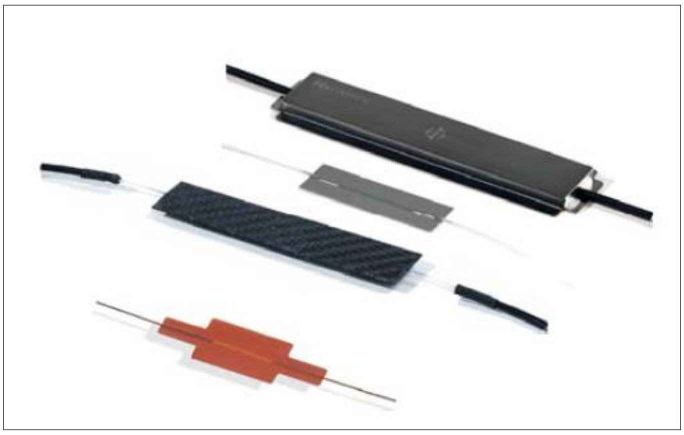
Figure 1. The principle of signal registration with FBG

By controlling the change in the central Bragg wavelength, it is possible to measure the parameters of deformation and temperature. There are several options for installing fiber optic deformation sensor on a controlled object, including gluing the sensor to the surface of the part, inserting the sensors into the controlled structure at the manufacturing stage (for structures made of polymer composite material) and mechanically fixing the sensors to the part to be controlled.

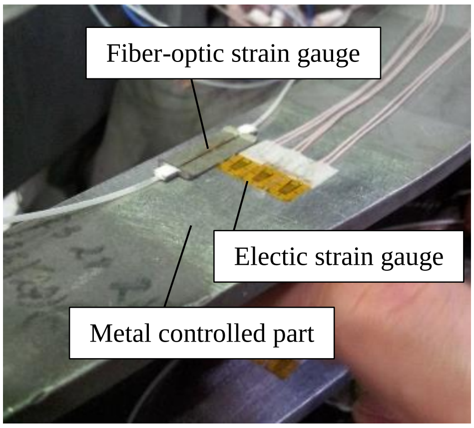
2.1.1. Bonded Fiber Optic Sensor

In the case of gluing, fiber optic deformation sensor can be performed in two versions:

- In the form of a protective substrate with glued or embedded FBG (Figure 2).
- In the form of optical fiber with FBG, which is directly glued to the part being monitored.



A)



B)

Figure 2. A) The appearance of various fiber optic deformation sensor in the form of a protective substrate with glued or embedded FBG on the example of sensors from Smartec, Switzerland. B) Gluing on the tested part fiber optic deformation sensor in the form of a protective substrate.

In the case of fiber optic deformation sensor in the form of a protective substrate with glued or embedded FBG, the sensors are glued on by applying an adhesive layer on the surface of the sensor substrate and the part with their subsequent contact with the pressure necessary for gluing.

In the case of fiber optic deformation sensor in the form of an optical fiber with FBG, which is directly attached to the monitored part, to ensure the technological installation of the sensors, it is possible to use specialized equipment that allows fixing the optical fiber relative to the part at the moment of gluing and providing the necessary pressure and shape of the adhesive layer. A variant of such equipment is presented in Figure 3 (A, B), developed at "Institute for the Development of Research, Design and Transfer of Technologies". In this case, the adhesive is introduced into the FBG contact zone with the surface of the tested part through the holes in the tooling. After curing of the glue, the equipment is removed, and the glued optical fiber with FBG with a protective adhesive layer against mechanical effects remains on the part (Figure 3C). This method of gluing a fiber-optic sensor to a monitored design ensures the convenience and stability of gluing.

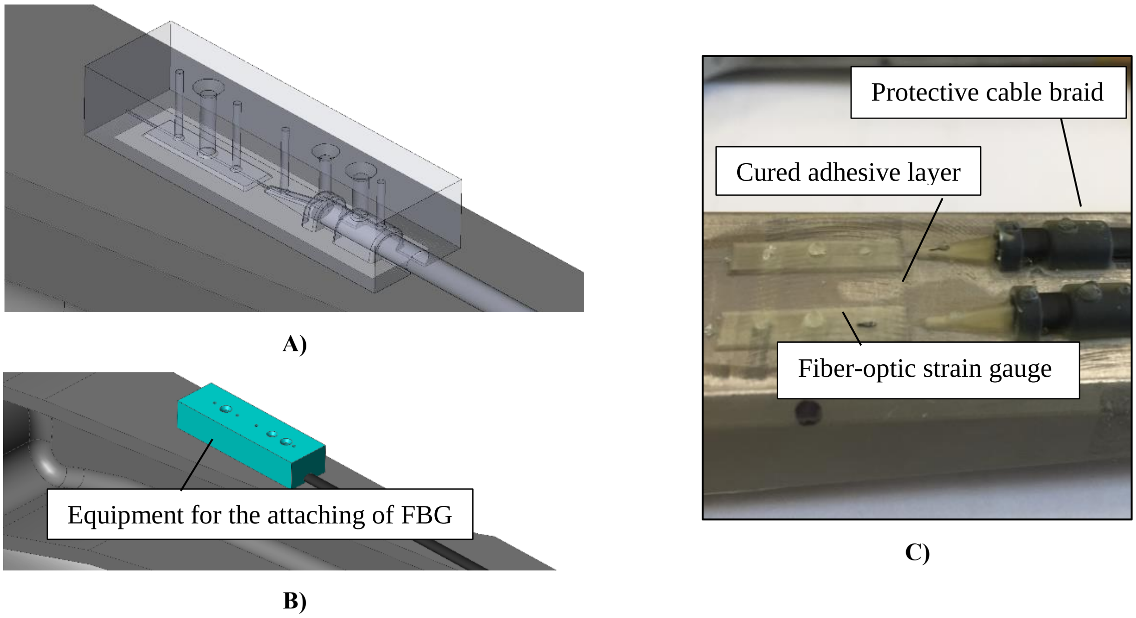


Figure 3. Gluing fiber optic deformation sensor in the form of optical fiber with FBG, which is directly glued to the part being monitored [A, B) specialized equipment for gluing; C) sensor appearance after gluing]

If we compare two types of bonded fiber optic deformation sensors, the sensor in the form of optical fiber with FBG, which is directly glued to the part being monitored, has a greater range of measurement of deformations than the sensor in the form of a protective substrate with glued or embedded FBG, provided that the same adhesive is used . This is due to the fact that the protective substrate has greater rigidity than the glued optical fiber, and thus large shear and tear stresses act in the adhesive layer.

Different types of adhesive compositions can be used for gluing fiber optic deformation sensors depending on the conditions of their further use, such as the range of measuring the deformation, the temperature working range, the type of external environment (aggressive / non-aggressive), etc. For example, cyanoacrylate-based glue is often used to measure deformations in a dry environment, which is easy to apply to an object and requires a minimum amount of time to completely cure it. In open air conditions (direct precipitation of glue on external glue), it is advisable to use epoxy glue, which is distinguished by a relatively long curing time (about 1 day), but is resistant to aggressive external environment.

2.1.2. Embedded Fiber Optic Sensor

To control the deformation parameters of parts of various types of equipment made of polymer composite material (PCM), it is advisable to use the structures embedded in the structure between the PCM and fiber optic deformation sensor at the production stage of the design [8]. In this case, fiber optic deformation sensor is a section of optical fiber with applied FBG with a diameter of up to 250 µm, which is comparable with the thickness of the PCM monolayer.

Additional sensor protection is not required with this fiber optic sensor installation method, since the sensor is in the material and the design itself is a protective element (Figure 4). The disadvantage of this installation method is the inability to repair a failed sensor, therefore, when designing a PCM design with embedded fiber optic sensor, it is necessary to take into account at least duplication of sensors installed at one point.

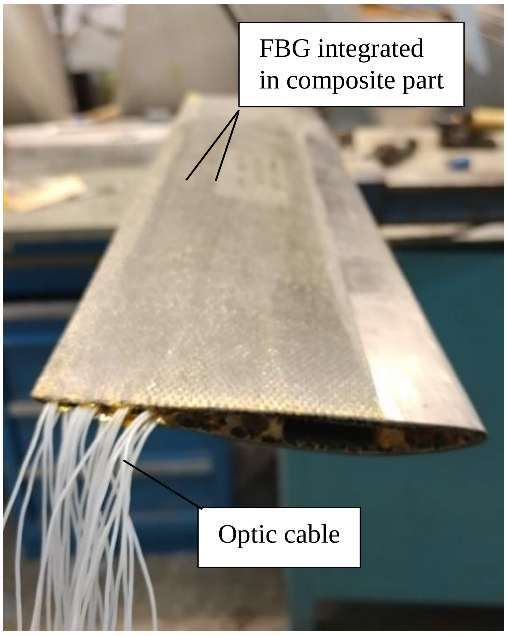
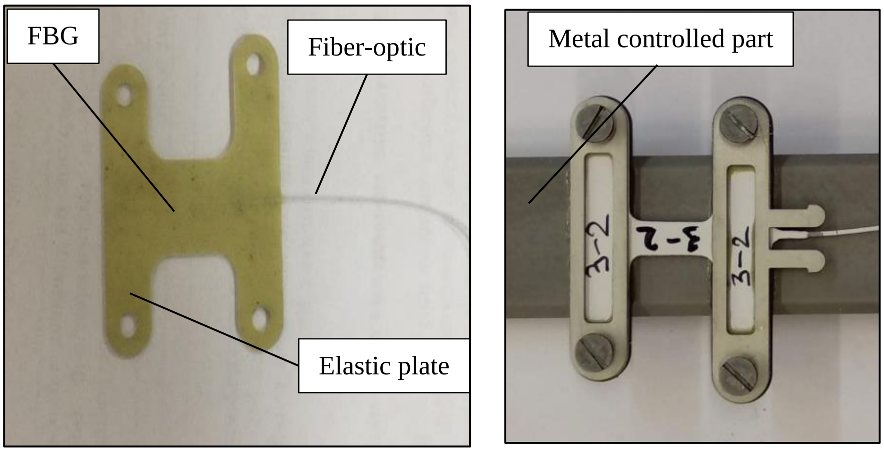


Figure 4. PCM helicopter rotor blade with integrated Fiber-optic deformation sensor

2.1.3. Fiber Optic Sensor on a Mechanical Mount

Fiber optic deformat sensor on a mechanical fastener may be an elastic element made of metal or PCM, with the FBG sensor installed, and having mounting places in the form of holes (Figure 5 A). To install this type of sensor, it is necessary to fasten with screws the sensitive elastic plate on the part being monitored, which has counter seats in the form of holes (Figure 5 B).



A) **B)**

Figure 5. The appearance of the fiber optic deformation sensor on a mechanical fastener; [A) is the elastic plate of the PCM with the embedded FBG sensitive element, B) Fixed fiber optic deformation sensor on the part]

This sensor design is easy to maintain and can be repaired.

3. Analysis of the Technical Requirements for Sensors Used in the Composition of the Standard SHM Systems in the Aerospace Industry

The following basic technical requirements are imposed according to the qualification requirements (Environmental conditions and test procedures for airborne equipment QR-160D) for typical sensors installed on high-loaded helicopter units:

- Deformation measurement range ± 3000 micron.
- Error of strain measurement no more than 5%.
- Sensor resource not less than 107 loading cycles.
- Working temperature range -60…+85 ^{o}C.

- Resistance to external vibrations.
- Resistance to external aggressive environment (salt fog, icing, etc.).
- Installation of fiber-optic strain sensors on a controlled part without additional machining of its surface.

3.1. Conducting Bench Tests of Fiber-Optic Strain Sensors of Various Designs

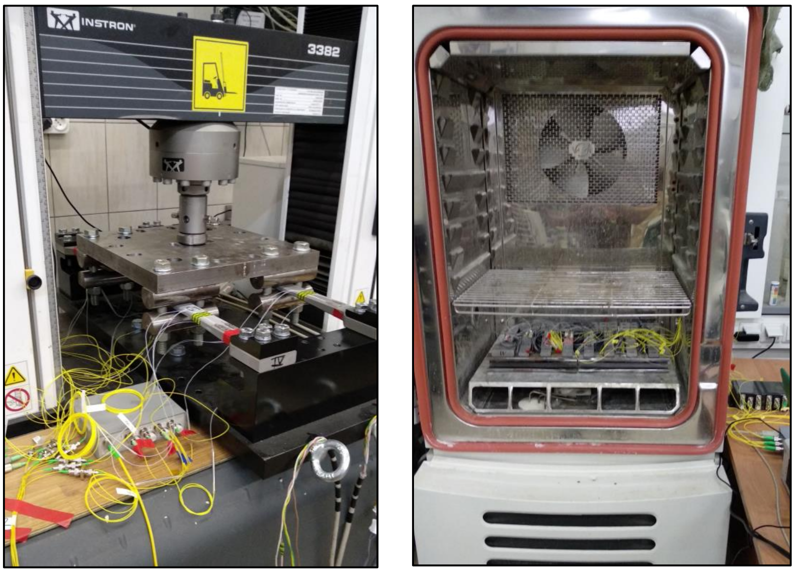
Based on the analysis of the technical requirements for sensors used as part of the standard SHM systems in the aerospace industry, a program and methods for bench testing of 3 types of fiber-optic deformation sensors were developed.

3.1.1. Test Methods

Methods for comparative bench testing of fiber-optic strain sensors include the following algorithm of actions:

1. Carrying out mechanical tests of sensors installed on parts according to the cantilever bending scheme (Figures 6A and 7B) in the range of changes in the relative deformations of the part ± 3000 μstr. With this test, the metrological characteristics of the sensors in comparison with the strain gage sensors installed next to the fiber-optic deformation sensors are evaluated.
2. Conducting temperature tests of fiber-optic deformation sensors installed on the parts in the chamber in the temperature range -60 ... + 85 ºC, Figures 6B, 7A. This test also evaluates the effect of temperature on the sensor mount.
3. Vibration testing of fiber-optic strain sensors mounted on the parts, with fastening on the vibrating stand. This test evaluates, among other things, the effect of vibration on the sensor mount.
4. Testing of fiber-optic strain sensors installed on the parts in the salt fog chamber. This test evaluates, among other things, the effect of salt fog on the mount and sensor.
5. Carrying out mechanical tests for cyclic bending of fiber-optic strain gauges installed on the parts in order to assess the resource indicators of the sensor.

For all types of tests, a spectral method was used to record data from fiber-optic deformation sensors using an interrogator manufactured by Institute for the Development of Research, Design and Transfer of Technologies.



A) B)

Figure 6. Testing of fiber optic deformation sensors of various designs [A) Mechanical tests; B) Temperature tests]

3.2. Analysis of Test Results of Fiber-Optic Strain Sensors of Various Designs

According to the results of the tests, the operability of 3 types of fiber-optic strain sensors after exposure to external factors (mechanical loads, vibration, climatic influences) was evaluated. The operability of the sensors was confirmed by comparing their readings with the readings of electrical strain gauges installed side by side on the parts (electrical strain gauges did not pass climatic tests). An example of the comparison of readings is shown in Figure 8. If the readings of the sensors differed by more than 5%, then these fiber-optic strain sensors were considered inoperative.

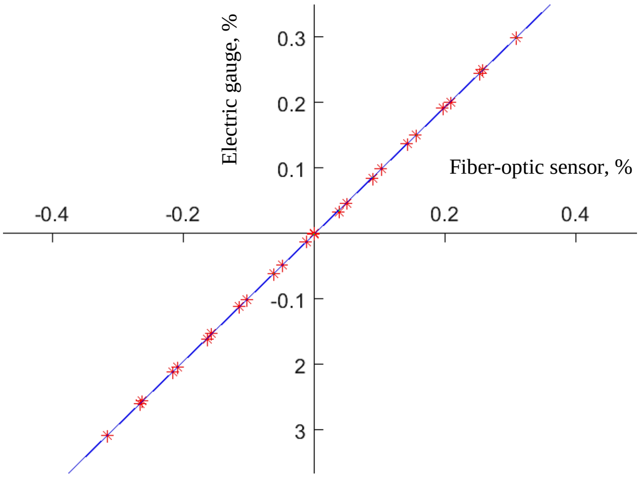


Figure 8. Comparison of indications of electrical strain gauges and fiber-optic strain gauges during mechanical testing (static bending)

According to the results obtained during the tests, the following conclusions can be drawn:

1) The range of strain measurement using embedded fiber optic sensor in a PCM part is comparable to the range of deformations of a PCM sample up to its destruction and is more than 10,000 micron.
2) Embedding the fiber optic deformation sensor in the structure and parts made of PCM does not affect the strength of the sample under study.
3) When choosing an adhesive for installation of the bonded fiber optic sensor, it is necessary to take into account the linear coefficients of temperature expansion of the sensor, adhesive and parts so that these values are as close as possible, since it is possible to peel the sensor when the external temperature changes cyclically.
4) To install the bonded fiber optic deformation sensor on a metal part, it is possible to use glue based on epoxy resins using the specialized tooling described in paragraph 2.1.
5) Fiber optic deformation sensors on the mechanical fastener may be used on parts that do not have counter seats in the form of holes. To do this, it is necessary to glue, for example, a metal plate with holes for attaching the sensor to the part being inspected. The measurement range of the sensor deformations in this case does not exceed ± 1700 micron.

According to the obtained test results, it can also be concluded that the fiber-optic strain sensor can be used as an element of the standard helicopter system for monitoring the technical condition of high-loaded parts using the example of non-rotating elements of the swashplate as it meets the qualification requirements.

In addition, a fiber-optic strain sensor can be used to monitor the technical condition of parts and structures of various other types of equipment and structures, for example, the power elements of bridges, the power elements of wind turbines, pipelines, etc. [9].

4. Conclusion

This article discusses various versions of fiber-optic strain sensors for monitoring the stress-strain state of the object being monitored, among which 3 main types can be distinguished: glued fiber optic deformation sensor, embedded fiber optic deformation sensor in the PCM part and fiber optic deformation sensor on mechanical fastening. Each of these types of sensors has its own installation features that affect the final characteristics of the sensor. A new method of gluing a fiber-optic sensor to a controlled structure is proposed. This method is the use of specialized equipment, providing convenience and stability of gluing.

According to the results of the qualification tests of the fiber optic deformation sensor according to QR-160D, it can be concluded that the sensor can be used as an element of the standard helicopter system for monitoring the technical condition of high-loaded parts using the example of non-rotating elements of the swashplate.

5. Funding

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6. Conflict of Interest

The authors declare no conflict of interest.

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