Sensitivity Analysis of Adaptive Holographic Fiber-Optic Acoustic Emission Sensors during the Registration of Acoustic Waves In a Plate

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Abstract. Paper presents the results of studying the features of recording acoustic emission waves by fiber-optic sensors. Fiber-optic sensors are used as an elastic medium that receives acoustic emission waves. Optical fibers were built between the layers of the polymer composite material during the manufacturing process. The measuring system is constructed on the basis of an adaptive interferometer. Optical fibers are part of the interferometer optical scheme. The elastic wave acting on an optical fiber changes its optical density, changing the interference pattern of the optical beam. The work of the holographic interferometer based on the fact that the interference pattern, formed by the object and reference light beams, is a dynamic hologram that is constantly recorded in the photorefractive crystal during the elastic action on the fiber. Sensitivity of fiber-optic sensors based on an adaptive interferometer allows recording acoustic emission waves. The acoustic emission waves were generated by the Hsu-Nielsen source. A significant difference in the speed of sound is explained by the anisotropy of the properties of the composite material. The structure and density of the material’s fibers in different directions are different. The wavelet transformation was used to form the signal front.

1. Introduction

The monitor of the status of highly assemblies and parts in the offline mode in air transport abroad have applied a monitoring system that allows you to get information from embedded sensors after the flight [1, 2]. Monitoring of the structural condition (Structural Health Monitoring) is carried out by collecting information from the permanently installed or built-in sensors. The most widely used of acoustic emission sensors, fiber optic sensors (Bragg grating), registrars Lamb waves, acoustic ultrasonic sensors [3]. However, piezoelectric sensors AE have low noise immunity and high linearity performance. Therefore, a wide use in embedded control aircraft structures have not received. Fiber Bragg grating sensors are used to record the performance static and dynamic loads [4-5]. Embedded fiber optic Bragg...
Grating sensors have. However, like strain gauges, these sensors are not sufficiently sensitive to microscratch, and are useful for the control of loads in their locations. Registrars Lamb waves and ultrasonic acoustic sensors mainly designed for remote or local determination of residual thickness of the material and do not carry information about the deformation and damage in materials. These drawbacks are the lack of reliable sensors and criteria for evaluating the structural state of PTP points to the relevance of the scientific direction and development of high-sensitivity and noise immunity of the sensors and registration systems in the overall damage of composite materials. The project aims to develop a multi-channel acoustic emission system with distributed ultrahigh optical fiber sensors and methods of built-in control and monitoring of developing defects and damages in fiber composite materials [6]. The high sensitivity of the measurement system based on fiber-optic sensors over the full dynamic range of the measured fluctuations can be obtained by the implementation of two main approaches: by providing accurate matching of the wave fronts of the reference and object light beams in an interferometer, and by providing a quadrature condition for maintaining the required phase difference between interfering waves. This was achieved by using holographic principles of adaptive interferometers, allows you to combine the wave with absolutely different and thus arbitrarily complex wavefronts. This was made possible with the development of measurement systems based on multiwavelength light beams interactions on dynamic diffusion holograms formed in photorefractive crystals. The possibility of using AE systems to determine the residual life of the structure is based on the implemented authors approach developed for polycrystalline materials. The approach uses data analysis activities of different types of AE sources to determine the stage of deformation under static loading and stages of fatigue damage accumulation under cyclic loading [7-9]. Approaches to the development of criteria for the division of AE sources for polycrystalline materials proved to be applicable to composite materials. Studies have shown the ability to source separation fracture of fibers and a polymer matrix based on wavelet analysis of AE signals localized in time wavelet spectrum [10-12]. Preliminary experimental study allowed us to estimate the sensitivity of the sensors, made in the form of optical fibers embedded in a composite matrix produced by vacuum infusion (check method of manufacture of samples) of the FRP sheet. The sensitivity of the optical fiber sensors proved to be comparable to broadband piezoelectric sensors. High linearity of the characteristics of fiber-optic sensors in a wide frequency range, distinguishing them from piezoelectric sensors, allows the analysis of AE signal parameters without taking into account the frequency response of the sensors. To solve the set tasks, it is necessary to conduct comprehensive studies of the features of the propagation of ultrasonic waves and damage accumulation in the PCM, to establish a relationship between the nature of the accumulated damage and the residual life of the structure.

2. Materials and Methods

The research consisted of several stages:
- preparation of samples of metal plates for studying the registration of AE waves propagating in the plates and fixing optical fibers on the plates,
- assembly of optical and electronic circuits of adaptive interferometers for their inclusion in the composition of fiber-optic acoustic emission sensors,
- setting the operating parameters of the AE signal registration system with fiber optic sensors,
- registration of AE signals by fiber-optic sensors upon excitation of acoustic waves in the plate and their analysis.

For research, we used the scheme developed by the authors in the process of implementing the project of an adaptive interferometer based on a photorefractive crystal. Multimode quartz fibers of the MM-0.125 type without a protective polymer sheath were used as sensitive elements of fiber-optic AE sensors. Diameter of optical fibers without a protective shell with an outer protective lacquer layer is 0.2 mm and the thickness of the quartz fiber itself is 0.125 mm. The interferometer circuit was assembled on a laboratory optical table (Fig. 1). The scheme included a highly stable single-mode diode-pumped emitting laser with a power stability of <1% after 4 hours of operation and a coherent radiation length of 50 m. Such high laser requirements are necessary when using a high sensitivity interferometer.
Two types of lasers were used in the study: at a wavelength of radiation in the infrared range of 1064 nm and at a wavelength of radiation in the visible range of 532 nm. To detect the light flux at the output of the interferometer, silicon (Si) or indium-arsenide-gallium (InGaAs) photodiodes and photodetectors based on them can be used. The level of their sensitivity to radiation at a wavelength of 1064 nm does not exceed 0.3 of the maximum level in the entire range of sensitivity characteristics. Silicon photodetectors require their placement in insulated boxes to reduce the influence of visible light on the photodetector sensitive element.

![Figure 1. Schematic of tensile specimen and AE sensor.](image)

For 1064 nm radiation, InGaAs PDA10CS-EC photodetectors were used with a radiation sensitivity range of 900-1700 nm and a frequency band of up to 17 MHz. For 532 nm radiation, PDA36A-EC Si photodetectors were used with a radiation sensitivity range of 350-1100 nm and a frequency band of up to 10 MHz. For an adaptive interferometer operating at a wavelength of 532 nm, a photorefractive bismuth silicate (Bi$_{12}$SiO$_{20}$) crystal was used. One of the important parameters of an adaptive interferometer is the cutoff frequency, which is inversely proportional to the recording time of the hologram in the crystal. For the selected crystal sample and radiation wavelength, the recording time is inversely proportional to the radiation intensity. However, an increase in the radiation intensity leads to heating of the crystal and is thus limited. The cutoff frequency of the Bi$_{12}$SiO$_{20}$ crystal is 0.1–10 Hz, and that of the CdTe crystal is 10–1000 Hz. The use of photorefractive crystals with a low cutoff frequency limits its use in suppressing external mechanical and low frequency temperature noises. The signals from the photodetector were recorded with a Rhode & Schwarz RTB2004 digital oscilloscope.

The studies were carried out on a rectangular plate of duralumin D16 with dimensions of 500 mm × 600 mm × 2 mm. Optical fibers without a shell were glued to the surface of the plate with an arrangement along the longest side of 600 mm. Optical fibers were placed on the test plate at distances of 125 mm, 250 mm, and 375 mm from the edge (Fig. 2). Thus, the arrangement of the fibers made it possible to register AE sources remote from the optical fibers, as well as to analyze the influence of the side walls of the AE signal plate.

Preliminary tests showed that there were significant differences between AE signals recorded by fiber-optic sensors with the output of fibers at the edges of the plate and fixed with a slight indentation. The influence was exerted only by the length of the fixed area. As a result, all subsequent studies were
performed with the indentation of the region of attachment of optical fibers to the plate of 50 mm from each edge. The use of several optical fibers made it possible to simultaneously record AE signals by various adaptive interferometers with a laser wavelength of 532 nm and 1064 nm. An adaptive laser interferometer operating at a wavelength of 532 nm was assembled on a mobile optical table and operated simultaneously with an interferometer operating at a wavelength of 1064 nm. The source of AE waves during registration of waves in the plate was a Hsu-Nielsen source, which is a kink of a pencil lead 0.5 mm in diameter with a hardness 2H.

![Test plate with optical fibers placed on it.](image)

**Figure 2.** Test plate with optical fibers placed on it.

### 3. Results and Discussion

The uniqueness of this AE wave simulator is that it provides a single pulse like a local laser pulse action of certain duration. From the point of point contact, an acoustic wave propagates radially across the plate. When analyzing the recorded signals, the shape, amplitude of the wave, the Fourier spectrum and the wavelet spectrum were estimated. The calculation of the spectral components of the signals was performed using the engineering mathematical package Matlab. For the convenience of mathematical processing, an interactive form-interface was created for loading, processing and analyzing signals (Fig. 3).
With a local location of the sensor on the plate at each point of the plate, a Lamb wave can be registered, which is a combination of symmetric and antisymmetric waves that form in the plate due to the dispersion of sound velocity. The speed of a sound wave is disproportionately small in comparison with the speed of light radiation passing through an optical fiber. Therefore, vibrational perturbations of the surface of the plate on which the optical fibers are glued provide a superposition of acoustic waves along the entire fiber at any time.

For AE waves detected by a fiber-optic sensor operating at a laser wavelength of 1064 nm, a high degree of repeatability of AE signals with a correlation coefficient of 0.65-0.7 is observed. Figure 4 illustrates AE signals recorded by a fiber optic sensor at a distance of 375 mm from the Hsu-Nielsen excitation source. The source was located on the edge of the plate farthest from the optical fiber of the sensor. The wave excited at the edge of the plate practically did not experience reflection from its edges until the shortest distance to the optical fiber of the sensor passed. The main range of the Fourier spectrum of the signal is located up to 30 kHz (Fig. 3). The wavelet signal spectrum is also highly repeatable.
When registering the waves with a fiber-optic sensor operating at a wavelength of laser radiation of 532 nm, an increase in the amplitude of signals and the magnitude of the Fourier spectrum was noted in comparison with signals recorded by sensors at a wavelength of 1064 nm. As studies have shown, this is due to the following reasons. The modulation depth in the optical system on a photorefractive bismuth silicate (Bi$_{12}$SiO$_{20}$) crystal was 0.5, when, as for a sensor based on a CdTe crystal, the modulation depth did not exceed 0.1. The second reason is related to the previously noted difference between the time period of the phase delay, which provides the maximum change in the intensity of interference radiation for emissions of 532 nm and 1064 nm. The third reason is associated with a lower cut-off frequency of the photorefractive crystal, which provides less suppression of low-frequency waves. This is a negative sign when using sensors in AE systems. In the operation of the optical system, an important role is played by adjusting the initial position of the working point of the adaptive interferometer. The operating point was adjusted to the maximum radiation intensity at the detector by changing the phase shift of the object beam relative to the reference. The recording time of a hologram in a photorefractive crystal, and, accordingly, the frequency cutoff value, depends on the radiation intensity. An increase in intensity could be achieved in two ways: by increasing the power of laser radiation or by reducing the size of a light beam passing through a photorefractive crystal due to focusing. The first method has limitations on the maximum radiation intensity, which ensures the operation of the crystal without significant heating, when the released heat has time to dissipate. A decrease in the transverse dimensions of light beams due to focusing leads to a decrease in the effective length of their interaction in the crystal due to the discrepancy. In order to increase the interaction length of the object and reference laser beams in the crystal, a cylindrical lens with a focal length of 160 mm was used as the focusing optical scheme. The location of the focusing lenses, which ensure the intersection of the object and reference laser beams in the place of their maximum focusing, was selected.

At the third stage of work, studies were conducted aimed at a comparative analysis of AE signals recorded by fiber optic and piezoelectric sensors. For this, piezoelectric sensors were located on the surface of the plate in the places where optical fibers were fixed directly near the fiber or on the back of the plate in the middle of the optical fiber. AE sources were excited on the surface of the plate along a line running perpendicular to the fibers and dividing them into two equal sections. Thus, the equality of the distances of the piezoelectric transducer from the edges of the plate was ensured for the localization and separation of the group wave components reflected from the edges of the plate. The imitation of various types of defects was set by the destruction of a pencil of various hardness. The pencil hardness in this case is a function of the defect development rate at a constant crack opening area.

The analysis of the parameters of the recorded AE signals, spectral Fourier analysis and the wavelet analysis of the AE signals were performed, which made it possible to reveal the dependence of the
parameters of the recorded signals on the distance and hardness of the destroyed simulator. When analyzing the signals, an analysis of the components of the group wave was performed. When analyzing signals and extracting wave components, the mathematical apparatus of the engineering package Matlab was used.

The last stage of work included the development of modules and a system for registering AE signals with fiber-optic sensors. This stage will be carried out throughout the project and was a continuation of the work of the previous reporting period. At this stage of research, the development and manufacture of an analog-to-digital AE signal registration module was completed, test software with a user interface was created that allows you to configure the parameters of AE signal registration by sensors, select connected sensors (fiber-optic, piezoelectric) that ensure matching of signals with input parameters of the analog-to-digital module, triggering the registration of AE signals, displaying the recorded signals in the oscilloscope mode, the ability to save the recorded signals.

4. Conclusion
As a result, it was found that a system based on an adaptive interferometer can provide registration of acoustic emission signals. Optical fibers have a natural resemblance to glass and carbon fibers used in the manufacture of polymer composite materials. The sensitivity of fiber-optic sensors allows you to register signals in them at frequencies corresponding to Lamb waves. Further studies are supposed to increase the sensitivity of interferometers and to establish the effect of optical fibers embedded in polymer composite materials on the change in their mechanical properties.

5. References
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