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The Sensitivity Investigation of Fiber Optic Paths in the Framework of an Intruder Localization at a Protected Facility

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Abstract: *The paper considers the possibility of using communication lines already existing at urban development sites based on such information transfer technologies as «fiber-to-the-office» and «fiber-to-the-desk» in relation to the tasks of physical protection of objects. The aspects of using distributed acoustic sensors based on a phase-sensitive optical time-domain reflectometer for localizing sources of acoustic impact in real-time, that is, for determining the location of an intruder on a protected object, are considered. The sensitivity of optical paths to acoustic influences corresponding to the speech signals of the alleged intruder was assessed. An optical path based on optical fiber in an optical module with a hydrophobic filling is considered. An analysis of the spectral sensitivity of the optical fiber samples under study has been carried out. An assessment of the influence of the conditions for the passage of the route of laying the optical cable and the interaction of the acoustic sensor with the surrounding objects was carried out. The analysis of the results obtained during the test events at the experimental site was carried out.*

Keywords: *optical fiber, distributed acoustic sensor, optical reflectometer, intruder, acousto-optics*

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Исследование чувствительности оптических волокон в контексте локализации злоумышленника в защищенном помещении

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Аннотация: *В статье рассмотрена возможность использования уже существующих на объектах городской застройки линий связи на основе таких технологий передачи информации, как «волокно в офис» и «волокно до рабочего места» применительно к задачам физической защиты объектов. Изучены аспекты использования распределенных акустических датчиков на основе фазочувствительного оптического рефлектометра для локализации источников акустического воздействия в режиме реального времени, то есть для определения местоположения нарушителя на охраняемом объекте. Оценивалась чувствительность оптических трактов к акустическим воздействиям, соответствующим речевым сигналам предполагаемого нарушителя. Рассмотрен оптический тракт на основе оптического волокна в оптическом модуле с гидрофобным наполнением. Проведен анализ спектральной чувствительности исследуемых образцов оптических волокон. Представлена оценка влияния условий прохождения трассы прокладки оптического кабеля и взаимодействия акустического датчика с окружающими предметами. Приведен анализ результатов, полученных в ходе тестовых мероприятий на испытательном полигоне.*

Ключевые слова: *оптическое волокно, распределенный акустический датчик, оптический рефлектометр, злоумышленник, акусто-оптика.*

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Introduction

The development of the digital economy, which is based on the development of information networks, served as an impetus for the creation of a system of optical fibers spaced apart in space, laid at almost every modern facility. These systems provide new opportunities in terms of information security. In particular, it becomes possible not only to pick up audio information but also to determine the location of the sound source with given accuracy and subsequent identification of the sound source. For example, an attacker, observing a 3D model of a system of spaced-out objects, can determine which employees work in which rooms, track their daily routine, etc. From the object security point of view, video surveillance systems can be supplemented with audio monitoring systems and create complete 3D models of space, which is why it is advisable to develop models of distributed fiber-optic acoustic sensors spaced in 3D space. Until recently, wireless sensor networks (WSNs) were the most widely used to solve problems of determining the exact location [1–7]. However, WSNs do not have sufficient accuracy in determining the location of the sensor itself, which in turn affects the error in localizing the sound source [6, 7].

To solve the problem of determining with a given accuracy the location of an intruder at a protected facility, it was proposed to use the fiber-optic communication lines available at the facility with distributed acoustic sensors (DAS) installed on them [8–12]. One of the implementation methods was proposed by Gubareva O.Yu. and Burdin V.A. in patent RU2702983 [13]. Time Difference of Arrival (TDOA) systems built on the basis of DAS have a span in the distance between sensors of less than 1 m and a sensitivity of up to 90 dB [14–16]. It is worth considering that in addition to the desired source of acoustic impact, many other factors affect the sensor. For example, sources of extraneous noise, fluctuations of the medium in which the optical fiber is located, micro- and macro-bends, as well as compression and stretching of the optical fiber itself [17]. Today, almost all buildings have a network of fiber optic communication lines. Free optical fibers can be successfully used as a DAS to determine the location of a sound source, including an intruder. Based on the data obtained, it is proposed to build a digital 3D map of the object with an overlay on the video surveillance system to form adequate threat models. In addition, we can include the means of identifying and classifying information security threats existing at the facility for objects of various types and classes, as well as supplement user identification technology on the object.

After choosing the Algorithm of Simple Triangulation as the main method [18], the possibility of using communication lines already existing at urban development sites in relation to physical protection tasks was considered. For this, an experimental test site was prepared on the territory of the university.

Intruder Localization at a Protected Facility

The simple triangulation algorithm investigates the acoustic impact on a set of sensor points [19]. Separate elementary sections $x_i.x_{i+1}$ etc. are determined. The section length is equal to the DAS gauge length. An optical fiber is represented as a set of such elementary sections. Fig. 1 shows the impact on the elementary sections of the optical fiber by the sound source. Here r_0 is the shortest distance from the sound source to the fiber. It is assumed that the sound wave is incident perpendicularly.

Fig. 1 shows, that α_i is the acoustic beam incidence angle on the i-th elementary section of the optical fiber. Then its value can be defined as:

$$\alpha_i = \arccos\left(\frac{\phi_{i+1} - \phi_i}{k \cdot \Delta x}\right), \quad (1)$$

here ϕ is the phase obtained by analyzing the fiber backscattering characteristics, k is the wavenumber, Δx is the gauge length.

Knowing how the wave number and the speed of sound in air are calculated, we determine the shortest distance to the sound source:

$$x_{0i} = \frac{x_i \cdot \mathrm{tg}\alpha_i - x_{i+1} \cdot \mathrm{tg}\alpha_{i+1}}{\mathrm{tg}\alpha_i - \mathrm{tg}\alpha_{i+1}}, \quad (2)$$

$$r_{0i} = x_{0i} \cdot \mathrm{tg}\alpha_i. \quad (3)$$

For 3D space, the shortest distance from the optical fiber to the sound source will be determined by the formula:

$$r_0 = \sqrt{z_0^2 + y_0^2 + x_0^2}, \quad (4)$$

where z_0, y_0, x_0 and x_0 is the shortest distances to the sound source in Z, Y and X planes, accordingly.

One of the options for the location of the optical cable in the room to localize the sound source is shown in Fig. 2.

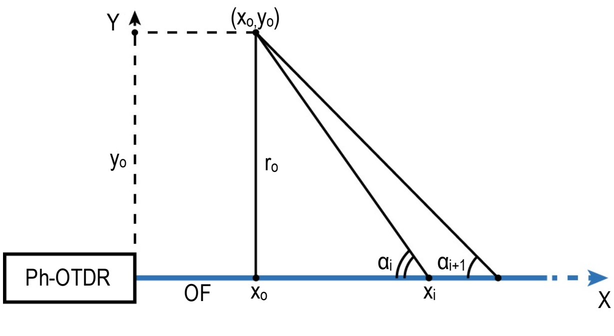

Fig. 1. Estimation of the Distance from the Optical Fiber to the Source of Acoustic Impact

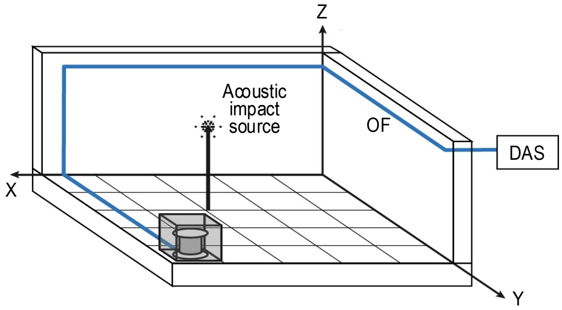

Fig. 2. Determining the Coordinates of the Sound Source

For each of the three axes of the optical fiber, we determine the corresponding values x_{01}, x_{02}, x_{03}. Then the sound source will be located on the plane as the intersection of three circles, the radii of which are equal to r_{01}, r_{02}, and r_{03}, accordingly. Next, we decompose the sound source into spectral characteristics and set the necessary conditions $\Delta\phi = \phi_{i+1} - \phi_i < 2\pi$, $k\Delta x < 2\pi$. All calculations are carried out only at low frequencies, cutting off parasitic noise and interference.

For typical DAS, the gauge length is in the range of 1.0–10 m [20, 21]. The response of the i-th segment of the DAS will be written as [22, 23]:

$$s_i(t) = \int_{x_{i,0}}^{x_{i,1}} \eta(x) \cdot \varepsilon(x,t)dx, \quad (5)$$

where $\varepsilon(x,t)$ is the optical fiber deformation equal to the ratio of fiber axial deformation Δl to fiber length l; $\eta(x)$ is the response factor. It depends on the cable laying conditions, cable design, the position of the optical fiber in the cable, etc.

In general, the coefficient $\eta(x)$ varies along the fiber optic cable. However, in the first approximation, within the construction length of the optical cable, it can be assumed to be constant.

Consider the case of a plane wave. If we confine ourselves to the analysis for the far zone (assuming that the conditions for such an assumption are satisfied), then the acoustic field of a point source acting on the optical fiber of the cable is described as [23]:

$$P(t,x) = \frac{P_0}{r}\exp[j(\omega t - kr)], \quad r = \sqrt{(z-z_0)^2 + (y-y_0)^2 + (x-x_0)^2}, \quad (6)$$

where x_0, y_0, z_0 are the coordinates of the source of acoustic signals, x, y, z are the coordinates of some point of the optical fiber, ω is the circular frequency, t is time, k is the wavenumber, P_0 is the amplitude of the acoustic signal at the output of the source.

Taking into account (5)–(6), the signal recorded by DAS from an optical fiber on an elementary section of the cable is described as:

$$P_C(t,x_i) = P_0 \times$$

$$\times \exp(j\omega t)\int_{x_{i,0}}^{x_{i,1}} \frac{\varepsilon(x,t)\eta(x)}{r}\exp(-jkr)dx. \qquad (7)$$

It should be taken into account that for the effective application of such algorithms, information is needed on the sensitivity of optical fibers in an optical cable to external vibro-acoustic influences, as well as the spectral dependences of their responses.

Experimental Studies

A room close to real operating conditions was equipped for testing. The dimensions of the room were 5×5×2 m. There were areas with furniture along the optical fiber and areas without it. That way we can assess the influence of parasitic objects on the propagation of sound within the room and on the accuracy of determining the coordinates of the sound source. The acoustic effect was in the frequency sweep mode in the range from 100 to 1900 Hz for 180 seconds. Measurements were made with a polling frequency of 5 kHz and a measuring base of 5 meters. The obtained characteristics were processed using the Fourier window transform. The spectral characteristics and their dependence on the level of the influencing signal were analyzed. One optical cable was used, located in a configuration (Fig. 3), where it was possible to characterize the distribution of the amplitude of the sound signal acting on the optical cable in three planes with a shifted center of coordinates, and also to compare the response to the acoustic signal source of two parallel sections of the fiber.

As we can see in Fig. 3, the optical paths, parallel with X and Y axes have a common center of coordinates, while the optical path, parallel with Z axis is offset by 3 meters. One end of the optical fiber is connected to the DAS, the other end of the optical fiber is located in a buffer coil, fixed in space and isolated from various sound influences. Since the principle of DAS operation is based on comparing the characteristics of backscattering between fiber sensors at a distance equal to the gauge length, the isolated part of the fiber did not introduce additional errors when analyzing the behavior of the amplitude and phase of the acoustic signal. Fig. 4 shows the spectral characteristics of the acoustic signal obtained with DAS.

Fig. 3. Testing Site Structure. The Nearest Wall is Hidden for Better Visibility

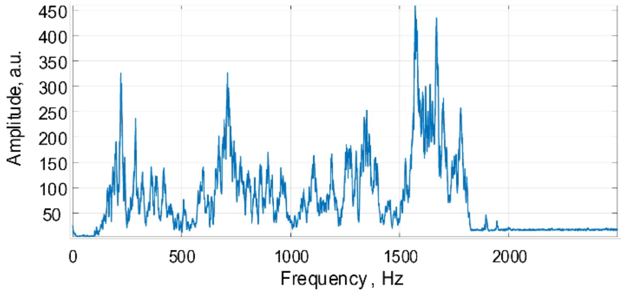

Fig. 4. Spectral Characteristics of the Acoustic Signal

As shown in Fig. 4, the maxima appear in the regions of 240, 650 and 1600 Hz. These ranges are typical for human speech and the sounds of object movement. The graph shown is the result of repeated testing under constant conditions. The constancy of the behavior of the maxima of the spectral components makes it possible to use them for statistical analysis.

Since in a real scenario the sound source (intruder) is not static in space, measurements were taken while moving the sound source. Fig. 5 shows the spectral characteristics of the acoustic signal. There is a homogeneity of the spectral characteristics obtained using DAS, which indicates the possibility of real-time acousto-optical analysis.

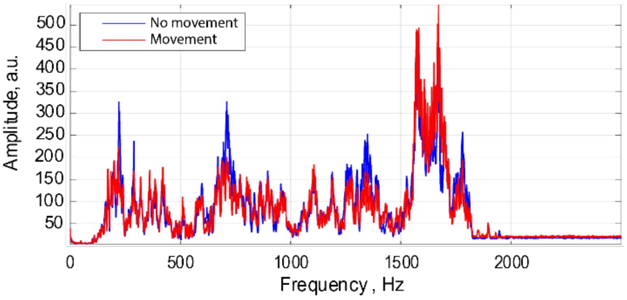

Fig. 5. Spectral Characteristics of the Acoustic Signal of a Source Moving in Space

It is also worth considering that measurements in real conditions can be carried out not from the point of the shortest distance from the fiber to the sound source, but from an array of fiber sensors in a particular room. Fig. 6 shows the results of the spectral analysis of the acoustic signal received from different points of the optical fiber on the test site. The characteristics of the amplitude distribution in three sections of the fiber were taken simultaneously, taking into account their mutual influence on each other.

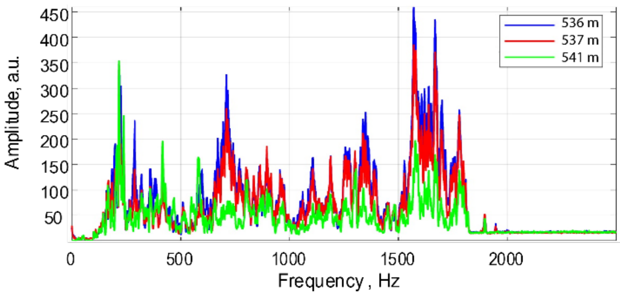

Fig. 6. Spectral Characteristics of the Acoustic Signal Obtained from Different Points of the DAS

The picture of the maxima is generally preserved, despite the presence of natural obstacles, the difference in distances from the sensor to the sound source, and the peculiarities of the location of the sensor itself.

In the course of the work, localization of the sound source was performed with the methods based on the amplitude and phase characteristics analysis of the acoustic signal spectral components. Fig. 7 shows the measurements of the ratio $P(t,x)/P_0$ amplitude distribution for the spectral component with a frequency of 240 Hz over time (with a step of 1 second) along the optical fiber. Fig. 8 shows a histogram of the values of the coordinate corresponding to the maximum of the spectral component. The approximation was made by the Gaussian function.

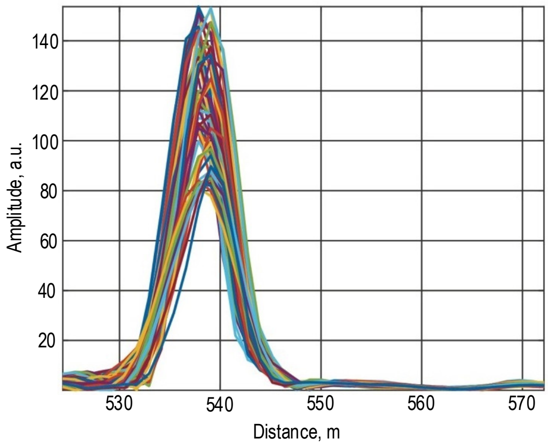

Fig. 7. Spectral Component Amplitude at a Frequency of 150 Hz, Time Variations with a Step of 1 Second

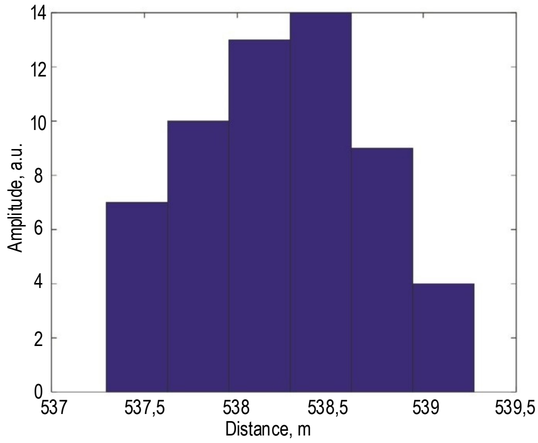

Fig. 8. Histogram of the Fiber Axis Coordinate Values Corresponding to the Spectral Component Maximum

The amplitude indicators of the spectral characteristics make it possible to judge the coordinate of the sound source on the axis of the optical fiber. The results obtained make it possible to use the simple triangulation algorithm for localizing a sound source in three-dimensional space in real time using DAS on the basis of communication lines already existing in urban areas, based on such information transmission technologies as "fiber-to-the-office" and "fiber-to-the-workplace".

Of great interest for further research are configurations with higher acoustic frequencies. Although low-frequency signal has a greater effect on DAS, it has a tangible effect on all surrounding objects leading to an increased proportion of parasitic influences on sensor.

Conclusion

During the experimental verification, the possibility of using DAS in the context of determining the location of the source of acoustic vibrations of different frequencies in space was established. The possibility of localizing the source of acoustic vibrations during its movement was proved. The possibility of source localization from different points of a DAS was shown. In addition, DAS can be used as an acoustic microphone. This will allow projecting onto the 3D map of the room not only the location of the source but also its soundtrack. Additional tests will introduce the classification and identification of sound sources. This will expand the understanding of the actions of a potential attacker in a protected area.

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