Algorithms for determining the location of an intruder using DAS in space

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Abstract—The paper considers algorithms for determining the location of a sound source created by an intruder using a system of distributed acoustic sensors in two and three-dimensional spaces.

Keywords— optical fiber, distributed acoustic sensor, phase-sensitive optical reflectometer, intruder, acousto-optics, localization.

1. Introduction

Today, the widespread use of fiber-optic communication lines has led to the development of such technologies as fiber to the building/home, office and workplace, replacing the electric cable in the user's near environment [1, 2]. In addition to communications, optical fiber (OF) is actively used in measuring instruments for security systems [3]. One of the main areas of use of OF in security systems is the use of optical interfaces to increase the communication bandwidth in video surveillance systems. OF is also successfully used in sensors and distributed measuring systems. Fiber optic cable system in the building becomes a distributed measuring network, which can be used to measure fields of various physical origins, including the acoustic field. Free fibers can be used as distributed acoustic sensors (DAS) to determine the location of a sound source, including that created by an intruder.

The algorithms for determining the location of the sound source (intruder) considered in the paper are based on the use of DAS. Such acoustic monitoring sensors include a phase-sensitive optical time-domain reflectometer (PH-OTDR), to which an OF is connected. DAS are characterized by high sensitivity and satisfactory resolution. It is a technology that uses the phenomenon of Rayleigh backscattering of light in an OF; external dynamic perturbations can be quantified and localized depending on the distance along the entire OF using appropriate interrogation schemes [4-9]. Due to continuous performance optimization, modern DAS systems are able to quantify and localize disturbances with centimeter-order spatial resolution and frequency resolution from 20 Hz to 2 kHz at distances up to 70 km [10-14].

2. Algorithms for determining the location of the intruder in space

In this paper, the authors considered three algorithms for localizing acoustic sources in 2-D and 3-D spaces.

A. Distributed acoustic source localization algorithm based on the array signal processing method

The Array signal processing (ASP) method uses spatial correlation to localize the sound source. The difference between the equivalent array of sensors and the array of point measurements, array aperture, and other parameters, cannot be neglected.

When building an array model, it is necessary to take into account the fact that the DAS detection channel differs from point sensors. The desired signal is determined by integrating acoustic signals in the spatial range along the sensitive fiber. Its level depends on the spatial phase difference between the two positions.

At the last stage, the spatial spectrum is estimated and the function of the spatial spectrum P_{MUSIC} (multiple signal classification – MUSIC) is calculated [15].

B. Method for determining the location of an intruder using DAS based on the algorithm of simple triangulation

With this method of determining the location of the acoustic impact source (intruder), it is assumed that the acoustic impact is on a set of sensor points [16]. Further, by analogy with the previous algorithm, the OF is represented as a set of separate elementary sections x_i, x_{i+1} etc., the length of which is equal to the DAS gauge length. For a more accurate picture of the intruder's location in space, it is necessary to use three spaced apart OFs (OF1, OF2, OF3) used as acoustic sensors connected in series to a PH-OTDR.

For a three-dimensional space, the shortest distance from the OF to the sound source will be determined by the formula:

$$r_0 = \sqrt{z_0^2 + x_0^2 + y_0^2}\ , \qquad (1)$$

where z_0 is the shortest distance to a sound source in the Z plane, y_0 is the shortest distance to a sound source in the Y plane, x_0 is the shortest distance to a sound source in the X plane. On the plane, the sound source (intruder) will be located at the intersection of three circles whose radii are equal to x_{01}, x_{02}, x_{03} accordingly. Then, the sound source is decomposed into spectral characteristics and the conditions are set as $\Delta\varphi = \varphi_{i-1} - \varphi_i < 2\pi,\ k\Delta x < 2\pi$. All calculations are made only at low frequencies without taking into account parasitic noise and interference.

The registered DAS signal from the OF on the elementary section of the cable is defined as:

$$P_S(t, x_i) = P_0 \exp(j\omega t) \int_{x_{i,0}}^{x_{i,1}} \frac{\eta(x)}{r} \exp(-jkr)\, dx. \qquad (2)$$

C. Algorithm for determining the location of an intruder using time difference of arrival systems built on the DAS

The localization of the sound source is carried out by combining the measurements coming from different nodes.

From a geometric point of view, given the time difference of arrival (TDOA) local positioning method estimate, the source must lie on the branch of a hyperbola (hyperboloid in 3D case). The foci of a hyperbola are at points $m_i^{(m)}$ and $m_j^{(m)}$, and the vertices $c\hat{\tau}_{ij}^{(m)}$ are far apart. The source can be obtained by finding the intersection of two or more hyperbolas, assuming the source and sensors are coplanar [17]. In case the source is far enough from the node, the branch of the hyperbola can be confused with its asymptote. In that case, TDOA is only informative about the direction in which the source is located, and not its distance from the array. It is more convenient to work with DOAs. For the 3-D case, the sound source is defined as a point at the intersection of the surfaces of all cones.

3. Simulation of Data on the Obtained Algorithms and Their Comparison

In the course of testing existing algorithms, it can be concluded that data modeling for 2-D space is not appropriate. In the work, all calculations were carried out only for 3-D space.

According to the results of numerical simulation, the most optimal for further research is to determine the location of an intruder using DAS based on the algorithm of simple triangulation (AST) for 3-D space. Fig. 1. shows a graph of the dependence of the error on the distance to the sound source (SNR level is 10 dB).

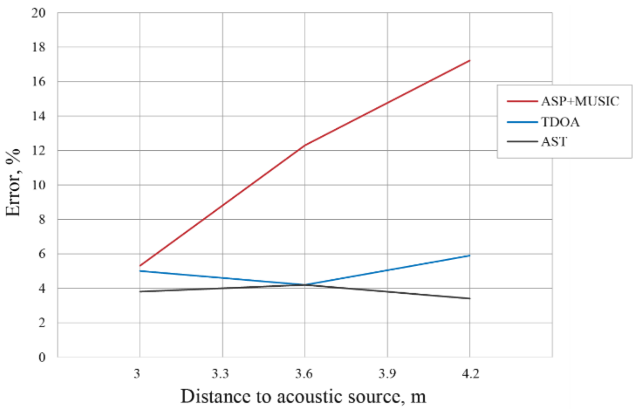

Fig. 1. Dependence of the source localization error on the distance to the sound source

4. Conclusion

Despite the approximately equal error levels of the TDOA and AST methods, the AST method is most preferable, due to the more voluminous and more time-consuming calculations for TDOA. In turn, the ASP method shows a low error rate when the optical fiber is wound on the resonator structure, thereby reducing the calibration length of the DAS. It should be noted, that such configurations are not found in real operational conditions. The AST method requires further study and optimization of the mathematical model. A low-frequency signal has a greater effect on the DAS, but it has a tangible effect on all surrounding objects and structures leading to an increased proportion of parasitic influences on various sensor points.

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