

Real-Time Surveillance of the railways via Distributed Fiber Optic Sensor

Andrey V. Timofeev, Dmitry V. Egorov

Abstract—This paper presents development results of the method of seismoacoustic activity monitoring based on usage vibrosensitive properties of optical fibers. Analysis of Rayleigh backscattering radiation parameters changes, which take place due to microscopic seismoacoustic impacts on the optical fiber, allows to determine seismoacoustic emission sources positions and to identify their types. Results of using this approach are successful for complex monitoring of railways. (*Abstract*)

Keywords— Distributed fiber optic sensor, C-OTDR systems, real-time surveillance of railways, Rayleigh backscattering (*key words*)

I. Introduction

At present the interest has greatly increased in efficient solutions allowing carry out real-time remote surveillance of superextended objects (railway tracks, oil-and-gas pipelines, national boundary, perimeters of strategic objects, etc.). Traditionally, monitoring systems for extended objects are built using distributed networks of seismic sensors and systems of remote video surveillance, when both stationary video systems and mobile platforms are used as carriers. As practice has shown, all these technological complexes demonstrate enough efficiency at solving many monitoring problems. But monitoring systems of those types have a high level of operational cost, since provision of energetic supply and telecommunication is extra expensive problem in case of point sensors network. The reasonable alternative to the above approaches is an approach based on the use of the high vibrosensitivity of the infrared energy stream injected into ordinary optical fiber (buried in the ground near the monitoring object) by means of semiconductor laser of low power. This optical fiber will be called a distributed fiber optic sensor (DFOS or FOS). Typically DFOS length is 40 km. In the systems of this class, all relevant information is transferred to Processing Center (PC) by the optical fiber which is not only a sensor (DFOS) but at the same time an effective and reliable channel for ordinary data transmission. We will call the systems of this class as optical fiber classifiers of seismic pulses (OFCSP or “OXY”), which by the principle of

operation belong to the multitude of so-called C-OTDR (Coherent Optical Time Domain- Reflectometer) systems [1].

II. Basics of OXY-method

The basis of the described method underlying OXY is the use of the vibrosensitive infrared stream injected into a standard monomode fiber (DFOS) by means of a coherent semiconductor laser at the wavelength of 1550 nm. The simplified scheme of OXY represented on Figure 1. Thus, the laser probes the DFOS with usage of infrared stream. This probing is carried out in the pulsed mode. Pulses have a length of ~ 50-200 ns, with an interval of ~ 50-300 mcs. The optical fiber is put into the ground, at the depth of 30-50 cm, at the distance of 5-10 m from the monitoring object and, as a matter of fact, it is an optical fiber sensor. When a pulse is moving along the optical fiber, the Rayleigh elastic backscattering is realized on its natural irregularities (impurities), which due to high coherence of the used laser of 3B class leads to formation of the so-called stable interference structures of chaotic type, otherwise called “speckles” or “speckle images”. A sequence of speckles is received in the point of emanation using an ordinary welded coupler or a circulator.

The central moment of the concept is the phenomenon that any seismic vibration arising on the surface of the optical fiber due to propagation of seismoacoustic waves from the sources of elastic oscillations, changes its local refractive index. Changes of the local refractive index are reflected in the time-and-frequency structure (TFS) of the respective speckle. Knowing the pulse duration and the velocity of wave propagation in the optical fiber, it is easy to determine the section where the TFS speckle deviation took place. Analysis of the sequence of speckle structures using wavelet conversion apparatuses (the phase of singling out of primary signs of target signals) and Lipschitz classifiers (the phase of classification of target signals) makes it possible not only to reliably detect the target source of seismoacoustic radiation, but also to determine its type and area of occurrence. In particular, location of the target source of seismoacoustic radiation is determined with the accuracy of up to 5..10 m at the distance of up to 40 km from the laser location. Actually, as a result of logical processing, several thousands of the so-called C-OTDR channels are formed on the monitoring distance, each of which transfers information on seismoacoustic activity at the well-defined point of the space. It is obvious that the width of the typical C-OTDR channel is 5..10 m.

Andrey V. Timofeev (*Author*)
LPP “EqualiZoom”
Kazakhstan

Dmitry V. Egorov (*Author*)
LPP “EqualiZoom”
Kazakhstan

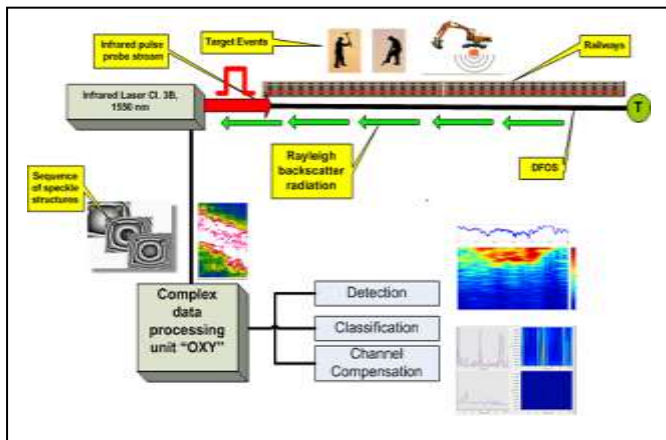


Figure 1. Simplified scheme of OXY (figure caption)

III. Overview of Data Processing Methods Used

The following problems are solved in the process of analysis of seismic activity:

- Target Seismic-Acoustic Event (TSAE or TE) detection;
- TSAE location assessment;
- TSAE type classification.

All these problems are solved on the basis of the so-called “front-end speckle patterns processing” (FESPP). As a result of FESPP, multidimensional information invariants, otherwise called primary signs or features, are singled out from the sequence of the speckle structures corresponding to various C-OTDR channels. Naturally, this analysis is carried out not on a stationary speckle corresponding to the channel state in absence of external disturbances, but on the difference between the speckles adjacent by probing time intervals, which is substantially different from zero. It is this information that is significant for the system and will be called “C-OTDR signal”. And it is C-OTDR signals that are subjected to profound processing in order to solve a complex of problems of remote monitoring. The so-called multidimensional GMM vectors [2] built either by spectral or wavelets coefficients computed above the speckles are used as primary signs in the OXY system. Then, in the space of primary signs, the problems of TSAE detection, location assessment and classification are solved. Use of such multilevel approach allows to significantly increase the anti-interference ability of the system, making it robust against the impact of noises of internal and external nature.

TSAE detection is carried out within the widespread concept of guaranteed detection of statistical disorder of observed processes in C-OTDR channels. Guaranteeing is understood in the sense of ensuring the a priori specified lower boundary of the confidence coefficient P_c with which the concrete time interval T contains the moment τ of discontinuous variation of statistical properties of

observations. In other words, $P(\tau \in T) \geq P_c$ and $|T| \leq \pi$ for the prior specified $\pi > 0$. Detection problems are solved using the principle of simultaneous processing of data from all channels of the adjacent group [7], which allows reducing the average time of observation needed for provision of the specified level of reliability.

TSAE location assessment is based on solving an ordinary triangulation problem using measurements of the adjacent group of channels. The TSAE classification problem seems to be the most difficult. For solving this problem, the approach is used which is based on the ensemble of Lipschitz classifiers, namely the Support Vector Machine ensemble [3]. As a rule, a multitude of target classes has the cardinal number of $m > 20$. Thus, the classification problem has to be solved in the multiclass formulation. In practice, the “one-against-all” approach has turned out to be efficient, within the framework of which the m-class problem is replaced by a series of m binary classification problems, each of which is solved efficiently with the help of the SVM ideology. The Bhattacharyya kernel [4] having good smoothing characteristics was used as the SVM kernel function. To assess reliability of the classification solution, the confidence set approach [5] was used. Use of the phenomenon of multichanneling, consisting of registration of data from channels of the adjacent group, made it possible to significantly increase reliability of solution of the classification problem, at the same time minimizing the impact of the medium of propagation of seismoacoustic waves. This approach is detailed in [6].

IV. Some details of system test results on the railroad testing area

System OXY was installed at the railroad testing area of Kazakhstan Railways Company (JSK “Kazakh Temir Zholy”). DFOS of OXY was buried at the distance of 5 m from railways, at the depth of 30-50 cm. On Figure 2 so-called waterfall chart represented. Here the axis Y relates to time, the axis X relates to distance. This chart was obtained from the part of FOS with length 300 m, on three frequency bands 4-10 Hz (left part), 20-40 Hz (central part), 60-150 Hz (right part). On this chart is reflected C-OTDR-image of a shunting train moving.

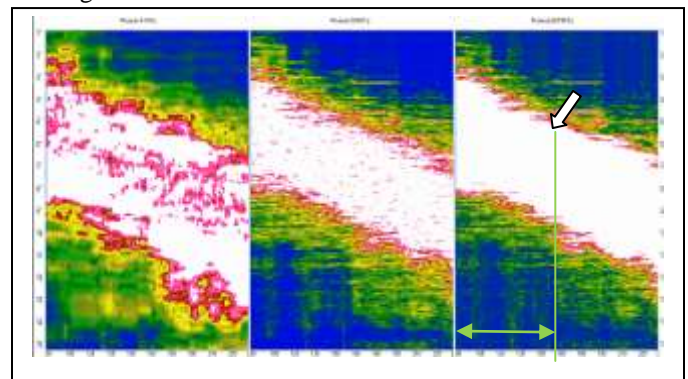


Figure 2. Simplified scheme of OXY (figure caption)

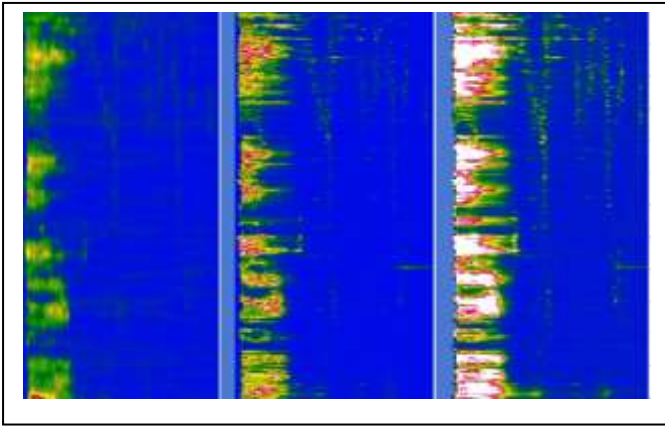


Figure 3. Technological activities on the railway (figure caption)

Red color on the third part indicates the high level of energy, which had been transmitted at the frequency band 60-150 Hz. At the same time, this C-OTDR-image has more fuzzy form and large width in the low frequency band (4-10 Hz). It can be due to a greater ability to spread inside the ballast prism of low frequency part of the seismic waves (LFPSV) versus of high frequency part (HFPSV). So, LFPSV's are moving faster than the train. Because of it effect, signals from train are detected in channels up to which train has not yet reached. The resolution of train place localization is approximately 10-15 m. The red line (it is marked by white arrow) shows the real localization train with very good accuracy. Strictly by this line we can see the explicit pulse of energy connected with the appearance of the train in nearest point to appropriate channel.

The Fig.3 contains the C-OTDR-image of technological activities on the railways. These activities were done at the same place and they continued 20 minutes approximately. The accuracy of estimation of the technological activities localization coordinates amounted to 10 m. Most part of the signal energy has been detected at the 60-150 Hz frequency band. Sharp specificity of the signal power pulsations allows using those pulsations as one of the features for classification the TSAE of this kind

v. System Accuracy Characteristics

Table 1 contains results of automatic classification of TSAE type. Those data are characterizing the quality of functioning of the system algorithmic complex. In the experiment, the control unit of the C-OTDR system was located at 2 km from the TSAE realization place. The symbol α denotes the value of the type 1 errors (target missing), and the symbol β denotes the value of the type 2 errors (false alarm). Values α , β were obtained experimentally for various types of TSAE. The findings demonstrate the acceptable accuracy of TSAE classification. It must be noted, that energetically weak events generated by small objects and taking place at a significant distance from the sensor are classified expectedly worse

TABLE I. THE PRACTICAL DETECTION RESULTS

№	Parameters of experiments			
	Type of TSAE	Distance (m)	α	β
1	Manual ground digging	12	0.1	0.12
2	Group of pedestrians	10	0.13	0.11
3	Pedestrian	5	0.16	0.1
4	Passenger car	10	0.09	0.1
5	Railroad train	10	0.01	0.01

vi. Conclusions

Complex surveillance of state of hazardous extended objects, such as railway tracks, oil-pipelines and gas-pipelines, national boundary sections, become a more and more topical task which needs application of modern methods of taking and processing of information. High efficiency of solution of the problem of monitoring of such objects was proven in the course of pilot operation of the OXY system based on the C-OTDR principle of data processing. To obtain seismoacoustic data, vibrosensitive properties of infrared stream injected into the optical fiber by semiconductor laser are used. To obtain seismoacoustic data, vibrosensitive properties of infrared stream injected into the optical fiber by semiconductor laser are used. The fiber had been buried near the monitoring object at the depth of 50-100 cm, with offset 10 m. Analysis of the backscattered infrared stream allows to identify and localize a fact of threat with high accuracy

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About Author (s):



Timofeev Andrey V. was born in Chita (Russia). He received Dr. habil. sc. ing.in Computer and Information Sciences from Tomsk State University of Control Systems and Radioelectronics, Russia, in 1994. A number of research publications in the International journals (JKSS, Stat.Methodology., Automation and Remote Control etc.) and International/National conferences are at his credit. He is on the editorial board of several journals and conferences and a referee of several others. His research interests include non-asymptotic nonlinear methods of confidence estimation of multidimensional parameters of stochastic systems; machine learning, large margin classification in Banach Spaces; confidence Lipschitz classifiers; technical diagnostics, C-OTDR systems; data mining; change-point problem; alpha-stable laws; statistical classification in application to biometrics and seismic.



Dmitry Egorov was born in Leningrad (Russia). His research interests include C-OTDR and security systems.