World Academy of Science, Engineering and Technology
International Journal of Computer and Information Engineering
Vol:9, No:7, 2015

The Rail Traffic Management with Usage of C-OTDR Monitoring Systems

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Open Science Index, Computer and Information Engineering Vol:9, No:7, 2015 publications.waset.org/10001859.pdf

***Abstract*—**This paper presents development results of usage of C-OTDR monitoring systems for rail traffic management. The C-OTDR method is based on 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 source positions and to identify their types. This approach proved successful for rail traffic management (moving block system, weigh- in-motion system etc.).

***Keywords*—**C-OTDR systems, moving block-sections, rail traffic management, Rayleigh backscattering, weigh- in-motion.

I. INTRODUCTION

CURRENTLY, there is a lot of interest in efficient solutions facilitating rail traffic management that does not rely on track circuits. Solutions using track circuits (TC) imply large electrical power consumption; they do not meet modern safety standards and are obsolete in general. Currently low-power systems resistant to the impact electromagnetic fields are needed. C-OTDR monitoring systems are a reasonable alternative to traditional TC-systems of rail traffic management. The C-OTDR approach is based [1] on the use of the high vibrosensitivity of the infrared energy stream injected into ordinary optical fiber (buried in the ground near the railways) by means of semiconductor laser of low power. This optical fiber will be called a distributed fiber optic sensor (DFOS). Typically DFOS length is 40-50 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 (OXY), which by the principle of operation belong to the multitude of so-called C-OTDR systems.

II. METHOD IDEA

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 Fig. 1. Thus, the laser probes the FOS 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 μs. 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 [2] (the phase of classification of target signals) makes it possible not only to reliably detect the target source of seismoacoustic radiation [3], but also to determine its type [4] and area of occurrence. In particular, location of the target source of seismoacoustic radiation is determined with the accuracy of up to 1.10 m at the distance of up 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 1.10 m.

Trains are sources of seismoacoustic emission of high power. Signals from them are very powerful and those signals have a high signal-to-noise ratio. Fig. 2 contains the C-OTDR image of a shunting train in form of waterfall diagram. Here, C-OTDR channels (one channel one meter) marked on Axis-X, time moments marked on axis-Y in increasing order, train seismic-acoustic energy is coded by color. Here red color represents the maximum of energy level, blue color represents the minimum of energy level. Thus, time train location (parameters **E**(t) and **B**(t)) may be determined very accurately (up to 1m) in real time. Here **B**(t) is starting point of train in moment t, **E**(t) is ending point of train in moment t. The mass (**m**) and velocity (**V**(t)) of a train are estimated also fairly

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accurately. All of those parameters (**E**(t), **B**(t), **m**, **V**(t)) are transferred to the Integrated Control Center (ICC) to form special control modes (SCM). SCM's are transferred to the locomotive by a wireless channel (Fig. 3). SCM's are designed to provide following control actions:

- To report to the locomotive the current status of the next block-section (non-occupancy / occupancy).
- To set the optimal speed.
- To provide the optimal traction.

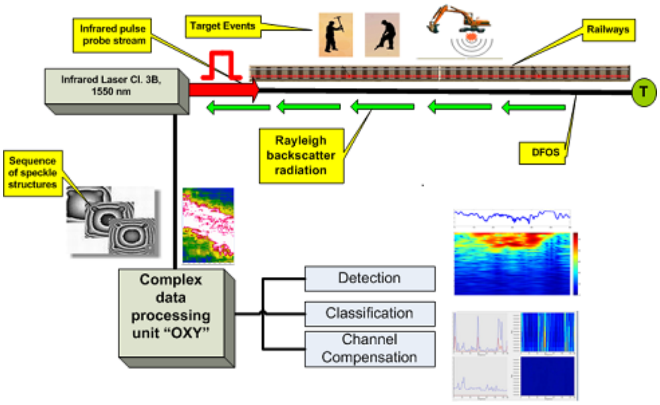

Fig. 1 Simplified Scheme of OXY

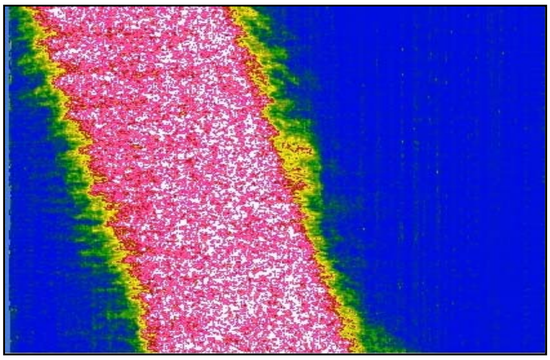

Fig. 2 OTDR Image of a Shunting Train

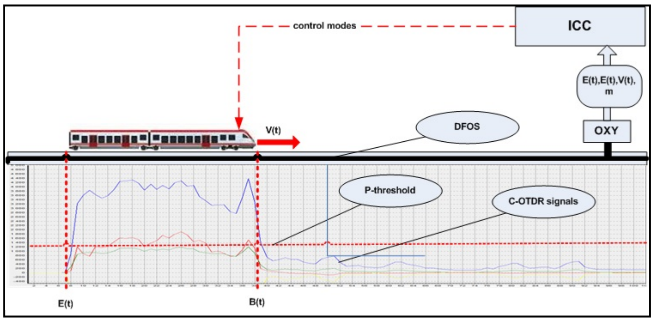

Fig. 3 Data Processing Scheme

The optimal energy consumption is ensured as a result of SCM's usage. At the same time, the highest safety standards of rail traffic management are provided. Using a fiber optic cable as a sensor to determine a train location allows saving a significant volume of electrical power compared tousing a TC as a localization sensor. Indeed, the TC- approach to control of rail traffic management is obsolete; this approach does not meet modern safety standards and consumes a lot of electrical power. Significant electrical power usage is a necessary condition to TC functioning.

In addition, OXY usage provides a solution to the following important problems:

- Dynamic estimation of a train mass **m** (it is used in weigh-in-motion system (WIMS)).
- Dynamic forming of moving block-sections (BS) (it is used in moving-block-system (MBS) [5]-[8]).
- Dynamic estimation of an average train speed **V**(t) (it is used in WIMS, and in MBS).

For estimation of the train mass we use estimates of the kinetic energy of the train. Those estimates are made based on observations of the train seismoacoustic energy (SAE), which we have obtained of OXY at moment *t* subject to the truth of the hypothesis of the approximate constancy of the train speed. Moving train generates the SAE, which is proportional to the train mass times the speed squared.

Let us denote:

- The train length is *L*.
- $S=[B(t),S(t)]$, $|S|=L$, t is a time moment.
- $\Theta=\{\theta_i \mid i\in I\}, |\theta_i|=\Delta$, is the given sequence of sections of the railway line of equivalent size Δ.
- $\mathbf{e}_{tr}^{S}(t)$ is train SAE on interval S at moment *t*.
- Hypothesis H_0 : there is no a train signal in OXY-channel (background model).
- Hypothesis H_1: there is a train signal in OXY-channel (signaling model).
- $\tilde{\mathbf{e}}_{tr}(t_i \mid S(t_i),H_1)$ is estimate of the train SAE on space interval $S(t_i)=[B(t_i),S(t_i)]$ in the moment t_i; $t_i=\sup\{t \mid t\in T_i\}$.
- $\varphi_i(s(t))$ is estimate of SAE in point $s(t)\in S(t_i)$;
- $\varphi_i^{(ns)}(S_N(t_i))$ is estimate of background noise on interval $S_N(t_i)$; $t_i=\sup\{t \mid t\in S_N(t_i)\}+\Delta+1$; the value $|S_N(t_i)|$ is determined by the given parameter *N*, where $Var\left(\varphi_i^{(ns)}(S_N(t_i))\right)\le N$; estimate $\varphi_i^{(ns)}(S_N(t_i))$ is calculated from the standpoint of sequential analysis.

We can estimate the $\tilde{\mathbf{e}}_{tr}(t_i \mid S(t_i),H_1)$ in each moment t during train moving along the DFOS. But there exists two important circumstances:

- The influence of background noises (we can measure only mix of signal and noises).
- The influence of the seismic wave propagation medium inhomogeneity on the various railways sections.

Both of these circumstances can be taken into account by averaging over time and space. Consider the sequence of time intervals $\mathbf{T} = \{T_i\}, \bigcap_i T_i = \varnothing$. Without loss of generality, the value of Δ is such that $\forall t \in T_i : \mathbf{V}(t) \square \mathbf{v}_i, \mathbf{v}_i - \text{constant}$. Train speeds $\mathbf{v}_i$ are estimated separately for any interval $T_i \in \mathbf{T}$ with usage of function **B**(t) estimates. The estimate of $\mathbf{v}_i$ will be denoted as $\tilde{\mathbf{v}}_i$. It is very important the values $\mathbf{T}$ are defined by the values $\tilde{\mathbf{v}}_i$ as following: $T_i \in \mathbf{T} : T_i = \theta_i / \tilde{\mathbf{v}} = \Delta / \tilde{\mathbf{v}}_i$. Further

$$\forall T_i \in \mathbf{T} : \tilde{\mathbf{e}}_{tr}(t_i \mid S(t_i), H_1) = \int_{T_i} \varphi(s \mid t)dt\,|T_i|^{-1} - \varphi_i^{(ns)}(S_N(t_i)) \qquad (1)$$

Let us denote:

$$u_i = \left(\tilde{\mathbf{e}}_{tr}(t_i \mid S(t_i), H_1), \tilde{\mathbf{v}}_i\right)_i . \qquad (2)$$

So, in this case, we have the sequence of tuples $U = \{u_i \mid i \in \mathbf{I}\}$. For each $u_i \in U$ we are calculating the following estimates:

$$M = \left\{2\tilde{\mathbf{e}}_{tr}(t_i \mid S(t_i), H_1)\tilde{\mathbf{v}}_i^{-2} \mid i \in \mathbf{I}\right\} . \qquad (3)$$

The Main Hypothesis is the existence of constant sequence $\Xi = \{\xi_i \mid \theta_i \in \Theta\}$ for which we have:

$$\mathbf{m} = \xi_i \cdot \mathbf{E}\left(2\tilde{\mathbf{e}}_{tr}(t_i \mid S(t_i), H_1)\tilde{\mathbf{v}}_i^{-2}\right) . \qquad (4)$$

The constants Ξ are definitely corresponded to the railways line; and those constants are depended from medium inhomogeneity. That is why those constants have to be estimated for each section $\theta_i \in \Theta$ separately. This problem is solved very easy with usage of a “benchmark-train”. As benchmark-train we can use the train with given mass $\mathbf{m}_{bm}$, for example, we can use the separately moving locomotive with given type. In our case, the locomotive of “VL-80” type was used. After the "benchmark-train" has passed all along the railroad line, where DFOS has been installed, we estimated the sequence *U*. It is easy to estimate the sequence Ξ, if we use given mass $\mathbf{m}_{bm}$ and estimates of *U*. So, we can estimate the value $\mathbf{m}$ by (4) because we had obtained the sequence Ξ. The estimate of $\mathbf{m}$ has following simple form:

$$\tilde{\mathbf{m}} = |\mathbf{I}|^{-1} \sum_{i \in \mathbf{I}} 2\xi_i \tilde{\mathbf{e}}_{tr}(t_i \mid S(t_i), H_1)\tilde{\mathbf{v}}_i^{-2} . \qquad (5)$$

BS is small part of the railway line. Each BS is used as an independent object of signaling and communication [6]. Set of BS is used when auto-lock or automatic locomotive signaling [9]. The moving block-section is the modern approach to control of rail traffic management [9]. In frame of traditional approach to this problem, TC and/or counters axes are used for determine the following BS status (non-occupancy/occupancy). Under a moving block approach, computers calculate a 'safe zone' around each moving train that no other train is allowed to enter. In this case, we need knowledge of the precise location, and speed, and direction of each train, which is determined by a combination of several sensors: active and passive markers along the track, and trainborne tachometers, and speedometers. So, OXY plays the role of a passive sensor along the track which allows us to estimate the location and speed of each train with a high level of precision. According to the concept of a moving block, instructions (SCM's) are passed directly to the trains through a radio-channel (Fig. 4). This conception has the advantage of increasing track capacity by allowing trains to run closer together while maintaining the required safety margins.

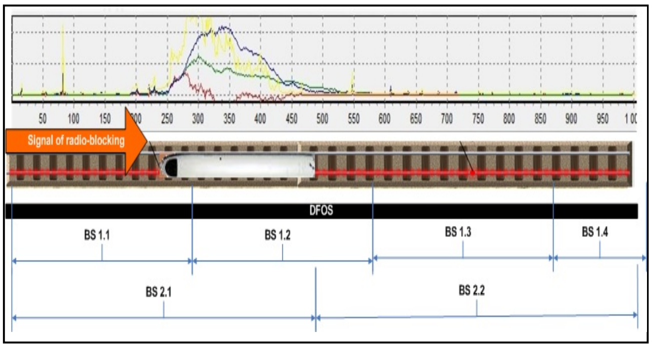

Fig. 4 Moving BS Scheme with OXY

On Fig. 4 is showing the example of moving block-sections formation. Here {BS1.1… BS1.4...} are block-sections in case of more intense traffic on railway line. On the other hand, {BS 2.1,…,BS 2.2...} are block-sections in case of less intense traffic.

III. 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. The experiments with 20 m DFOS offset were also completed.

Parameters of the C-OTDR monitoring system:

- the probe pulse duration – 10..100 ns;
- frequency sensing – 3..5 kHz;
- the probe signal power - 15 mW;
- DFOS length – 1 200 m;
- laser wavelength - 1550 nm.

Table I contains results of parameters estimation, which have been estimated by OXY-system, and which widely used in railways signaling systems (in WIMS, in MBS, etc). The range of speed measurement is 10…220 km/h. The accuracy of the train location is defined by the C-OTDR channel width, and it is equals to 5 m. The OXY-estimates accuracy for these parameters (**V**(t) and TL) is quite sufficient for MBS. On other hand, the train mass OXY-estimation accuracy is not quite sufficient for practice yet (this is due to the physical nature of the C-OTDR principle); but there is possibility to accuracy improve (increasing the value $\sum_{i\in I}\left|\theta_i\right|$ implies decreasing the Ξ estimate dispersion, and therefore, this will be increased the accuracy of the train mass estimate). To radically improve the estimation weight, it is necessary to use a complex approach: "a coherent" and "a not-coherent". This way is promising for our future research.

TABLE I
THE PRACTICAL RESULTS

Parameters	Inaccuracy
Average Train Speed (**V**(t))	Not more than 2 km/h
Train Location (TL)	Not more than 5 m
Train Mass (**m**)	Not more than 15%

IV. CONCLUSIONS

Using C-OTDR monitoring systems in the railway signalling system represents a brand new trend in developing of rail traffic management systems. High efficiency of such approach was proved in the course of an OXY-system pilot operation. The OXY-system is based on the C-OTDR concept of data processing. In frame of this concept, vibrosensitive properties of an infrared stream, which have been injected into the optical fiber by semiconductor laser, are used to obtain seismoacoustic data. 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 seismoacoustic energy sources with high accuracy. In particular, a moving train is a seismoacoustic source of high-energy. Because of it, OXY-system allows to determine train location, train mass, and train speed with sufficient accuracy even though DFOS offset from railways may be more than 20 m.

ACKNOWLEDGMENT

This study has been produced under the project "Development of a remote monitoring system to protect backbone communications infrastructure, oil and gas pipelines and other extended objects (project code name – OXY)", financed under the project "Technology Commercialization", supported by the World Bank and the Government of the Republic of Kazakhstan.

REFERENCES

[1] A.V Timofeev., D.V Egorov., “Real-Time Surveillance of the railways via Distributed Fiber Optic Sensor”, ASEE-2014 Conference Proceedings, Kuala Lumpur, IRED, (2014).

[2] A.V Timofeev, “The guaranteed estimation of the Lipschitz classifier accuracy: Confidence set approach”, Journal Korean Stat. Soc., 41(1), pp.105-114 (2012).

[3] A.V Timofeev, “The guaranteed detection of the seismoacoustic emission source in the C- OTDR systems’, ICDSP 2014: International Conference on Digital Signal Processing Conference Proceedings, Barcelona, (2014).

[4] A.V Timofeev., D.V Egorov., “Multichannel classification of target signals by means of an SVM ensemble in C-OTDR systems for remote monitoring of extended objects”, MVML-2014 Conference Proceedings V.1, Prague, (2014).

[5] D. C. Gill and C. J. Goodman "Computer-based optimisation techniques for mass transit railway signalling design", IEE Proc.-B, vol. 139, no. 3, pp.261 -275 (1992)

[6] R. J. Hill and T. K. Yates "Modelling railway block signalling systems using discrete-event simulation", Joint ASME/IEEE Railroad Conference, pp.1 -9 (1992)

[7] A. Simpson, "Towards the Mechanical Verification of Moving Block Signaling Systems," Technical Report CMS-TR-99-06, School of Computing and Mathematical Sciences, Oxford Brookes University, UK (1999).

[8] A.E. Haxthausen and J. Peleska, "Formal Development and Verification of a Distributed Railway Control System," In Proc. 1st FMERail Seminar (1998).

[9] R., Takagi, “Synchronisation control of trains on the railway track controlled by the moving block signalling system”, Electrical Systems in Transportation, IET, Vol. 2 , Issue 3, pp. 130 – 138 (2012).

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