The Rail Traffic Management with Usage of C-OTDR Monitoring Systems
Andrey V. Timofeev, Dmitry V. Egorov, Viktor M. Denisov

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 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 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 1 m) 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

Andrey V. Timofeev and Dmitry V. Egorov are with the LPP “EqualiZoom”, Astana, 010000, Kazakhstan (phone: +7-911-191-42-67, +77713717097; e-mail: timofeev.andrey@gmail.com, edvo17@gmail.com).

Viktor M. Denisov with Company “Flagman-Geo”, Saint-Petersburg, Russia, (phone: +7 911 982 39 09).
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.

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.
- \( \Theta = \{\theta_i | i \in I\}, |\Theta| = \Delta \), is the given sequence of sections of the railway line of equivalent size \( \Delta \).
- \( e^S(t) \) 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).
- \( \tilde{e}_o(t_i | S(t_i), H_i) \) is estimate of the train SAE on space interval \( S(t_i) = [B(t_i), S(t_i)] \) in the moment \( t_i \);
- \( \phi(t_i) \) is train speed in point \( s(t_i) \) of S(t_i);
- \( \phi_i^{(na)}(S_n(t_i)) \) is estimate of background noise on interval \( S_n(t_i) = \{t | t \in S(t_i)\} + \Delta + 1 \);
- \( \var{\phi_i^{(na)}(S_n(t_i))} \) is calculated from the standpoint of sequential analysis.

We can estimate the \( \tilde{e}_o(t_i | S(t_i), H_i) \) 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
The Main Hypothesis is the existence of constant sequence of tuples \( U = \{ u_i \mid i \in I \} \). For each \( u_i \in U \) we are calculating the following estimates:

\[
M = \left\{ \tilde{e}_{uv}(t_i \mid S(t_i), H_i), \tilde{v}_i \right\}.
\]

The constants \( \Xi \) 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 \( m_{bm} \), 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 \( \Xi \), if we use given mass \( m_{bm} \) and estimates of \( U \). So, we can estimate the value \( \mathbf{m} \) by (4) because we had obtained the sequence \( \Xi \). The estimate of \( \mathbf{m} \) has following simple form:

\[
\mathbf{m} = \sum_{i=1}^{1} 2 \xi \tilde{e}_{uv}(t_i \mid S(t_i), H_i)\tilde{v}_i^2.
\]
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 equal 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 \( \sum \theta \)) implies decreasing the \( \Xi \) 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>
<thead>
<tr>
<th>Parameters</th>
<th>Inaccuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Train Speed (V(t))</td>
<td>Not more than 2 km/h</td>
</tr>
<tr>
<td>Train Location (TL)</td>
<td>Not more than 5 m</td>
</tr>
<tr>
<td>Train Mass (m)</td>
<td>Not more than 15%</td>
</tr>
</tbody>
</table>

**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**


**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 seismics.

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

**Viktor M. Denisov** was born in Pskov (Russia). He received Dr. habil. sc. ing.in Computer and Information Sciences from ITMO University in 1994. A number of research publications in the International journals and International/National conferences are at his credit. He is in main research interests include information and computer technology, instrumentation, measuring devices and systems, geotechnical monitoring, mobile and cloud computing, sensors and sensors, intelligent sensor networks, mobile medicine. Viktor M. Denisov is the CEO of FlagmanGeo, ltd. He is an expert of the Ministry of Education and Science of the Russian Federation in the field of information and computer technologies. Also, he is a member of the editorial board «International Journal of E-Health and Medical Communications» (IJEHMC). He is also the chief designer of the family of the newest field of geophysical sensor devices. Under his leadership made a lot of major projects for the monitoring of complex engineering structures and dangerous natural objects. He developed a new method for geotechnical monitoring based on the use of arrays of micromechanical sensors based on flexible chassis.