Distributed acoustic monitoring to secure transport infrastructure against natural hazards - requirements and new developments

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ABSTRACT

The Austrian Federal Railways (OEBB) rail-network operate several trans-European connections, thereof approximately 20% are exposed to natural hazards. For trains, obstacles in the tracks, damage to the track bed and direct train hits are the most relevant hazard scenarios. Classical permanent protections structures are sometimes hard to realize due to technical reasons and the limited time windows available for construction work. Therefore detection technologies gain more importance as an alternative to classical protection measures. Distributed acoustic sensing (DAS) with fiber optic cables is in use worldwide for monitoring pipelines or e.g. securing industrial and military facilities. This study evaluates if reliable detection of hazardous processes in the track area is possible by using existing fiber optic communication cables. We show that processes such as rock fall or tree-throws can be detected well, but due to the high sensitivity of the monitoring system, interfering signals still produce a relative high number of false alarms.

KEYWORDS

railway; rock fall detection; DAS monitoring; OTDR fiber cable; natural hazard

INTRODUCTION

In Austria the Austrian Federal Railways (OEBB) operate several important trans-European railway routes. Thereof, especially transalpine railway lines show long slope-traverses, which are often exposed to gravitational processes such as rock falls. Protection nets and frequent rock wall clearing and track inspection typically cover the resulting protection needs. However, in implementing these expensive measures, the demand for high track availability and thus the small number of maintenance windows is becoming a challenge. Therefore, the future focus must be on cost effective alternatives with low maintenance intervals.

One approach is to directly monitor protection nets or install slider fences. With them rock fall activity is detected promptly and maintenance work or even track closure can be arranged in time (Schorno et al 2011). But this monitoring technology is costly and requires the installation of protection nets or slider fences in advance.

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Here distributed acoustic sensing (DAS) using fiber optic cables might be an alternative. This technology is frequently used in different professional fields such as pipeline monitoring, securing industrial facilities or structural health monitoring. Recently it is also applied to other purposes such as the detection of avalanche activity (Prokop et al 2014) or railway tracking (Zeni et al 2013).

AIM OF THE STUDY AND MAIN ACTIVITIES

This study was carried out in close cooperation between NBG FOSA GmbH and PULSE Engineering GmbH on behalf of OEBB Infrastructure AG. It was defined the main goal to evaluate if the technology of distributed acoustic sensing (DAS) can meet the OEBB standards for automatic rock fall and tree-throw detection as follows:

- Automatic detection of a minimum rock fall impact of 1.5 kJ on the railway track with a detection certainty of 97%. 1.5 kJ was defined as the lowest impact level, which may cause initial damage to track or train material.
- The responsible operators shall receive up to four simple alarm thresholds with clear action plans following up.
- For maintenance reason no direct installation of fiber cables in track ballast is acceptable. Standard fiber cable material and standard cable troughs or cable mounting techniques have to be used.
- For secure operation and easy maintenance the main equipment should be installed in railway control centers and not wayside of the tracks.

First tests in 2012 were promising and build the basis for the feasibility - study which is presented in this paper. This study is structured as follows:

As different parameters (meteorology, track bed, cable properties, etc.) may have influence on the monitoring quality with fiber optic cables, a basic parameter assessment was carried out at the beginning of the study. Field experiments under laboratory conditions followed. They had the aim to analyze and understand the rock fall induced signal pattern and its frequency band. Then full-scale tests on an operating railway track during maintenance windows were used to gather signals of artificially produced rock falls and tree-throws and to develop recognition patterns. To test system stability and improve alarm parameters, finally the system was applied on an operating railway track for four months.

BACKGROUND ON DISTRIBUTED ACOUSTIC MONITORING

A so-called interrogator unit attached to one fiber of the cable induces the pulses of light and analyses the natural backscatter (e.g. Rayleigh, Brillouin and Raman scattering) of each point of the fiber (Akkerman et al 2013). Thus it can be interpreted like an array of countless microphones along the length of the fiber (Inaudi et al 2007).

The detection principle of fiber optic cable is the Optical-Time-Domain-Reflectometry (ODTR). It is used to determine and analyze travel time and reflection characteristics in the electromagnetic spectrum of light and hence to define location and kind of disturbance. In this study the principle of Rayleigh backscattering is applied, using a commercially available interrogator unit (iDAS, Silixa Ltd.). Imperfections of the fiber but also movements or vibrations along the cable (e.g. induced by rock fall activity) result in different backscattering characteristics. By assessing the attenuation of the pulse, the type of interference can be characterized and traced with a spatial resolution of approximately 10 m (Fig 1).

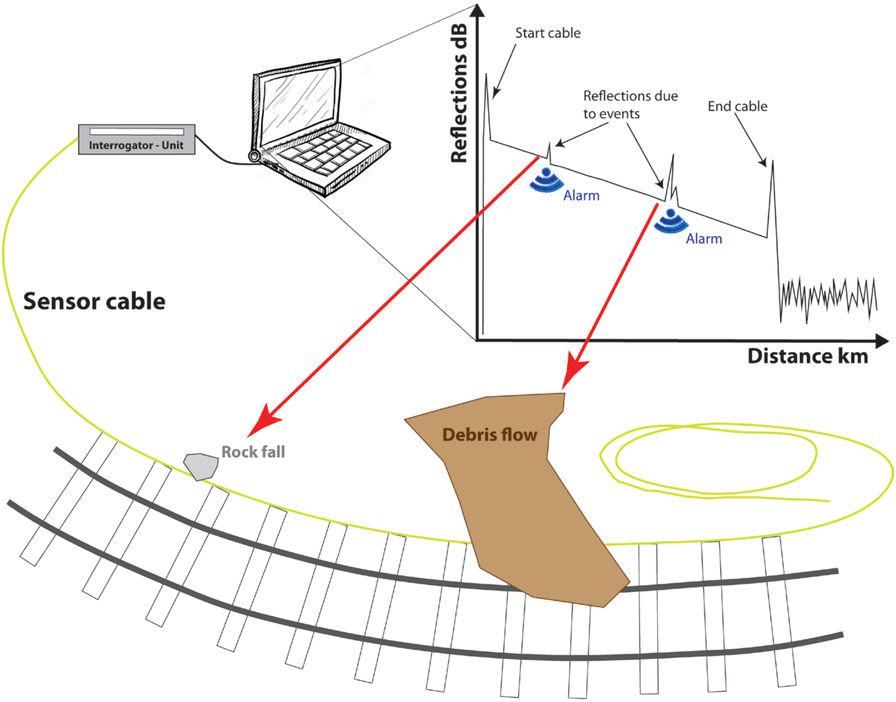

Figure 1: System sketch of a distributed acoustic monitoring system using fiber optic cables.

BASIC ASSESSMENT

The first test results clearly showed that for automatic event detection many different factors need to be considered and investigated along the railway track. The most important ones are summarized below:

- Natural Hazards and the lack of protection along the railway: To achieve an efficient and accurate monitoring system the following questions need to be addressed: i.) Where are the potential risk areas and active protection measures located along the track? ii.) Where are the boundaries between different hazardous processes and secure area?
- Properties of the fiber optic cable: Especially when operating telecom fiber optic cables are employed, it is crucial to be aware of their present location and condition. Cables, earth-buried or located in a cable trough, underground or overhead, show different sensibility to rock fall events. If multiple cables are installed in a cable trough, their

placement may influence the sensing quality. Cable crossings and overlaying produce noise in the data.

- Properties of the track bed: The construction of track and track ballast has substantial influence on signal attenuation and propagation. The track bed is originally developed to obtain optimal load transfer and to minimize vibration. Tests revealed that the elastic pads between the rails and ties and - more importantly - the elasticity of the ties and track ballast lead to significant signal attenuation and in consequence to different sensing results, depending on the location of the fiber optic cable. Therefore it has to be answered in advance: How does the construction of the track and track ballast look like?
- Interfering external signal sources: To eliminate interferences from other transport carriers (e.g. cars, planes, helicopters, etc.) their influence has to be quantified. Knowing source, amplitude and distance of possible interfering signals, these signals can be characterized. Therefore, the following questions need to be addressed: i.) Are there roads or crossings nearby? ii.) Is there air traffic? iii.) Is construction work going on and can it be registered in advance?
- Meteorology: The influence of meteorological events such as wind or rain can have severe impact on the monitored signal. They may induce vibrations in the cable trough or the cable itself. Consequently, the forecast of gusting wind or rain is crucial in order to prevent false alarms.

FIELD EXPERIMENTS UNDER LABORATORY CONDITIONS (SPRING 2013)

The objective of these experiments was to analyze the signal and in particular the frequency band of different kinds of rock fall impacts under known conditions and to evaluate the performance of different cable placements. Using this information, a preliminary definition of detection parameters was carried out and preliminary recognition patterns, so called “events”, were defined. For this purpose a 150 m long privately owned shunting track was adapted. Both sides of the track were equipped with different cable layout according to OEBB regulations. One was set up as underground cable, one was placed inside the newly build cable trough and a third one was directly attached to the rail. Then impacts by objects with various weights and materials were induced and their different signals were analyzed (Fig.2). The field experiments lead to the result that the optimal frequency range for rock fall detection is between 100 Hz and 500 Hz. For these frequencies, a pulse rate of 4 kHz delivers an optimal relation between detection range and sensitivity. The variable resonance behavior and frequency domain of rails, ties, ballast and foundation can be utilized for improved event discrimination along the track. However, with a single cable layout no reliable detection crosswise to the track axis is possible. That is because at the same distance to the fiber, direct impacts on the rail may result in higher signals than collisions on foundation or adjacent ground. Here fiber optic cables directly mounted at the rail may be a promising alternative as they enable a better discrimination between direct rail-track impact and ballast impact due to different signal attenuation.

Figure 2: Left: impact on rails with a granite bowl from a predefined drop height. Right: Installation of cable trough according to OEBB regulations for the field experiments.

TEST SITE HIEFLAU ADMONT – FULL SCALE FIELD TESTS (SPRING AND FALL 2013)

After the field experiments full-scale tests on an operating railway line (Hieflau – Admont, Styria, Austria) were carried out. This line is a 40 km single track, with approx. 280 trains/month. This alpine type track is characterized by 4 bridges and 4 tunnels as well as different types of fiber optic cables and different laying systems (earth-based or overhead). One fiber of an operating telecom fiber optic cable was connected to the interrogator unit and signals of artificially produced tree- and rock falls were analyzed. The goal was to gather data on a railway track in operating state and redefine the preliminary detection patterns under realistic conditions. Therefore 30 rocks of different size (up to 50 kg) and shape were thrown down a wall and an excavator was used to simulate around 20 tree-falls (Fig. 3).

Figure 3: Left: Rocks thrown down on railway tracks. Right: Simulation of tree-fall using an excavator.

The full-scale tests showed that rocks of 20 kg or more and a dropping height above 10 m can be easily identified along the railway axis, but a precise definition of drop height and weight cannot be achieved. For the tree-throws the characteristic frequency spectrum is similar to rock fall but has less energy. They can be identified, if the drop height is higher than 4 m.

During the experiment blasting operations were carried out on a construction site close to the test site, which produced strong interfering signals. It can be concluded that the automatic detection system must be deactivated in case of nearby blasting or construction works. Similar the influence of traffic nearer than 10 m becomes dominant and hampers automatic detection based on defined event patterns. These influences fade out for distances above 50 m.

TEST SITE HIEFLAU ADMONT – LONG-TERM TEST (SPRING 2014)

After the full-scale tests and in-depth analysis of the gathered data the detection parameters were modified and three recognition patterns were defined. For events with an impact energy lower than 1.5 kJ, we defined the category "rock fall manual", meaning interaction of a specialist is needed to define whether this was a rock fall or an interfering signal. For impact energy higher than 1.5 kJ we defined the category "rock fall automatic", meaning that an automatic alarm will be triggered. The last category was "train" in order to identify trains on the track.

In a final step a 6 km long section of the railway track Hieflau-Admont (Styria, Austria) was monitored for four months during operating state. The goal was to test the stability of the detection parameters and to test the stability of the whole system setup (interrogator unit, data storage, automatic data analysis) during constant operation over a longer period. The interrogator unit and the alarm server were installed in the railway control center at the railway station Hieflau. The server transmitted alarms to a web-interface, enabling the geographically referenced visualization of train positions, event-location and alarm type. It also enables email notifications and remote modification of the alarm parameters in case of malfunction or maintenance windows.

After a few weeks it was clear that the monitoring system itself runs stable, however the existing cable placement in a concrete trough produced more false alarms than expected and the alarm parameters therefore needed adaption. Here the remote access to the permanent data logging enabled quick improvement of the detection parameters. Problems were caused by several unexpected incidents. For example, a train passing the monitored area can be easily tracked and identified with less than 0.5% error rate, but e.g. maintenance trains stopping in the area for several minutes and then starting again were hard to identify. The Implementation of train detection to differentiate from rock fall, the masking of bridges, crossings, overhead troughs, or save-guarded track section, improved the recognition quality tremendously.

Moreover thunderstorms passing the area of our test operation produced a lot of false alarms. After signal analysis and site investigations we found out that the source of the interfering signals was not the wind or rain itself, but rather signposts, cable-masts and trough covers that induced vibrations into the ground, the cable through and the cable itself. To reduce false alarms they need to be acoustically uncoupled from the fiber cable.

It can be concluded that within the 4-months period we were able to reduce the false alarms for rock fall events higher than 1.5 kJ from 35/day down to 5/day, which is still too high, to meet the error rate of 3%, defined as criterion for automated detection. Up to now our experiences suggest, that this error rate may be met for rock fall events larger than 15 kJ. calAt the moment, operator's expertise is still required for events smaller than 15 kJ to prevent false alarms.

The long-term test further showed that the system must allow for quick and easy entry of maintenance action where automatic alarms are disabled, and the integration of the monitoring system into the OEBB IT architecture can be achieved via TCP/IP interface and alarm notification can be triggered via SMTP-interface.

CONCLUSIONS AND FUTURE OUTLOOK

With standard telecom fiber optic cables the impact of potentially hazardous processes such as rock fall on the railway track can be detected. However, for the development of an automatic detection system still some challenges exist. Above all, the sound installation of existing fiber optic cables along the track and even the placement of the cable itself in the trough is of high importance. Harsh meteorological conditions, especially strong wind and rain, can cause additional noise in the signals and need to be considered. In the long-term test operation false alarm rates of 35/day could be reduced to 5/day. These values are still too high and far away from the predefined goal of detecting a rock fall event of 1.5 kJ with a probability of 97 %.
As an alternative to further reduce the false alarms we tested a fiber optic cable mounted directly to the rails. Thereby, interfering signals caused by variable underground or inhomogeneous cable installations can be removed. At the moment it is unknown if this setup will cause other interfering signals. Akkerman et al (2013) tested a similar setup with a cable installed in the track ballast and reached a minimum false alarm rate of 1/day. Therefore alternative mounting setups of fiber optic cables seem promising but on the other hand a reduction of the false alarm rate below 1/day at the moment is not realistic.
The detection of rock fall or other natural hazards along many kilometers of railway tracks using fiber optic cables has huge potential but also still needs a lot of research work. In this feasibility study we were able to demonstrate the advantage of a linear acoustic sensing system providing gapless monitoring of many kilometers of railway tracks but also faced many challenges with the automatic detection due to interfering signals. We believe that the potentials of the cable itself, the cable installation and the detection algorithm are not fully exploited yet. Therefore, a great need for research in this area still exists.
The authors hope that this study will stimulate interest in this field and encourage other engineers, scientists and supporters to get active in this fascinating work of distributed acoustic sensing.

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