THE EFFECTIVENESS OF DISTRIBUTED ACOUSTIC SENSING (DAS) FOR BROKEN RAIL DETECTION

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Abstract

Broken rails remain one of the main causes of railway accidents despite improved rail quality and inspections. Today signalling system track circuits are generally used to detect broken rails, however new signalling systems such as ETCS replace track circuits and therefore new methods are needed to detect broken rails. One promising technology is distributed acoustic sensing (DAS). This paper describes field tests carried out on DAS to evaluate its ability to detect broken rails and the moment when rails break. The testing showed that DAS has good potential for detecting broken rails in both scenarios. The paper describes the tests and results.

Keywords: rail defects, infrastructure, track, vibrations, analysis

1 Introduction

The UIC project Broken Rail Detection [1] identified fibre optic distributed acoustic / vibration sensing to be a highly promising low-cost technology for identifying broken rails. Distributed acoustic sensing (DAS) measures changes in the intensity of light reflections caused by sound or vibration waves radiating against a single mode fibre optic cable. Algorithms transform these data into valuable information. As part of the project a detailed evaluation of DAS was carried-out by a team from the University of Applied Sciences St. Pölten, the Austrian Federal Railways (ÖBB-Infrastruktur AG), and Frauscher Sensonic GmbH, a developer of railway sensors. The research consisted of three parts:
a) Literature review DAS and broken rail assessment,
b) Field testing of DAS under various test scenarios,
c) Evaluation of results. This paper summarises the research results.

2 Broken rails and distributed acoustic sensing

2.1 Broken rails

Broken rail is a leading cause of mainline track derailments today [2]. Broken rails are caused by the accumulation of small surface cracks on the rail surface created by rolling contact fatigue (RCF) from passing trains. Overtime these cracks grow and create transverse defects. These defects can cause a rail to break if they are not detected and removed in time.
An important technique for preventing broken rails is detecting cracks in their initiation phase (10 µm to 100 µm), before they start growing in number and size to a critical quantity where they cause rail to break under the load of a passing train [3]. Early detection enables

DOI: https://doi.org/10.5592/CO/CETRA.2022.1381

railways remove cracks and reduce rail RCF stresses by grinding the rail before it reaches the critical phase. Today broken rails are generally detected with track circuits. However, many new signalling systems such as ETCS replace track circuits with axle counters or other technologies that cannot detect broken rails. Therefore, a new approach is needed. Furthermore, track circuits can only identify rail breaks, it would be better to be able to proactively identify critical situations before the rail actually breaks. Initial research showed that distributed acoustic sensors (DAS) was a promising technology for identifying broken rails [1].

2.2 Distributed acoustic sensors

The research objective was to test the use of distributed acoustic sensors (DAS) to identify broken rails and conditions that could lead to a broken rails in the future. Acoustic sensors are used to detect vibrations. The vibrations differ depending on what caused them. In this research, the vibrations would be caused by train wheels moving over a gap in the rail (representing a rail break) and at the moment the rail breaks. In a DAS system, vibrations are manifested as signals in a fibre optic cable and received ("heard") at acoustic sensors distributed along the track. It is known that acoustic sensors can detect transient stress waves emitted from rail deformations, fractures, and cracks and convert them to electrical signals that can be recorded and analysed by data acquisition systems [4]. The key challenge in using DAS for identifying broken rails is determining the type and size of the defects generating the signal. Therefore, this research evaluated the ability of this technology to identify specific vibrations caused by broken rails. The rail defects are detected by applying acoustic signal processing techniques to the real time data obtained from the acoustic signal sensors. These data consist of changes to fibre strain that are generated by the wheel/rail interaction. The research tested various fibre optic cable alternatives (type, location), technologies to clean the signal data for analysis, and pattern recognition algorithms. The experiments tested various rail damage scenarios that can lead to rail break over time.
In each scenario the track was physically modified to create a physical gap in the track and then the signals generated by trains rolling over the gap during testing were compared to the base condition (no gap). These signals were evaluated to assess whether they could be used to identify specific defects. As outlined in the following sections, the research tested several different magnitudes (e.g., gap size) and types of physical modifications. Note that a similar methodology could be used to assess the use of sensors for detecting other types of rail damage such as head check, RCF, fracture, spalling, flaking, shelling and corrugation failures.

2.3 Using and analysing DAS data

The process of using and analysing DAS data to identify broken rails consists of two main steps: preparing the acoustic signal data (acoustic emissions) collected from the track for more detailed analysis (rail signal detection) and using this data to identify rail defects including broken rails (rail defect detection). These steps and their sub-steps are illustrated in Figure 1.
In the first step the raw acoustic emissions data must be filtered because it includes noise resulting from wave reflections, mechanical rubbing, electromagnetic interferences, and environmental conditions such as rain, wind, wind-born debris etc. Noise creates large amounts of data and reduces the effectiveness of results.

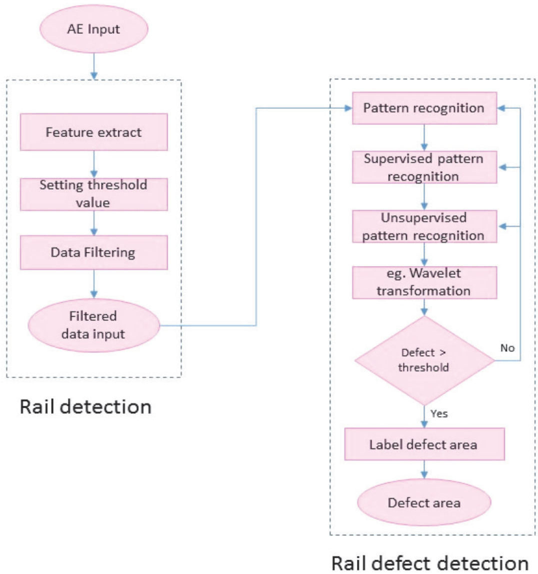

Figure 1 Broken rail detection methodology flowchart

Therefore, during the rail signal detection step the raw input data are pre-processed to reduce noise using data cleaning, normalizing, filtering, and eliminating meaningless acoustic signatures. This requires setting a threshold for data acquisition that removes low amplitude signals to separate data from noise. The threshold values for filtering can be set using previous test results and experience.

There are several parameter-based filters that can be used in this process including duration filters, frequency filters, signal strength filters. For example, a parameter-based noise filter for filtering signals with low amplitude and long duration can be developed by plotting amplitude versus log duration. Abdelrahman presents an excellent summary of the literature on noise filters [4]. The filtered acoustic emissions data and physical data about the track section (e.g., rolling stock types, axle loads, total traffic, weather conditions, track geometry) are used as inputs for the rail defect detection algorithm. The success of this algorithm depends upon developing correlations between the acoustic emission data collected by DAS and the actual condition of the rail.

In the rail defect detection algorithm pattern recognition techniques are applied to categorize data into identifiable classes. Pattern recognition consists of three steps: data perception, feature extraction and classification. After the features have been extracted from the input signal data these data are categorized into identifiable classes of rail failure. There are two classification methods:

- supervised pattern recognition – each unknown pattern is classified to an already known rail defect (this method is suitable if the types of the rail defects are known in advance). Learning processes such as Neural Networks (NN) can be used in this method.
- unsupervised pattern recognition – data are classified into groups based on their similarities.

The accuracy of signal classification algorithms depends on the computational time required by the algorithm to analyse and link a specific event to an acoustic emission source. [5]

The following section outlines the experiments performed to test DAS and techniques for using the DAS data to identify rail defects such as broken rails.

3 Field test methodology

The research performed a series of experiments to test the ability of distributed acoustic sensors to detect broken rails. These experiments were carried out at an Austrian Federal Railways training facility in Wörth (Bildungszentrum Wörth) from 21 to 23 January 2019.
A total of 77 experiments were performed, all of which were carefully documented and recorded. Most of the experiments consisted of running a test train over different sized rail gaps at varying speeds. An additional experiment consisted of using a pulling device to break a rail. All the experiments assessed whether signals produced by the vibrations caused by driving over a broken rail (or breaking a rail) in a fibre optic cable could be used to detect broken rails. The data from these experiments was subsequently processed using the techniques outlined above and represented in a MATLAB for analysis and interpretation.
If DAS is to be an effective technology for identifying broken rails, then the signal generated by the vibration must be clearly identifiable: both the fact that there was a vibration and what caused the vibration. More specifically it must be possible to distinguish between the following irregularities:
- Gap in rail
- Broken rail
- Gravel on rail (often misinterpreted as broken rail by train drivers).

The experiments were carried out on a 100-metre length of test track. The test train consisted of a locomotive (ÖBB 2070-080) and two flat wagons (type 21 81 3310). The tests were carried out in January because the rails were expected to be more brittle in cold weather. Moreover, since metal contracts at low temperatures, the tracks move further apart in case of a break.
The acoustic sensor equipment used in the experiments consisted of fibre optic cable laid along the rail or in an adjacent trough, an interrogator device (which transmits the light signal in the cable), an optical time domain reflectometer (which collects and digitises the light signal as well as the returning light), and a processing unit (which digitizes the signal and saves, filters, and displays the data). An overview of the fibre installation is shown in Figure 2. Accelerometers were attached to the rail to measure track acceleration and data was collected on train movement (e.g., speed), track temperature, and weather.

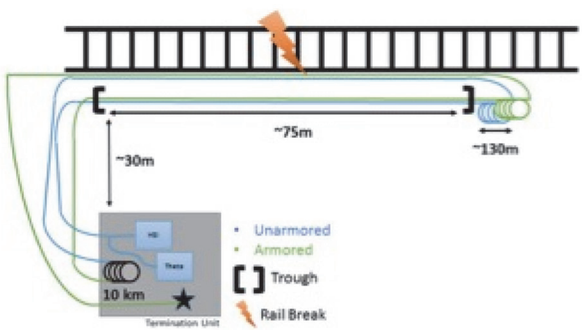

Figure 2 Schematic illustration of experiment test track section

The tests were performed by operating the vehicles over the test track described above. During the test, the train speed was kept as constant as possible in the measuring area. The following tests were performed:
- 22/01/2019: Running over an unwelded track joint with varying gap widths (3.5 mm/5 mm/9 mm/12 mm/18 mm/25 mm) at speeds of 5, 10, 15, 20 and 25 km/h in both directions (oscillating over the measuring point).

- 23/01/2019: Breaking of the cut rail and running over the resulting fracture (38 mm) at the same speed as on the previous day, also in both directions.
- 23/01/2019: Running the train over gravel stones placed on the tracks (25 km/h).

The test results are outlined in the following section.

4 Field test results

The first set of tests investigated if DAS could detect a train traversing a rail joint with a specified gap. In all experiments acceleration sensors on the rail and on the floor of the trough confirmed that the train running over the gap caused vibrations.

The raw acoustic data was collected by the DAS sensors and several digital signal processing techniques were tested to evaluate their ability to detect the vibrations. The three most promising techniques were gradient analysis, train consist convolution, and 2D sinusoidal convolution. Figure 3 illustrates the raw data, Figure 4 illustrates the data after processing with gradient analysis. The position and time at which each axle traverses the rail joint is indicated by red crosses. This feature can be seen to be more prominent at these positions.

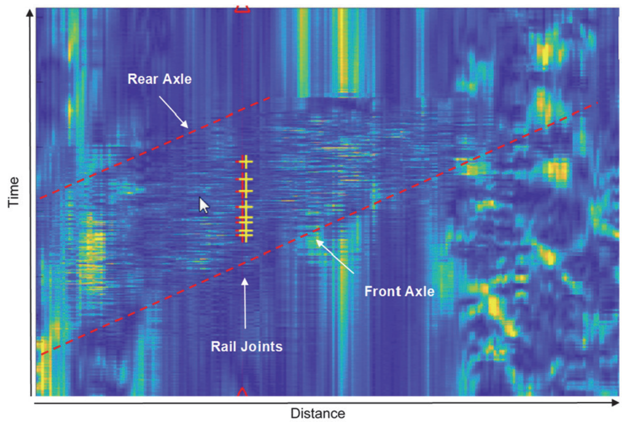

Figure 3 Raw DAS data with train position shown in red dashed lines and positions of two rail joints (red and yellow crosses)

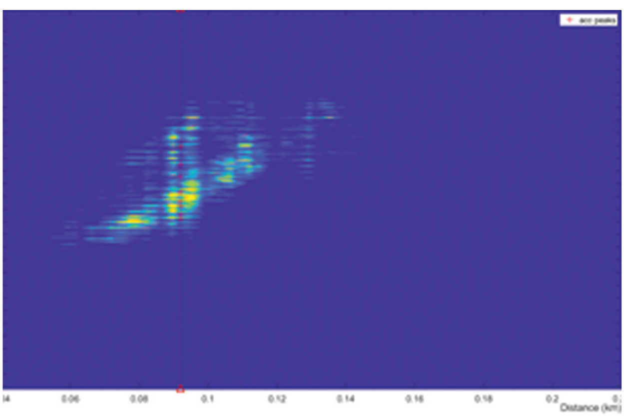

Figure 4 Gradient analysis on Measurement 26 (25 mm gap at 25 km/h). Vertical axis is time, horizontal axis is distance. The position and time at which ach axle traverses the rail joint is indicated by red crosses. This feature can be seen to be more prominent at these positions

The test results showed clearly that the rail gaps (simulated rail breaks) can be found in the DAS data with the right means of signal processing. The best signal clarity was observable at the higher speed of 25 km/h. At lower velocities the signal processing methods were not as likely to represent the significant features of the rail break. This should not pose a problem for practical use of DAS since most trains operating on open line, where rail breaks are most dangerous, will be traveling over 25 km/h.
The second experiment tested the ability of DAS to identify breaking rails by analysing the data generated when a partially cut section of rail was mechanically pulled apart using a hydraulic press. Again, the accelerometer data clearly showed vibrations at the moment when the rail breaks. The same pre-processing steps were applied to the DAS data and then frequency analysis was used to evaluate the data. The frequency analysis results are shown in Figure 5.

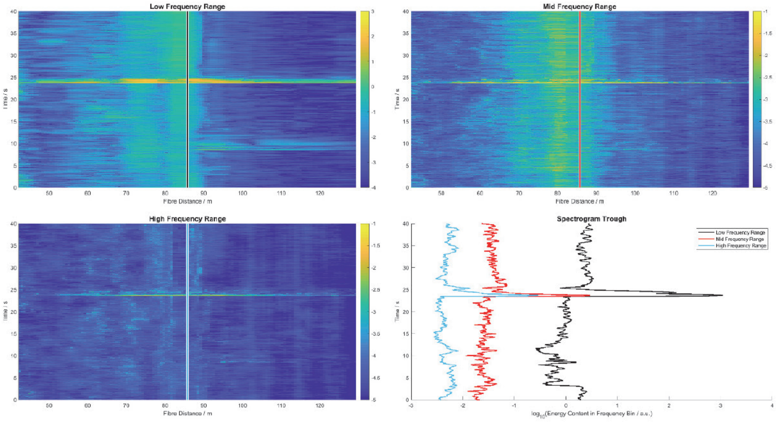

Figure 5 Bandpass analysis of rail break event. Low frequency (top-left), Mid frequency (top-right), High frequency (bottom-left), Overlapped bandpass powers at the position of the event (bottom-right)

As shown in Figure 5 the processed DAS data clearly shows when the rail break event occurred. A high amplitude, impulsive signal can be observed clearly in all frequency bands, as is expected for such a broadband event.The final experiment investigated if a train running over and pulverising stones or rocks placed on the top surface of the rail could, first, be detected, and, second, be distinguished from a train passing over a rail joint or broken rail. Raw DAS data for these experiments were analysed using the same procedures described above. One example result is shown in Figure 6.

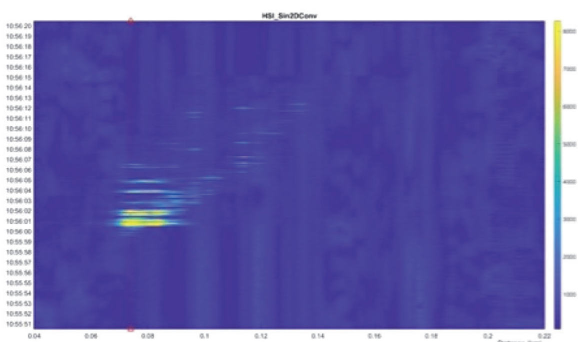

Figure 6 2D sinusoidal convolution applied to DAS data of train running over two stones. Signal is observed at the position of the stones (red triangles)

5 Conclusions

The main research conclusion was that distributed acoustic sensing (DAS) has good potential for detecting broken rails. The processed DAS data was able to identify a rail gap (break) at all the widths tested, but the gaps were most obvious at velocities ≥ 25 km/h. The most promising analysis techniques for identifying gaps were gradient analysis, convolution using the train consist, and 2D sinusoidal convolution. The DAS data was also able to identify the moment a rail breaks and was able to distinguish between stones on the tracks and rail breaks. In Figure 6 the individual impacts from each wheel on each stone can be observed. Additionally, it is noted that with each successive wheel traversal the signal reduces in amplitude, probably due to the pulverized stone being subsequently flattened by each pass of a wheel. This is not the case for a rail break where each axle should create a similar impact force. This difference may therefore potentially allow the distinction between stones on the rail and a rail break.
The full research report and data has been documented in the UIC Broken Rail Detection Project Work Package 6 Report [6].

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