ACOUSTIC EMISSION INSPECTION OF RAIL WHEELS

KONSTANTINOS BOLLAS, DIMITRIOS PAPASALOUROS, DIMITRIOS KOUROUSIS and ATHANASIOS ANASTASOPOULOS
Envirocoustics SA, El. Venizelou 7 & Delfon, 14452 Metamorphosis, Athens, Greece

Abstract

The ever-increasing demand for safer and faster surface transportation such as railway imposes many challenges for the inspection of critical components such as train axes and wheels. These components, mostly during usage, are subjected to highly complex dynamic loads and active defects may result in catastrophic failures, possibly with human casualties. Within the scopes of an R&D project, aiming to develop novel methodologies and techniques for the inspection of wheel sets, extensive acoustic emission (AE) measurements have been performed on various trains and trams. AE sensors were mounted on the rail in order to diagnose wheel problems by monitoring the AE transferred through the rail in real-time and while the vehicles were moving. The purpose of the trials was to investigate the usage of AE for on-line detection of defects on wheels such as flats, bearing failures and possibly significant cracks, and to establish optimum setup parameters in this respect. The present paper presents the raw data and evaluation results from AE experiments on train and tram wheels, (both healthy ones and wheels having known defects). During measurements different AE sensors were placed on the side of the rails while the railcars or trams were passing at different speeds. The effect of sensor frequencies and placement were investigated. Multiple AE datasets, i.e., Time Driven Data (TDD), Hit Driven Data (HDD) as well as long (>10 sec.) waveforms were acquired simultaneously. Data analysis involved traditional AE features, source location and digital signal processing of acquired waveforms. Initial results presented highlight the different AE behavior for defective and non-defective wheels, and indicate clearly the potential of AE as diagnostic tool. Furthermore, results show that the availability of acquired long, continuous waveforms significantly enhanced analysis capabilities, when combined with advanced AE DSP software and pattern recognition analysis.

Keywords: Train wheels inspection, rail axes monitoring, long waveforms

Introduction

Inspection of rail wheels poses inherent difficulties due to accessibility issues, when the wheels are mounted on the train, but also due to the complex geometry of the wheels, their shape and their attachments. As a result, current inspection methodologies are mainly based on dismounting the wheels and inspecting them off-vehicle, or, in the best case, on an immobile train, either on a periodic or on a need basis (e.g., see [1]), by means of localized NDT (MT, PT, UT, EC, VT etc.). Still, however, failures occur, that occasionally lead to catastrophic accidents. The need to identify wheel flaws at early stages and in a more efficient way, reducing maintenance costs, has steered research efforts towards on-line wheel inspection techniques, such as vibration and AE. The aim of such techniques is to be able to identify flawed train wheels, while the train is in-service (moving) and the “screen out” of bad wheels for further inspection and maintenance, in a fast, effective way.

In this respect, AE [2] method has been identified as a very promising tool. Acoustic emission uses high-frequency, passive piezoelectric transducers, which are mounted on the side of the
rails, in order to detect the stress waves generated by the various possible flaws of the wheel, for instance, flats, or other circularity defects, which are impacting on the rail while the wheel is turning, or crack opening, or even faulty bearings from the axes. Since other AE sources are present, even in a healthy train (engine noise, frictional noise, banging noise, etc.) the technique, at a first stage, usually involves acquiring the AE “signature” of a vehicle with healthy, “reference” wheels, and comparing this to the one of a vehicle with defective wheels. The method offers significant advantages compared to other passive methods, mainly due to the high sensitivity it offers, as well as the fact that the AE transducers operate within high-frequency range (30-1000kHz), eliminating to a large extent, mechanical noise. Once calibrated and standardized, the method may be employed very effectively, for instance by mounting sensors on all rails of a depot and “listening” to the trains or trams as they exit for their shift. Each wheel is “inspected” as it passes from the point of the rail where the AE sensor is located, thus, within a single day, all wheels in usage may be inspected.

Acoustic emission has already been applied for the detection of rail track faults at laboratory level [3, 4]. However, only a limited number of field experiments have been carried out [5, 6].

The present research has received funding from the European Community’s Seventh Framework Programme (FP7/2007-2013) under grant agreement no 218674 of SAFERAIL project [7]. The SAFERAIL consortium seeks to minimize wheel set failures by developing and successfully implementing a novel on-line system for the inspection of wheels and axles of moving trains, and a combined ultrasonic-electromagnetic system for faster and more reliable inspection of the quality of new and old wheel sets during their production and maintenance. The present work studies the application of AE for the on-line inspection of rail wheels, investigating various hardware parameters such as sensor frequency, test parameters such as type and velocity of vehicles, as well as data acquisition and analysis strategies. Results show the ability of the technique to detect wheel flaws, while the methodology is still under optimization in terms of resources used, and analysis time.

![Fig. 1 – 56 tons ALLAN railcar with distances between wheels.](image-url)
**Instrumentation**

All presented data has been acquired using systems based on the Physical Acoustics Corp. PCI-2 AE boards [8], which have the capability of acquiring AE data with long (>10 s) waveform streaming directly to hard drive. Four different types of AE sensors have been investigated: Physical Acoustics’ R3i (30 kHz resonant), R15 (150 kHz resonant), R30 (300 kHz resonant) and R50 (500 kHz resonant). Data was acquired by AE-Win real-time data acquisition software [9], while advanced data analysis has been performed using NOESIS, a specialized AE data analysis and pattern recognition software [10].

For the scopes of this work three different data sets of field trials are presented, which were acquired at three different sites, two involving trains and one involving trams. AE equipment has simultaneously acquired TDD, HDD and waveform streams (WFS). The importance of the availability of each individual data set and its significance in data interpretation are clearly demonstrated. Additionally, advanced and versatile software tools were utilized in order to fully analyze multiple aspects of the acquired data.

**Case Study - AE Monitoring of Train Wheelsets in EMEF Depot, Oporto, Portugal**

*Experimental Setup and Wave Propagation Study*

A 56-tons ALLAN railcar (Fig. 1) was used for the AE measurements and was provided by EMEF. On all experimental setups the sensors were placed on the external rear side of the rail, using silicon grease and supported by magnetic clamp, as shown in Fig. 2a. Pencil-lead breaks (Hsu-Nielsen sources) were performed on the rail track for attenuation and wave velocity estimation (Fig. 2b).

Sensors were installed in ways that could lead to location detection of possible wheel defects during train passing along the rail. On the 3&1 setup, three sensors were placed on one rail on a distance equal the half of the wheel perimeter and a fourth sensor was placed on the other rail opposite to sensor No. 1 position (Fig. 3). The same setup was maintained for all sensor types, e.g. 3&1 setup for R15s, the same 3&1 setup for R30s etc. in order to be able to compare directly the sensitivity differences of each sensor type.

In order to be able to have location evidence of possible wheel defect, different location settings were investigated, using the calculated wave velocities and placing the three (3) sensors at a
time within known distances from each other. For the specific setup the distance between sensors was 1.8 m. Pencil-lead breaks (PLB) were performed on distances approximately 0.6 m, 1.2 m, 1.8 m and 2.4 m from sensor No. 1. Figure 4 shows the results of a location check. Y-axis shows the sum of AE events caused by the PLB while X-axis shows the sensor position using the first sensor as reference. It is evident from Fig. 4 that the specific location settings and/or setup are adequate to locate four distinct pencil breaks in a 3.6 m span with high accuracy. Therefore, any possible wheel surface defects are expected to yield similar results.

![Fig. 3 – 3 & 1 Sensor setup (3 on one side and 1 on the opposite side).](image)

Fig. 3 – 3 & 1 Sensor setup (3 on one side and 1 on the opposite side).

![Fig. 4 - Location check graph showing the real position of the PLB and the position as located by the AE system.](image)

Fig. 4 - Location check graph showing the real position of the PLB and the position as located by the AE system.

Figure 5 shows the arrival times and amplitudes of a PLB signal performed at 0.6 m from sensor No. 1, as acquired from three sensors located on the same rail track at 1.8-m distance from each other. The corresponding waveform as received for the sensor No. 1 at reference position is shown in Fig. 6, while Fig. 7 shows at sensor No. 2 at 1.8-m distance from sensor No. 1 position and 1.2 m distance from the PLB source. From the sensor No. 3 at 3.6-m distance from sensor No. 1 and 1.8-m distance from the PLB source, waveform in Fig. 8 was observed. Note sensor numbers correspond to channel numbers in Fig. 5, which shows 7 dB attenuation over 0.6-m distance from No. 1 to No. 2 and 13 dB over 2.4 m from No. 1 to No. 3.
AE Monitoring of Train Wheelsets

AE acquisition measurements were performed during train passes at the area where the sensors were installed. Train passes were made with different speeds from 5 to 40 km/h as reported by the train driver and in different directions (to left or to right). In all cases the train speed was kept constant. Three parameters were selected as most probable either to produce and/or change the AE activity during the test runs. These are the actual speed of the train, the geometry of the railcar and the actual surface condition of the wheels.
AE data was analyzed using special pattern recognition software (NOESIS v.5.5). AE features like signal amplitude, duration, energy, average signal level, etc. of acquired AE signals were compared using the different resulting data sets from:
- Same Railcars - Different Railcar Speeds,
- Different Railcars - Similar Railcar Speeds.
- Railcar before Defect Generation – Same Railcar after Defect Generation

All comparisons were performed using data from same train direction.

Specifically for the testing of the surface condition parameter, flat surfaces were generated (Fig. 9) on the defect-free wheels by applying the emergency brakes multiple times. The AE after each emergency brake was acquired enabling the comparison of the damage accumulation in different states of the flat surface development. An example of raw waveform streams of 10-s duration after seven emergency brakes is shown in Fig. 10. Here, 3 & 1 setup was used, and the side with three sensors shows slightly lower amplitude. Note increasing signal attenuation in channel 1, 2 and 3. Since the surface of each wheel during emergency braking is accumulating damage in the form of either newly created flat surfaces or enlargement of the existing ones, each wheel can be characterized by a “defect status” directly dependent on the number of emergency brakes. The defect status is shown in Fig. 11 as AE events location graphs, representative of AE signals density for 40-km/h railcar travel.

![Fig. 9 - Flat defect on a wheel surface created by emergency breaking of the train. Courtesy of EMEF.](image)

The same data analysis was applied on location capabilities of hit-driven AE data (HDD) for all datasets. In cases where location was applied, more events appeared during defective railcar movement. As can be observed in Fig. 12, at low (5 km/h) and medium (20 km/h) speed the number of located AE events is higher for the defective railcar. In contrast, at higher speed (40 km/h) less AE events can be located.
Fig. 10 - Waveform stream of 10-s duration with 3&1 setup using 4 R50 sensors after seven emergency brakes. Amplitude full-scale is 10.2V.

Case Study - AE Monitoring of Tram Wheelsets, Antwerp, Belgium

Experimental Setup

AE acquisition was performed on four different trams of different types (see an example on Fig. 13a) and defect status (two with defective wheel sets and two with non-defective ones). AE was acquired during 22 tram passes at varying speeds, in both directions. Four different types of AE sensors were used (PAC R3i, R30, R15, R50). Due to the difficulty of accessing the rear part of the rail, no location groups could be setup and no magnetic clamps could be used for placing the sensors. All sensors were attached on the rail using special adhesive grease (see Fig. 13b). Depending on the different resonant frequencies of the sensors, measurements using various low- and high-pass frequency filters were performed.
Fig. 11 - AE events location graphs of AE signals density for 40km/h railcar speed with different defects statuses.

Fig. 12 - AE events location graphs of AE signals density for different railcar speeds of 5, 20 and 40 km/h, before any emergency brake (clear wheelsets) and after 7 emergency breaks (defective wheelsets).
Various types of analyses have been performed. These include comparison between data of defective and non-defective railcars, repeatability check of data acquired with same conditions (same railcar and railcar speed, same railcar direction, etc.), attempt to separate signals of different wheels by long-duration waveform analysis, filtering effectiveness check on acquired data. However, the analysis of this particular set of data (tram measurements) focused mainly on long-duration waveform processing with advanced DSP methods.

Prior to experimental measurements, signal attenuation was calculated across the rail. Placing the sensors on a steady point on the rail and using three different AE sources (Hsu-Nielsen, and small/large metallic spherical impactors) across the rail, attenuation measurements were performed and graphs were created (Fig. 14).

Fig. 14 - Attenuation graph showing signal amplitude (in dB) vs. distance from sensor, for four different types of sensors (R3i, R15, R30, R50), (a) using a Hsu-Nielsen source (PLB), (b) using a small metallic spherical impactor.
Case Study - AE Monitoring of Tram Wheelsets

Analysis of long-duration waveforms either by visual observation or using DSP tools revealed the potential that continuous AE data offers. Observation of the overall signal acquired during passing of a wheel above the sensor position allows the determination of the effective monitoring time, i.e. the period of time during which the train creates detectable AE signals, thus, allowing data collection period determination for future tests (Fig. 15). Focusing on the waveform allows the user to observe peaks in the voltage signal, which are generated when each axis passes right on top of the sensor. Furthermore, the existence of flats may also be demonstrated as voltage peaks, thus, zooming on such, and performing frequency analysis on specific sections, it is possible to observe the frequency contents of specific sources, enhancing signal interpretation. Finally, RMS or ASL processing, which basically offer a “smoother” or averaged representation of the signal, allows the user to conveniently perform time-based calculations, such as observe the time difference of the axes and bogies as they pass from each sensor and allow macroscopic observation of signal level differences, which may be periodic, indicating transient/banging AE from flats, or continuous, indicating possible bearing problems.

Fig. 15 - AE waveform (top) and RMS graphs (bottom) acquired by a PAC R50 sensor during passes of a railcar (tram) with 3 bogies (6 axes) and a flat on the first axis.

AE acquisition measurements were performed during 22 tram passes at the sensor installation point (see e.g., Fig. 16). Trams were passing with different speeds from 15 to 40 km/h, as reported by the train drivers, and different directions (back or front). In all cases the tram speed was kept constant, while passing on the sensor position. Data was analyzed using pattern-recognition software (NOESIS v.5.5). AE features like signal amplitude, duration, energy, average signal level, etc. of acquired AE signals were compared using the different data sets from:

Same Trams - Different Trams Speeds,
Different Trams - Similar Trams Speeds.

Tram before Defect Generation – Same Tram after Defect Generation
It was expected that tram passes with same characteristics (same tram, same speed, same direction) would result in similar signals and waveforms.

Following the above measurements and preliminary analysis of the acquired data, observations made on the conditions of the experiments produced recommendations below:
(1) Location groups have to be setup by placing AE sensors on known distances along the rail. The reporting of vehicle speed has to be done exactly. Signals acquired with similar but not equal speeds may result in inconsistent results.

(2) As noted on the last experimentation in Oporto Portugal, the defects have to be created on the wheels surface by controlled damage and their number, size and position on each wheel has to be known on-site. They also have to be characterized as “accepted” or “not accepted” according to international or local (train company) standards. Their position on each wheel has to be known, in order to be able to calculate exactly the position of the contact point between the flat defect and the rail, for location purposes.

(3) A trigger, in combination with known train speed, has to be used on the AE system, in order to be able to synchronize the train position with the acquired data.

Fig. 16 - AE waveforms acquired by (a) R15 sensor and (b) R30 sensor during passing of the same defective tram at 40 km/h. Display duration: 4 s.

Fig. 17 - Sensor setup on the right rail track.

**AE Monitoring of Train Wheel sets at VTG Site in Long Marston UK**

Previous results have demonstrated the potential of location analysis for feature-based AE data, as well as long-duration AE waveform analysis. It is concluded that geometric wheel
anomalies appear in the time domain as specific peaks of the voltage signal. In order to fine-tune the detection capabilities of AE to be used for the real time monitoring a 4&2 (4 sensors on 1 track an 2 on the opposite) setup was used.

Two R30a sensors and two R15i sensors were mounted on the same track at 1/3 distance from the tracks ends (Fig. 17). Similarly on the opposite track two R15i were mounted in order to acquire any AE transients that may propagate through various wave paths. The use high-frequency sensors are deemed necessary in a noisy environment. The acquired signals are less prone to active mechanical noise sources (engine, etc) that are usually found at lower frequencies of the spectrum and contaminate or even mask useful AE data. The results presented here are based on raw data acquired with high-density TDD while full analysis is ongoing. Using TDD with a very high sampling rate, a near-continuous acquisition of time-based AE Features can be achieved (ASL, RMS, Absolute Energy, etc.). In order to correlate the AE activity generated with the active defects, two different flat surfaces that spanned 2.5 cm and 5 cm on the wheels circumference were generated with an angle grinder (Fig. 18).

![Fig. 18 - (a) 2.5-cm flat surface on wheel, (b) 5-cm flat surface on wheel.](image)

The train’s configuration was a locomotive and two attached wagons with identical dimensions. The first wagon after the locomotive was used as a reference wagon, since its wheel sets had no defects. AE activity was acquired during forward (left-to-right) and backwards (right-to-left) movement. Different data sets were acquired for different speed levels for both directions.

As shown in Fig. 19, both defects are clearly depicted as periodic spikes in the ASL vs. time graphs. Such spikes are completely missing from the reference (healthy) wagon. Additionally, time measurements between the edges of the spikes have shown that these occur at a frequency coinciding with the wheel rotation frequency.

**Conclusions**

Work on AE monitoring of train wheelsets on moving trains and trams using AE sensors mounted on the rails has verified the potential of the method in detecting geometric defects, such as flat surfaces on wheel circumference. To achieve optimum results, multi-dimensional analysis has been performed, combining TDD, HDD and long-duration waveform streams acquired simultaneously. Combined analysis with specialized software is required to reveal the full potential of all available data in the time and frequency domain. Placing more than one AE sensor on the rail track and setting up a location group can show existence of flats on lower railcar speeds, but for exact location of the defect further work is required.
Fig. 19 - (a) Reference train movement, (b) 2.5-cm flat defect surface, (c) 5-cm flat defect surface. All top graphs: Channel 5 ASL vs. time, bottom: Channel 6 ASL vs. time.
Acknowledgment

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement no 218674, SAFERAIL project (http://www.saferail.net/). The authors would like to thank all Project Partners and gratefully acknowledge the contribution of Vlaamse Vervoersmaatschappij De Lijn, Belgium, VTG Rail, UK and EMEF SA, Portugal for providing access and resources for the tests.

References

1. Norme Européenne CEN/TC 256, prEN 15313:2007: Railway applications — In-service wheelset operation requirements and in-service and off-vehicle wheelset maintenance.