Autonomous Embedded Vibroacoustic Measurements: an efficient tool for railway monitoring

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Abstract

Efficient maintenance and monitoring are key points for rolling stock or railway network operators. A good knowledge of the structural health and a capability to predict evolution are main assets to ensure a high level of performance. Vibrations and dynamic forces borne by the wheel-rail contact contain the main information to reach this objective. Therefore, mechanical health features can be deduced from the signal measured on the bogie or on the rail using appropriate data processing algorithms. Moreover, the improvements in electronics and communication technologies make it possible to integrate measurement and data processing functions in a compact embedded system.

VibraTec's wheel-rail contact experience leads to consider an indirect measurement: a sensor mounted on the bogie to monitor the rail and/or a sensor mounted on the rail to monitor the rolling stock. Upon this assumption, VibraTec developed a new tool able to detect defaults and assess their evolution. To reach the objectives, the device had to be able to measure vibrations, acoustics, train speed and location, then to process and send the data. A key point is to apply dedicated algorithms developed to identify and quantify defaults from different origins operating in time domain or in frequency domain.

1 Introduction

In order to increase maintenance efficiency in the rail industry, several condition monitoring solutions have been developed over the past few years. Rolling stock or railway network operators need real-time accurate information about the structural health of their equipment. Early damage detection is a powerful tool for maintenance management: avoid customer complaints, save equipment from hard cracks, limit repair and operation times, and consequently, reduce global maintenance cost.

This paper focuses on the rail corrugation monitoring system developed in the scope of the MAVICO project. This prototype solution dedicated to railway maintenance management teams was developed in order to prevent rail corrugation effects on the track and on rolling stock equipment.

The development of communication tools and electronics components, the increase in computation capabilities, the enhancement of MEMS sensors make it possible to design an efficient Proof Of Concept (POC) for corrugation analysis. This embedded system provides timely information about the state of the rail infrastructure.

This paper begins by introducing the theoretical background of the methodology: from rail roughness to bogie (or axle box) acceleration. Then, the embedded monitoring system and its calibration process are presented. Finally, results deduced from measurements carried out on a tramway bogie running on an urban network are given. The measurement campaign was performed in partnership with Keolis Lyon, involved in the MAVICO project. The analysis focused on rail corrugation, quantified by its roughness and wavelength.

2 Theoretical background

2.1 From corrugation to bogie acceleration

During the rolling of a railway vehicle, the vertical acceleration on the bogie or the axle box may be considered, in first order, as proportional to the amplitude level of the surface defects on the rail. This consideration is true if the wheels do not have any high-amplitude default (new or recently reprofiled wheels).

The physical phenomena involving the bogie acceleration are shown on the following equations:

Step 1: Dynamic force at rail/wheel contact,

$$F(f) = Z(f).[A_w(f)+ A_r(f) + A_c(f)]^{-1} \tag{1}$$

With:
F(f), the dynamic force at contact point,
Z(f) the rail vertical defect,
A_w, A_r, A_c respectively the admittance of the wheel, the rail, and the contact,
f, the frequency dependence.

Step 2: Bogie (axle box) acceleration

$$\Upsilon^2(f)= F(f).A_{cb}(f) \tag{2}$$

With:
$\Upsilon(f)$ the acceleration on the axle box,
$A_{cb}(f)$ the transfer function between the rail and the bogie (or axle box)

2.2 Step 1 : from Rail vertical defect to Dynamic force

The vertical dynamic force spectrum at the contact generated by the defect is deduced from the product of the vertical defect spectrum of the rail *F(f)* with the transfer function $[A_w(f) + A_r(f) + A_c(f)]^{-1}$ with:
the vertical receptance of the path seen from the contact $A_r(f)$,
the vertical receptance of the vehicle seen from the contact $A_w(f)$,
the receptance of the contact $A_c(f)$, defined as the inverse of the Hertz stiffness.

N.B. The receptance corresponds to the dynamic flexibility; it is defined as the ratio between the vibration amplitude *Z(f)* at the excitation point and the applied dynamic force *F(f)*.

These three receptances are available by calculation or/and by measurement; VibraTec has developed GroundVib software which calculates them, using the track and material properties. This calculation approach makes it possible to take into account the impact of track design in the transfer function between the default and the acceleration on the vehicle.

This step is presented in section 3 of this paper.

2.3 Step 2: from dynamic force to bogie acceleration

The level of acceleration on the bogie is deduced from the contact force spectrum using the transfer function $A_{cb}(f)$. This transfer function can be calculated from the ratio between:

- the roughness Z ($1/\lambda$) measured by the corrugation measurement trolley (e.g. Figure 1) on a portion of the track, and

- the vertical acceleration recorded on the bogie $\Upsilon(f)$, in running conditions at the speed V of the train on the same portion of track.

Figure 1: rail corrugation analysis trolley

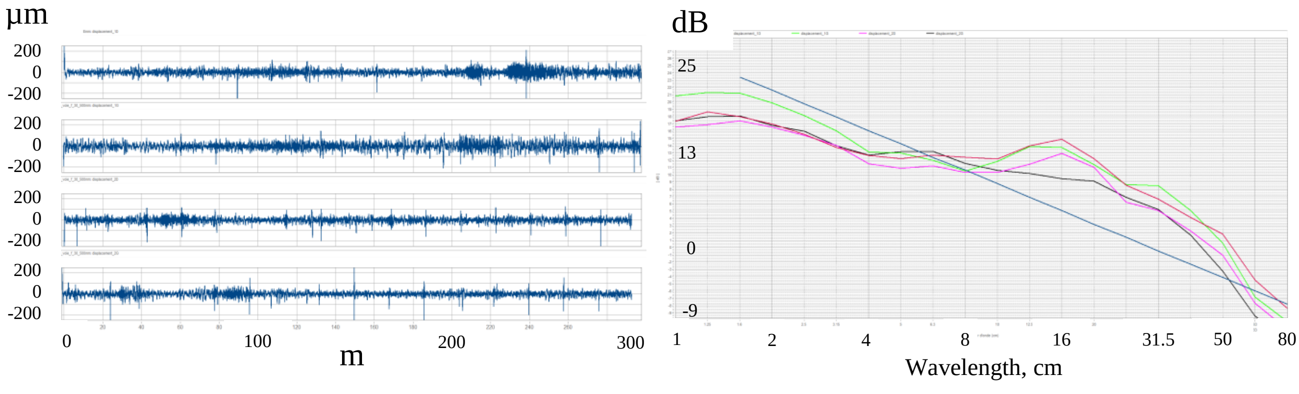

Figure 2: Left side: roughness in µm measured on 4 track lines.
Right side: Associated roughness spectra (1/m) of a portion of track

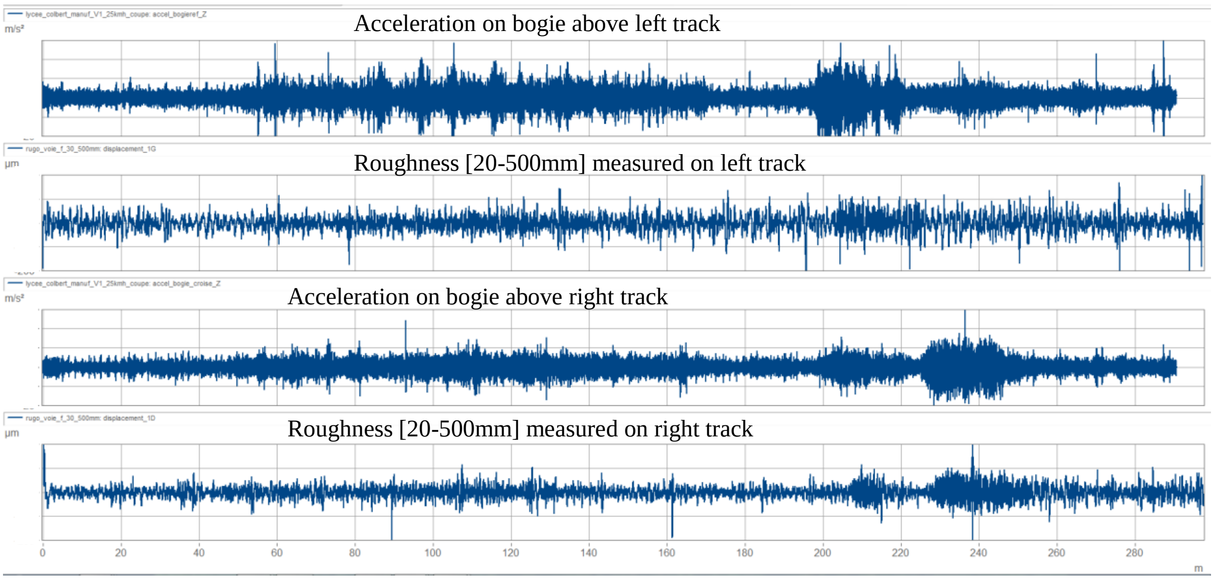

Figure 3: Accelerations measured on a bogie and roughness on the same portion of track at 25 km/h

A post-processing of these two measurements makes it possible to compute the transfer function $\Upsilon^2(f)/Z^2(f)$, by a conversion of the roughness abscissa '1 / λ' to a frequency abscissa 'f' using the train speed 'v'.

3 Practice: From bogie acceleration spectrum to rail corrugation

The methodology for determining the track roughness from the acceleration measured on the bogie is shown in the equation (3).

Part of the input is the transfer function $[\Upsilon^2(f)/ Z^2(f)]$ established in paragraph 2 of the preceding process. The reference transfer function, estimated on one or more reference sections, is inverted to obtain the transition function between the bogie acceleration and the track roughness: $[\Upsilon 0^2(f)/ Z0^2(f)]^{-1}$.The roughness PSD is then directly computed using the product of the acceleration with the transition function.

$$Z^2(f) = [\Upsilon_0^2(f)/ Z_0^2(f)]^{-1}. \Upsilon^2(f) \quad (3)$$

With:
$\Upsilon^2(f)$ the bogie acceleration PSD
$Z^2(f)$ the rail roughness PSD

Results can be evaluated by comparing the calculated roughness with the direct roughness measured by the trolley on a section of track which was not used in the transfer function definition. Figure 4 presents this kind of comparison for a 50m section.

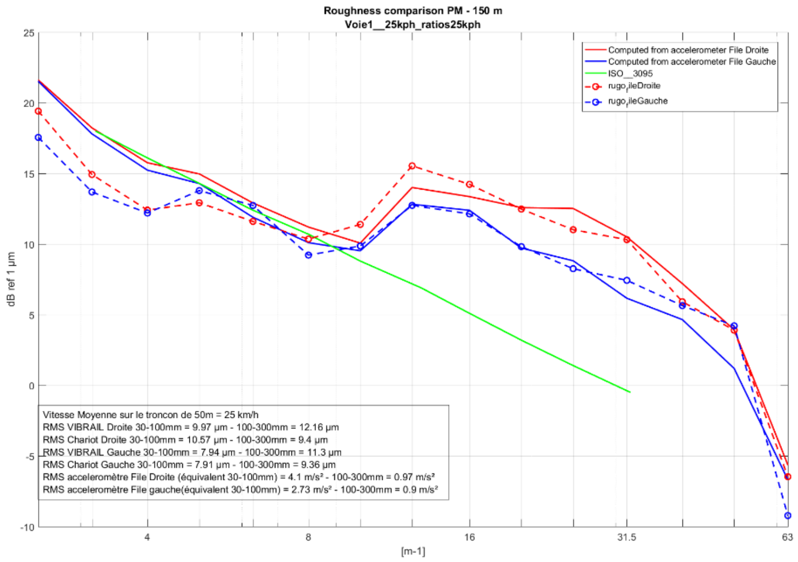

Figure 4 : 1 Third octave spectra (in 1/m) measured (with trolley in dashed lines) and computed (with inverse method in solid lines). In green, the ISO 3095 standard

4 Developed tools

A dedicated tool has been developed to monitor the bogie acceleration, the acoustic pressure in the bogie area, the speed and localisation of the train on the network.

The device contains:

-A data logger that records analogic channels and stores high-speed (acoustic pressure, vibration, and speed tachometer), and low-speed sampling rate signals such as GPS data,

-A 4G router that transmits the data from the train to VibraTec servers,

-A battery to ensure the transfer of data during train electrical power outages.

The sensors used are a mix between common sensors used for vibration investigations and new MEM's technology. The global approach for the complete processing, from the sensors' raw data to the corrugation defect alert is shown in the Figure 5.

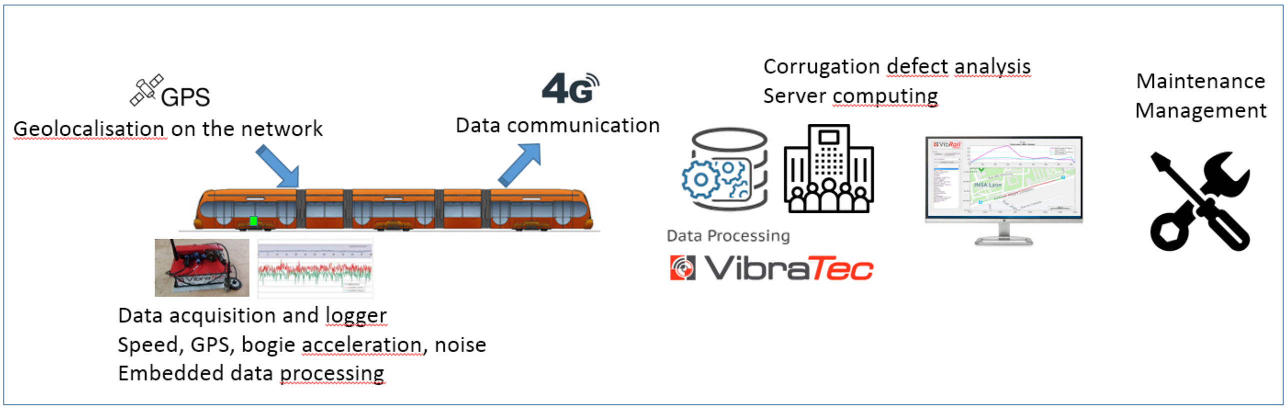

Figure 5: Global approach – from raw data to corrugation analysis

Figure 6 presents the VibRail Proof Of Concept. The tool is installed and fixed directly, wireless, on the tramway bogie, without impacting passengers, e.g. Figure 8.

Figure 6: VibRail Proof Of Concept n°2

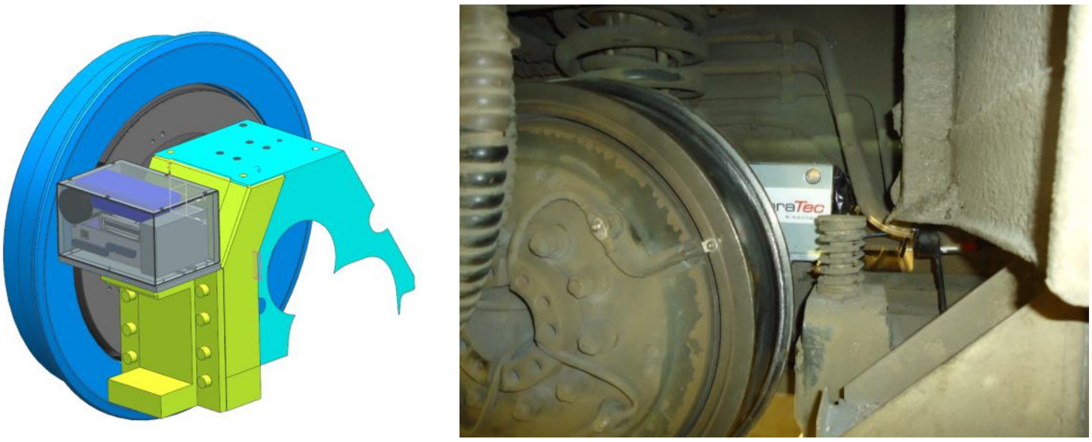

Figure 7: localisation of VibRail Concept n°1 on a tramway bogie

Examples of raw data are presented in Figure 8 and Figure 9.

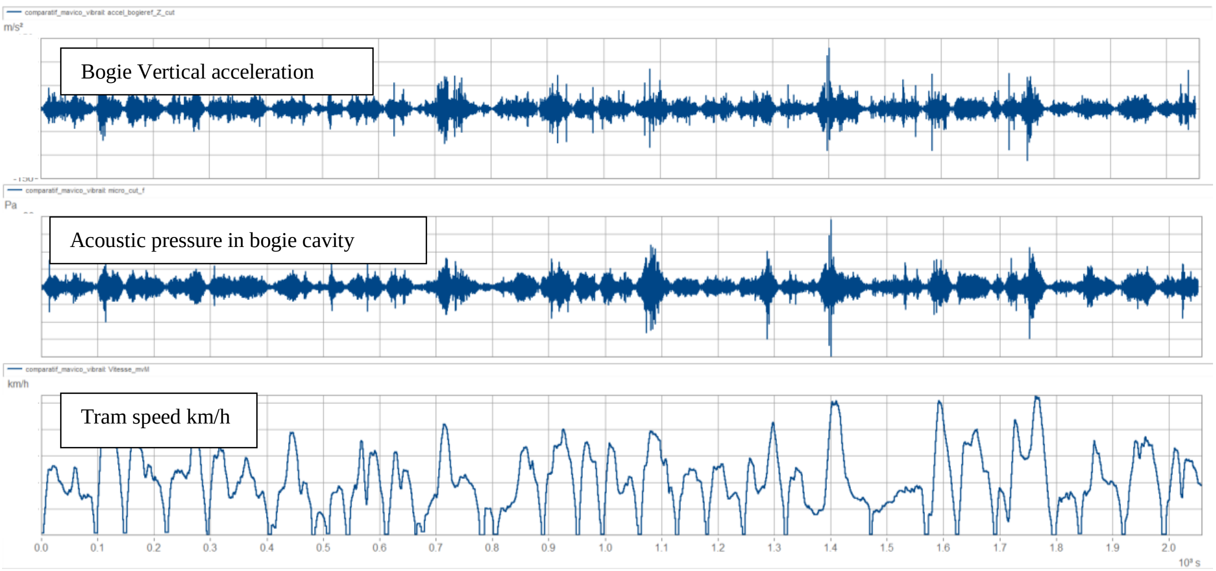

Figure 8: raw data measured by the device on the Lyon tramway network T1 Line

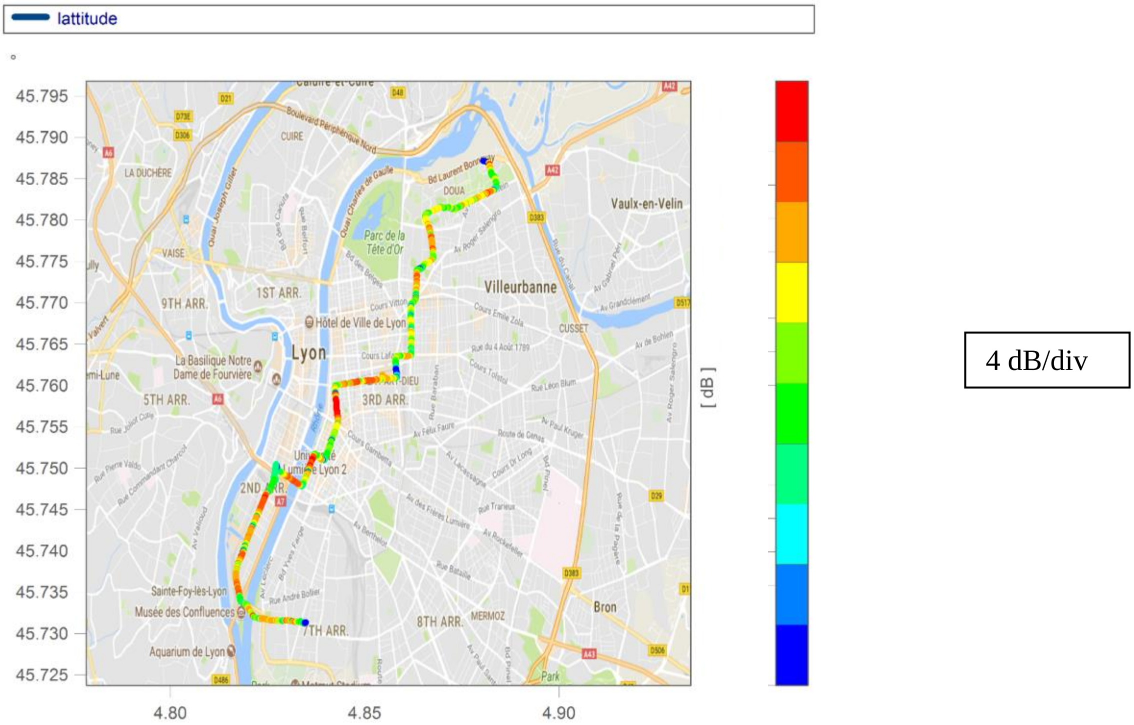

Figure 9: Lyon tramway network T1 Line. GSP track, with a color scale corresponding to RMS acoustic pressure under the bogie in dB

NB: The acoustic pressure under the bogie was monitored to detect screeching noise and send an alarm to the tramway operator to avoid disturbing the neighborhood. The principle of detection based on wheel mode resonance is not developed in this paper.

5 Measurement results

In the scope of the MAVICO research project, 3 online measurement campaigns were carried out, spaced about 6 months apart, on the full tramway network in Lyon.

Each measurement campaign was used to determine the roughness of the network tracks. Having 3 campaigns spaced in time made it possible to assess the evolution of the roughness from both operation and grinding campaigns.

5.1 Identification and quantification of Rail roughness

The wavelengths taken into account on tramway tracks are in the [30-300]mm range. The relation between excited frequencies and train speeds is presented in Table 1.

Speed	20 km/h	40 km/h	50 km/h
Frequency band	18.5 Hz – 185 Hz	37 Hz – 370 Hz	46.3 Hz – 463 Hz

Table 1: relation between excited frequencies and train speed for wavelengths from 30mm to 300mm

The people who are in charge of track surveys select the areas to be ground by riding the network aboard the tram and listening to the emergence of noise related to corrugation. A first part of the data processing was to analyse and compare the online measurement data to human perception, in order to establish a correlation between human detection and accelerations measured on the bogie. Figure 10 presents an example of this correlation.

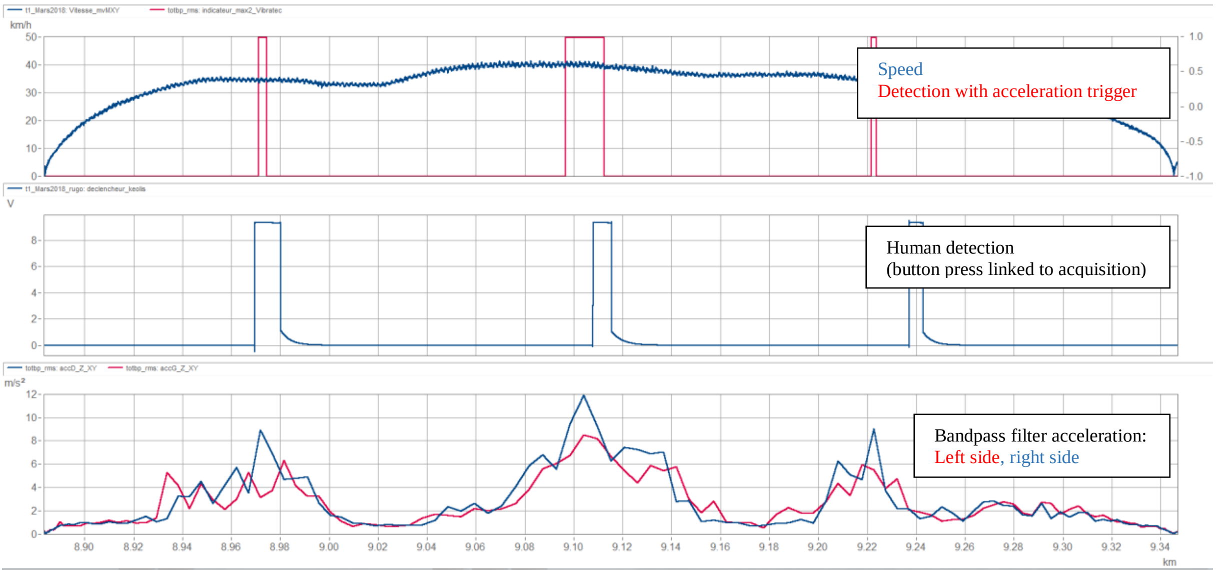

Figure 10: correlation between bandpass filtered acceleration and human detection on an interstation

In this example, a trigger was activated when the bandpass filtered RMS acceleration reached 8m/s². The correlation with human detection is satisfying and the defect localisation is more accurate than the human detection thanks to the GPS signal acquisition. One of the conclusions of this correlation with human perception is that the wavelengths involved are in the [30-100]mm range.

The second phase was to compute the absolute value of the roughness thanks to the measured accelerations and the transfer functions (equation (3)). For this purpose, algorithms have been developed to:

- locate the train on the network: line number, train direction,
- split the signals according to the interstations,
- calculate the roughness RMS level for each interstation. This level is computed versus the distance, with a sampling of 20m,
- plot this criterion on GPS maps and generate reports that allow the customer to communicate with the team in charge of grinding and/or to evaluate the actual roughness of the network.

An example of a GPS map is presented in Figure 11.

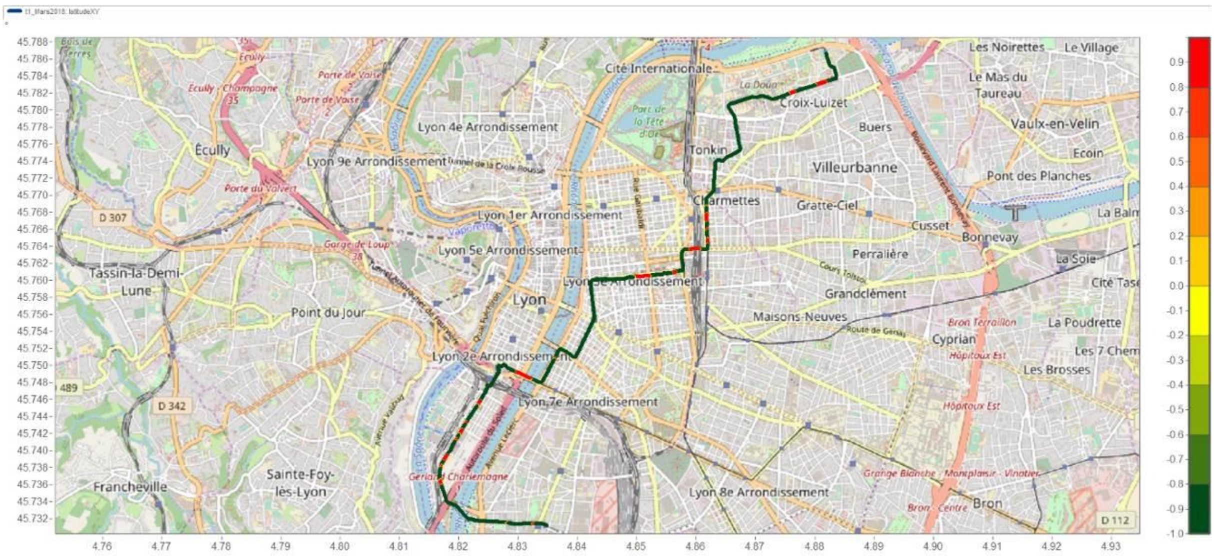
Figure 11: Example of a GPS map of the roughness level (Lyon tramway network T1 Line).

The criteria used to determine the zones to grind can be defined from the literature. In the [30-150]mm wavelength range, a criterion of 10 µm RMS can be implemented [1]. This limit can be tuned according to the corrugation expert's sensitivity, and also on the grinding budget.

Figure 12 presents the RMS roughness levels in the [30-150]mm wavelength range calculated related to the distance (for example, the starting point 0 km is the beginning of the line). The RMS level was only computed when the speed of tram was sufficient to have a good acceleration signal/noise ratio. Below this speed, the RMS was set at zero.

The red line represents the limit/criterion tuned in accordance with Keolis' corrugation expert, to fit with their detection zone (presented below).

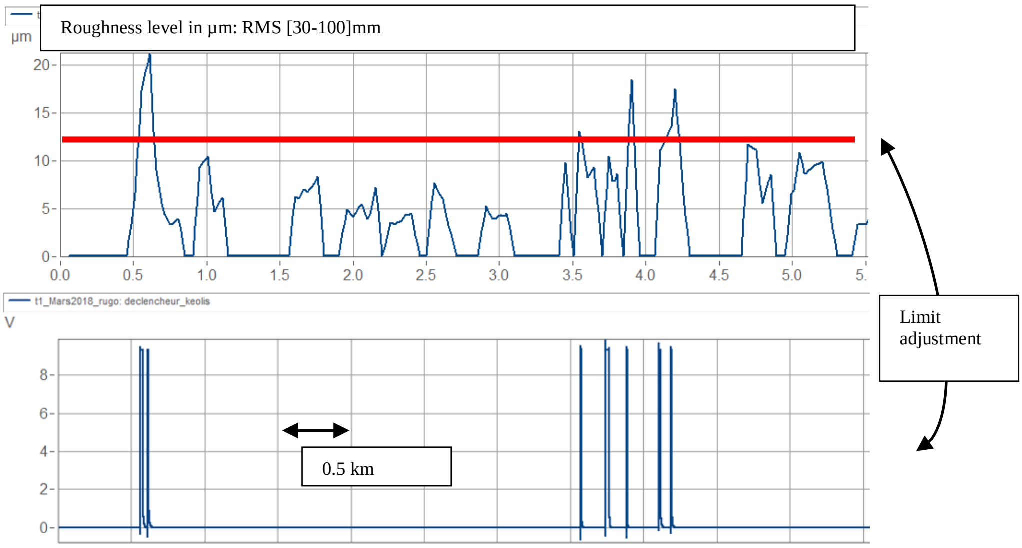

Figure 12: Top: Rail roughness - RMS level in the [30-150]mm wavelength. Bottom: Correlation with subjective detection

5.2 Interest of regular monitoring of rail roughness

Usually, grinding campaigns are performed each year. However, there is a great interest in monitoring the rail roughness more often: impact of grinding, impact of exploitation.

Figure 13 presents the rail roughness measured on the same interstation at different times. The initial roughness is presented in blue (time t_0). The roughness just after a grinding campaign (time t_1 = 8 months after t_0) is presented in red. The third roughness, 4 months after the grinding campaign, is presented in green (t_2 = 4 months after t_1).

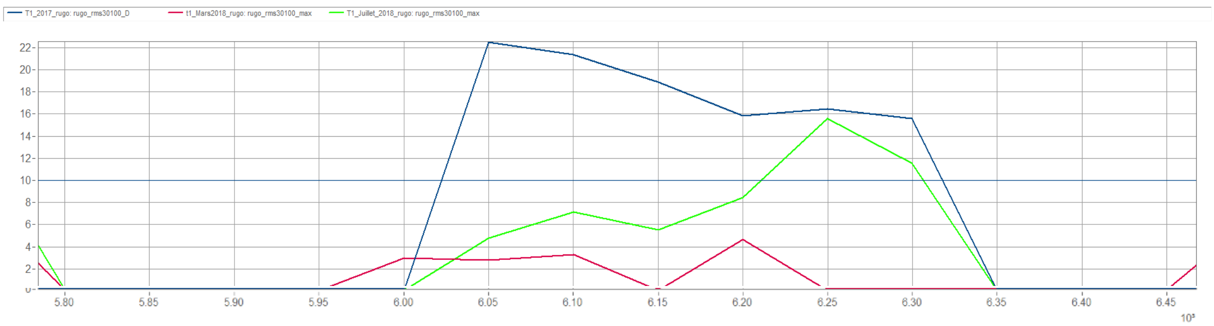

Figure 13: rail roughness - RMS level in the [30-150]mm wavelength. Status July 2017, Status March 2018, Status July 2018

In this example, the grinding campaign reduced the roughness from 22µm to 4µm RMS [30-150]mm, in the first 100m of the interstation.

The comparison of the red and green curves shows that the roughness has increased by a factor 2 in 4 months.

6 Summary/Conclusions

In the scope of the MAVICO project, a POC of an embedded monitoring system has been designed in order to detect corrugation defect on tracks. The developed algorithms are based on an inverse approach, using bogie acceleration measurements to determine the state of corrugation. This system has been assessed on the complete Keolis Lyon tramway network. This tests have confirmed the interest in the roughness level as a first indicator of corrugation defects. Moreover, steady corrugation controls are interesting for track monitoring and for early damage detection.

On dedicated track areas used for validation, the estimation of the roughness RMS level based on the indirect method is satisfying, in comparison to the classical direct measurement method using a trolley. The system described in this paper can estimate the roughness level of a complete tramway network of more than 100km in one day. In comparison, such measurements using the direct method would take several weeks.

The corrugation threshold alert has been tuned using the correlation with subjective human detection of corrugation defects. This corrugation alert described in this paper is a powerful indicator for track maintenance management.

Through a new collaborative project (MEEQUAI), an improvement of the rail-to-bogie transfer function, based on a calculation/measurement hybrid approach, is currently being studied.

Acknowledgment

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