ACCURATE QUANTIFICATION AND FOLLOW UP OF RAIL CORRUGATION ON SEVERAL RAIL TRANSIT NETWORKS

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ABSTRACT

In the scope of the European Research Project “CORRUGATION”, which focuses on corrugation in curves with transit vehicles at low speed, an instrument to quantify corrugation was developed in order to study the effect of parameters such as rail support stiffness, rail type and friction modifiers on the appearance of corrugation. This paper consists of two parts. The first part describes the development of a portable, accurate and easy-to-use instrument to measure corrugation. Within the development of the instrument, issues regarding measurement precision and measurement length, which came forward in the new prEN ISO 3095, are addressed. The second part of this paper describes the results of extensive corrugation measurement campaigns at STIB (Brussels metro and tram). It is found that in most cases, corrugation wavelengths correspond with vertical track anti resonances and/or with lateral track and wheelset resonance frequencies. Vertical track resonances can be avoided by using highly damped embedded rail or very soft rail fixation. Horizontal track resonances can be shifted outside the ‘dangerous‘ frequency band (corresponding with 20 mm - 200 mm wavelength) by using very rigid or very soft lateral rail fixation.

INTRODUCTION

Rail corrugation is a widely spread problem experienced by virtually all railway administrations around the world. Rail corrugation can have a significant impact on the maintenance effort with an increase of costs up to 30% (Krabbendam, 1956). The rail wear results in reduced rail and wheel life and can lead to urgent safety measures such as rail replacement. The increased dynamic interaction forces between wheel and rail caused by corrugation give rise to fastening, sleeper and ballast deterioration. The increased noise and vibration emissions can also be a source of significant community reaction. The European funded research project called CORRUGATION aimed at the design and validation of efficient and cost effective solutions to reduce or eliminate the corrugation problem.

Within the scope of the project, the corrugation phenomenon was considered for vehicles with low axle loads, running at low speeds (typically urban transport) and corrugation with wavelengths from 20 mm to 200 mm.

This paper describes the development of a portable easy to use rail roughness measurement device, called Rail Surface Analyzer (RSA). This device was developed to accurately quantify roughness/ corrugation in terms of its amplitude and wavelength on a large scale. It is now also used in the quality control of the grinding process which showed to be very important to avoid immediate reappearance of corrugation. The device was developed to cope with limitations such as transportability, accuracy and autonomy of other commonly used devices.

Further this device was used to study the influence of rail roughness on noise and vibration levels: a test section and the results of a measurement campaign at Brussels tram network are described in this paper.

Extensive research was also done to determine all relevant parameters in the corrugation process. This information was eventually used in the design of several solutions able to eliminate corrugation. The Rail Surface Analyzer was used to conduct extensive measurement campaigns to evaluate the efficiency of these solutions. This paper evaluates the use of a very resilient rail fastener installed on wooden sleepers in Brussels metro as one of the solutions.

DEVELOPMENT OF A MEASUREMENT DEVICE TO QUANTIFY RAIL ROUGHNESS AND CORRUGATION

The ISO 3095:2005 describes how to measure rail roughness in the support of noise measurement emitted by railbound vehicles. Up to now, this is the only widely spread protocol for rail roughness measurement that can be referred to.

Rail roughness can be measured in several ways. The measurement methods are generally divided into direct and indirect measurement methods.

Indirect measurement methods can be performed by measuring noise or vibration with an axle-box accelerometer or a microphone located under the train or in the passenger coach. Alternatively, the measurements are not measured on-board a running train but at the track by measuring rail vibration during train passage. However, to minimize the influence of the wheel roughness in these measurements, indirect methods should be performed with permanently smooth, disc or sinter-block braked or unbraked wheels. This is often difficult to control and verify.

With a direct measurement method, the rail surface is scanned directly and separately from the wheel roughness. To determine the parameters responsible for rail corrugation development, to study the influence of rail corrugation on noise and vibration levels and eventually to develop and evaluate systems which limit roughness growth or eliminate rail corrugation, it is important to use a direct measurement technique and accurately quantify rail roughness/corrugation in terms of its amplitude and wavelength.

Rail roughness measurement is also becoming increasingly important with respect to strategic noise mapping which will be required in Europe for major railways in 2007 according to the European Environmental Noise Directive adopted on 25 June 2002. Generally accepted computation methods for railway noise now take into account rail roughness, as this can lead to noise level differences up to 15 dB(A) as reported by several researchers (e.g. Alias, 1986).

Within the scope of the Corrugation project, a portable, affordable, easy to use measurement device was developed as no suitable product was commercially available to quantify corrugation in terms of their wavelength and amplitude on a large scale and on several different networks. This device is now commonly used and referred to as Rail Surface Analyzer (RSA-figure 1).

When speaking of short wave irregularities, better known as corrugations, one should typically think of peak to peak values, in a waveband between 0 and 200 mm, in the order of 0.05 mm. Although corrugations with amplitudes of some hundredth of a millimeter can be recognized by the human eye, it is difficult to measure them sufficiently accurate with a low noise floor; with an error of less than 0.01 mm.

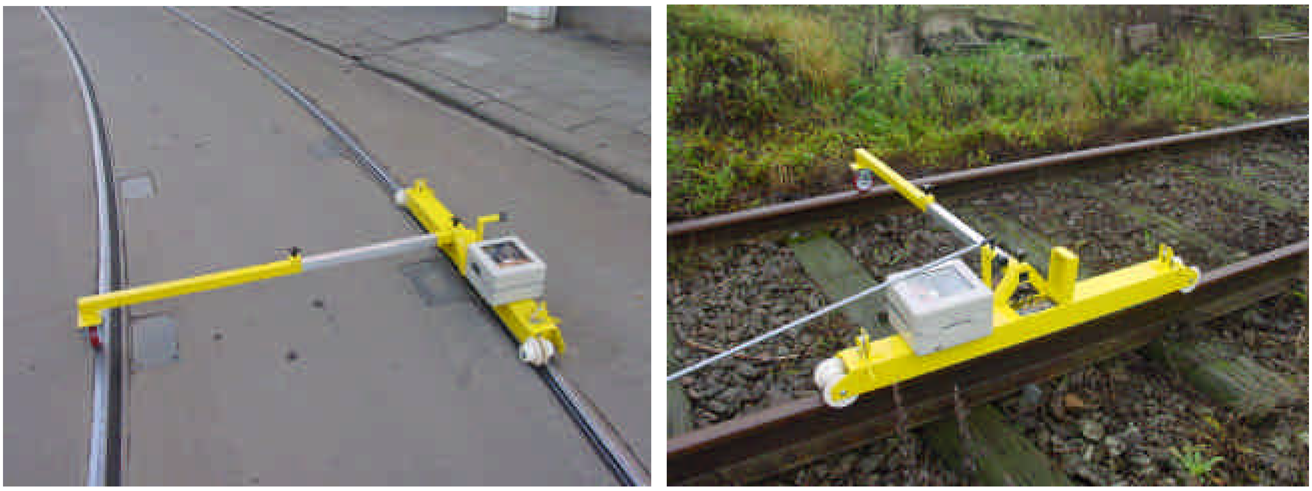

Figure 1: Rail Surface Analyser on embedded tracks and ballasted tracks

Specifications on how to measure rail roughness are described in ISO3095:2005. However, with traditional techniques this procedure can be very time consuming when measuring over a longer distance sometimes adding up to a total of 36 discrete measurements for one section. As a consequence, roughness measurements over larger distances are often performed indirectly. As mentioned above, the wheels should be permanently smooth, disc or sinter block braked or unbraked, to minimize the influence of the wheel roughness.

The Rail Surface Analyzer copes with the above described limitations, whilst still complying with the ISO standard.

The roughness measurements are performed by three contact making displacement sensors inside the housing of the Rail Surface Analyzer (see figure 2). The device is manually pushed forward by one person at walking speed (3.6 km/h).

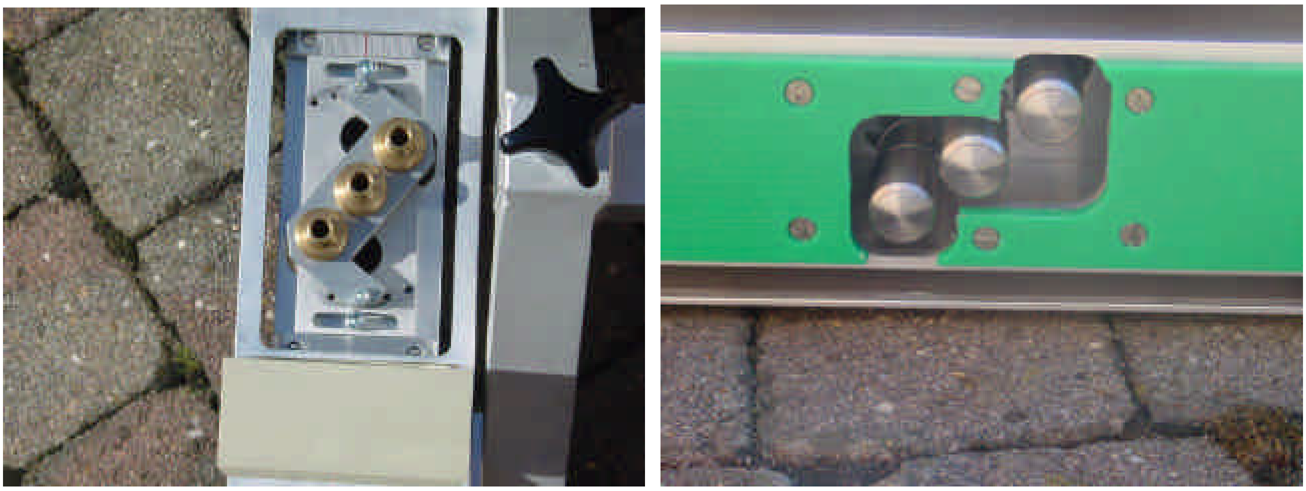

Figure 2: Three adjustable but equidistant contact making measurement probes with a large contact radius

By means of a 128 pulses/revolution encoder data is collected every 1 mm for each of the three sensors. The noise floor of the measurement system is approximately 0.03 µm for a measurement range of 5 mm. The data recording is done by a 4 channel simultaneous sampling 16 bit A/D converter which stores data into its 1 Gigabyte internal memory (4.5 hours of measurement). With a measurement speed of 0.8-1 m/s, this results in autonomy of 3 to 16 km of measurement.

Since measurement is done continuously, the reference is a sliding beam, which is in contact with the railhead for a length of 1 meter. All measurement results are referenced to this sliding beam. This leads to a quantification of corrugation and grinding patterns wavelengths from 4 mm till 500 mm. A wheel on the second rail is foreseen to have a smooth and stable running on track. This wheel can be adapted for all track widths. (e.g. 1 m, 1.43 m, 1.67 m, ...). The position of the measurement (and the displacement sensors) is function of shape of the rail, width and location of the running surface and can be adapted accordingly.

Rail roughness is usually measured on a line in the centre of the running band. The running surface however can be as wide as 60 mm for old track or as narrow as 10 mm for new track. If the running surface is wide enough it is recommended to measure two additional equidistant lines, at either side of the centre line. The Rail Surface Analyser makes it possible to measure simultaneously along 3 equidistant lines and modify this intermediate distance in function of the wide of the running surface. An equidistant interval of 5 mm is used for running bands from 10 mm to 20 mm wide, and an equidistant interval of 10 mm is used for running bands wider than 20 mm.

It is possible to download all data to a laptop/computer by a standard USB connection immediately after the measurement session. After downloading the data, the results are processed automatically and visualized in a few seconds.

In order to produce a representative 1/3-octave band roughness wavelength spectrum for each measured roughness line, the roughness data is processed. Certain pits and spikes will not be followed by the vehicle wheels which will not vibrate in return. However, those spikes and pits can be sensed by displacement sensors and are therefore removed from the signal, as they will contaminate the spectrum.

The Rail Surface Analyser does not remove negative spikes in the processing of the measurement data but during the actual measurement: the displacement sensors have a larger contact radius (figure 2) and as a consequence, the sensors feel the same roughness as experienced by the vehicle wheel (Cordier et al, 1999). Optionally and depending on the application of the roughness measurement, the shape of the contact probe can be modified to a smaller radius. Positive spikes can be eliminated in the processing by setting a spike detection threshold and a spike edge criterion. The spike is then replaced by linear interpolation of the signal. The processing of the measurement data without spike removal mainly influences the shortest wavelengths (<20 mm) and is less visible in the longer wavelengths.

Spectral analysis is applied to the signal to produce the 1/3-octave band roughness wavelength spectrum. This is not done via Fourier analysis but directly via band filter of the measurement data. The result of this processing is demonstrated in the figure below.

The roughness spectrum (figure 3) shows the dependency of the roughness level on roughness wavelength. The upper plot shows the vertical rail deviation (m) in function of the distance along the rail. The middle plots shows the Leq spectrum, averaged 1/3 octave band RMS level of the vertical rail deviation in dB (re.1e-6m) as function of wavelength in cm. This Leq spectrum is averaged over the selected distance in the upper plot and corrected for the excluded zones. The spectrum is automatically compared to the limit spectrum in the ISO. To summarize these results, the lower plot shows a colored spectrogram which is a combination of wavelength (cm), distance along the rail (m) and amplitude of vertical rail deviation in dB (re.1e-6m).

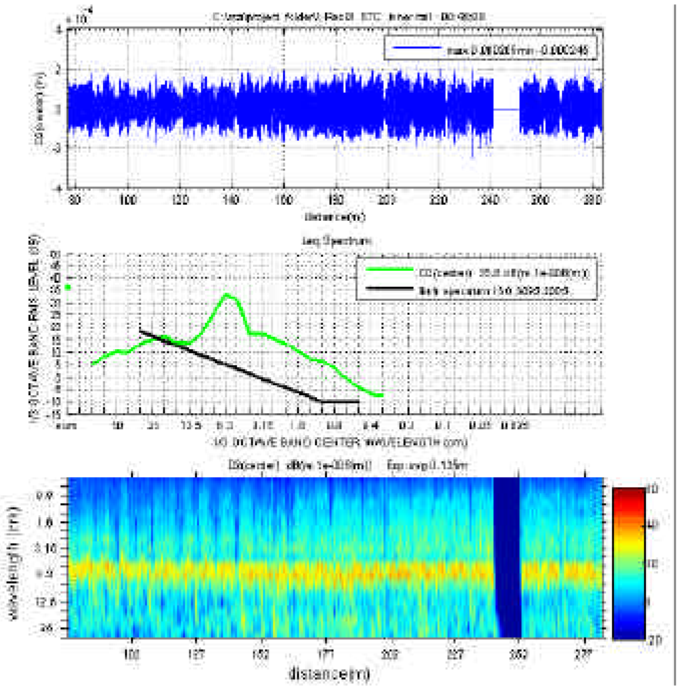

Figure 3: Typical measured roughness spectrum

The Rail Surface Analyzer was successfully developed and tested to inspect the rail surface fast and reliable. A variety of applications can be found in performing rail corrugation surveys, rail roughness measurements for track work acceptance after grinding; or rail corrugation measurements to qualify a site as candidate to perform rolling stock noise measurements.

PREVENTIVE GRINDING AS SOLUTION FOR INCREASED PASS-BY NOISE & VIBRATION LEVELS CAUSED BY AN INCREASED RAIL ROUGHNESS AND CORRUGATION

Irregularities on the surface of the wheel and the track cause vibrations that lead to the generation of noise. The level of roughness is in most cases proportional to the generated noise levels. Vibrations from the track are also transferred to the adjacent residences and induce so called ground borne noise inside the residence. The peak in the vibration spectra often corresponds with the first wheel/rail resonance frequency which is determined by the wheel mass bouncing on the ballast spring. In case of corrugation, the vibration levels at this frequency can be amplified by the high corrugation levels on the rails which also excite this first wheel/rail resonance frequency.

Preventive grinding of new rails delays the development of corrugation (Frederick, 1983). Often it is found that once corrugation appeared, its amplitude is characterized by an exponential growth. This was also demonstrated for corrugation measurements at STIB’s metro network in Brussels. Research within the CORRUGATION project also indicated the importance of high quality grinding. Insufficient grinding (remaining roughness) leads to a rapid increase of roughness levels (and noise & vibration levels as a consequence). Therefore, it is recommended to verify the quality of the grinding process with the Rail Surface Analyser after completion of the grinding process. This results in an optimized maintenance strategy and in the long term decreased maintenance costs.

A specific test was defined to evaluate "on-site" the efficiency of rail grinding. Six consecutive measurement campaigns were carried out on one test site every two months with a STIB tramway vehicle (type 7700) running on a ‘reference’ ballasted track with wooden sleepers of the Brussels tramway network. For each measurement campaign, pass-by noise, vibration levels and track roughness were monitored for several vehicle speeds (17 km/h - 58 km/h) at several distances from the track (7.5 m; 20 m; 25 m).

The test site was easily accessible, tangent track with a low inclination. A dedicated test vehicle was made available and authorized to run in both directions. The test vehicles were articulated tramway vehicles with 3 bogies equipped with low roughness wheels. The measurements were carried out at night to minimize to influence of road traffic on the test results.

The equivalent noise and vibration levels of each passage have been determined over a measurement time interval T that is long enough to include all the energy related to the event. This time interval corresponds to the period during which the overall level is comprised between the maximum level and the maximum level minus 15 dB.

Finally, levels were expressed in transit exposure levels (TEL) by normalizing the equivalent noise and vibration levels to the pass-by time.

Measurement results clearly indicate that the vibration level is linearly dependent of the vehicle speed while the relation between the noise level and the speed is logarithmic. The transit noise and vibration exposure levels at an average speed of 30 km/h at 7.5 m from the track centerline are plotted against the average measured roughness spectra (figure 4). The trend lines indicate that an increase in vibration level of 7.5 dB at 30 km/h and 5 dB at 58 km/h for an increase in roughness of 10 dB. The grinding of the tracks is responsible for the decrease in roughness, noise and vibration levels between September 2005 and November 2005. The global reduction in roughness level is about 8 dB.

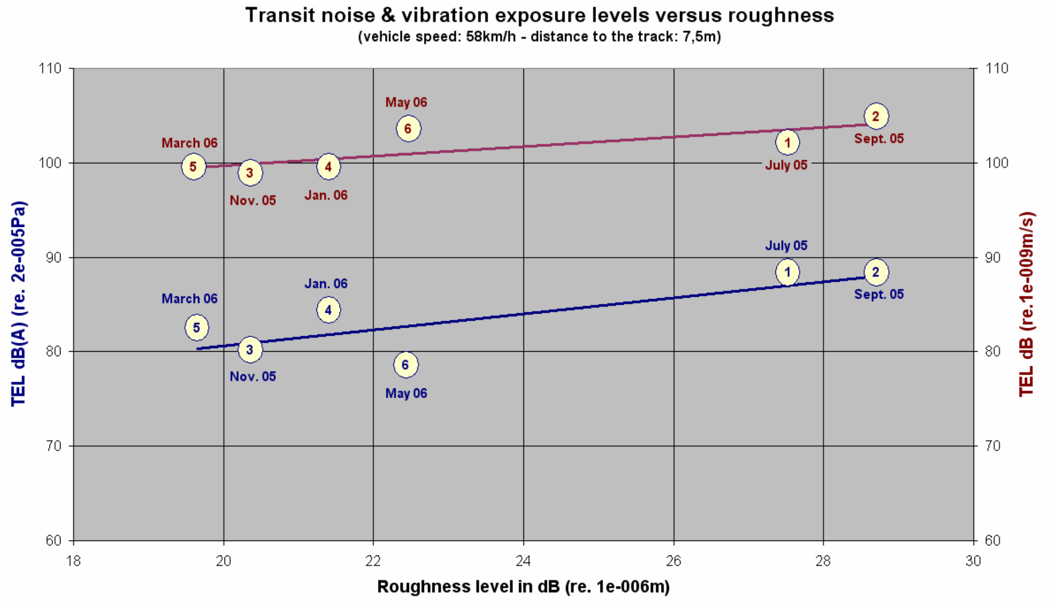

Figure 4: Transit noise and vibration exposure levels vs roughness
at 7.5 m from the track with a vehicle at 58 km/h.

There are some deviations from the global trend which are probably due to the different weather conditions, small variations in wheel roughness levels etc. Spectral analysis of the roughness levels before and after grinding indicates that grinding reduces the roughness mainly between the wavelengths 500 mm to 2 mm (corresponding with 31 and 800 Hz at a velocity of 60 km/h).This corresponds with the spectral analysis of the vibration levels before and after grinding, which indicates a reduction of the 40-63 Hz peaks after grinding. The noise is mainly reduced between 250-800 Hz after grinding.

CURES AGAINST CORRUGATION BASED ON THE UNDERSTANDING OF THE CORRUGATION PHENOMENON AND ITS RELEVANT PARAMETERS

There are a large number of parameters which influence corrugation development and growth. In order to design track products which are effective against corrugation it is important to understand these parameters. Within the scope of the CORRUGATION project these parameters were identified and modelled. The parameters can be divided into geometrical parameters (such as 3D lay-out of the track, wheel and rail geometry, roughness, …), physical parameters (such as steel grades, vehicles mass, polar moments of inertia, rail support stiffness's, …), dynamic characteristics (such as driving forces, dynamic behaviour of wheel/rail interface, friction forces, rail stresses, …) and other parameters (such as traffic characteristics, presence of joints, …).

The mechanism responsible for corrugation in curves can be described as follows: the passage of a bogie in small curves leads to important dynamic forces between wheel and rail in all directions (tangential, axial, and radial). These forces are due to important friction between wheel and rail due to curving (tangential and radial friction forces); rail and wheel imperfection (including welds). The amplitude of these forces is potentially increased by flange friction at high rail, misalignment of wheel sets in a bogie, rail support stiffness variations, important slip between wheel and rail due to difference in wheel diameter between wheels of the same wheel set, existing corrugation and poor bogie steering.

These forces are modulated by resonances of track and wheel set such as the P2 low frequency resonance (non suspended mass bouncing on track spring), wheel/rail bending mode, axle torsion mode (especially 2nd order torsion), sleeper resonance (e.g. Stedef block (mass) bouncing on rail pad spring), axle bending/wheel lateral mode and others (e.g. Grassie & Kalousek, 1993) . This leads to rail corrugation in two different forms:

1. Excessive corrugation: the curving forces generate plastic flow of rail, plastic bending of rail or contact fatigue with important corrugation pattern on inner and outer rail; it can grow up to 1 mm in 6 weeks of time.
2. Wear corrugation: the friction forces create a wear pattern mainly on the lower rail with a wavelength corresponding with one of the track/wheelset resonances; under normal conditions, corrugation amplitude growth is moderate, e.g. amplitude of 0.05 mm in 1 year time, but amplitude grows exponentially.

It was also found that the track dynamic behaviour has a far greater influence on the development of most corrugation types in comparison with the wheel or vehicle dynamic behaviour. In most cases, corrugation wavelengths correspond with vertical track anti resonances and/or with lateral track resonance frequencies. Vertical track resonance’s can be avoided by using high damped embedded rail or very soft rail fixation. Horizontal track resonance’s can be shifted outside the ‘dangerous‘ frequency band (corresponding with 20 mm - 200 mm wavelength) by using very rigid or very soft lateral rail fixation. Based on these principles, several track systems were developed and demonstrated to be effective against corrugation. The validation of these track systems was done on several rail transit networks: for embedded tracks in Bobigny, France (RATP) and as illustrated below for resilient rail fasteners on wooden sleepers at STIB’s metro network in Brussels.

USE OF VERY RESILIENT DIRECT FIXATION FASTENERS AT BRUSSELS METRO

A double track test section was selected at STIB’s metro network in Brussels between Bizet station and La Roue station. This section was previously known for its severe corrugation problem on both tracks. The track is standard ballasted track with wooden sleepers, has an EB50T rail profile and no rail inclination.

The result of the corrugation measurements carried out on one of the rails before installation of the very resilient rail fasteners is given in figure 5 as measured in April 2005; this was 8 months after the complete removal of the corrugation by grinding. An average corrugation amplitude over the complete length of the curve of 34 µm has been measured with a wavelength of 150 mm.

Numerical simulations demonstrated it was necessary to develop a rail fastening system with a vertical dynamic stiffness below 10 kN/mm in order to avoid track resonances corresponding with the 20 to 200 mm corrugation wavelength range. A direct fixation system with the above described stiffness requirements was developed and installed at the complete test section (figure 6).

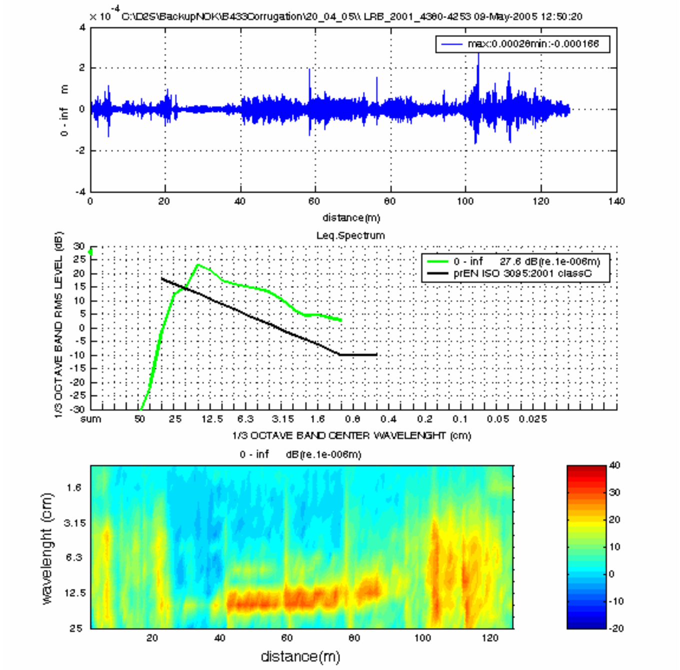

Figure 5: Spectral analysis of the roughness levels at Brussels Metro, measured 8 months after grinding

Figure 6: Detail of the very resilient fastening system

The existing corrugation was removed by installing new rails on both tracks. Rail roughness was monitored 3, 5, 14 months after installation of the fasteners. The results of the measurements after 3 and 14 months are given in figures 7 and 8 below (this is for the same rail as was measured before installation of the fasteners):

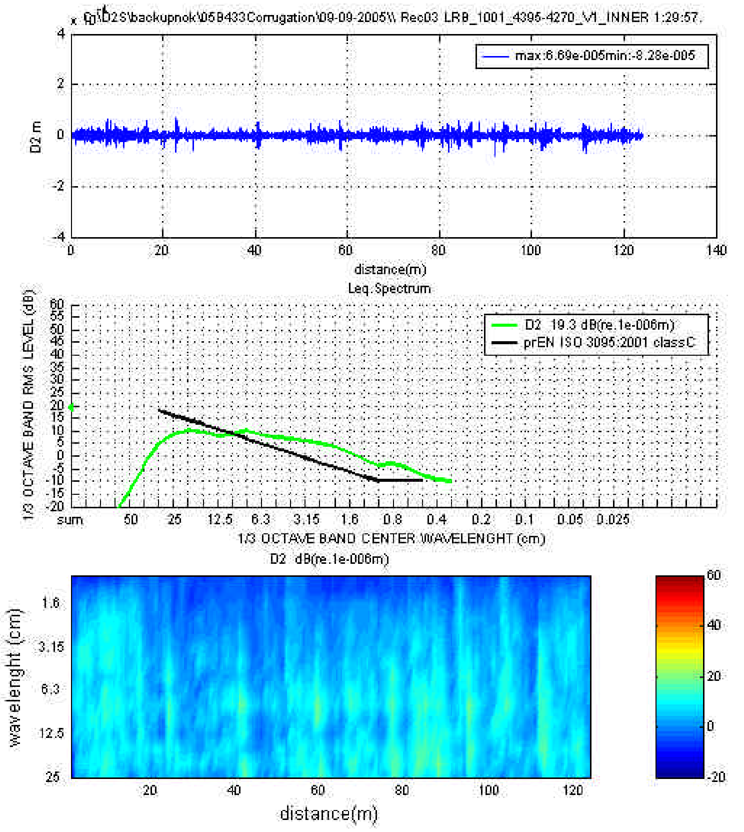

Figure 7: spectral analysis of the roughness spectra
3 months after installation of the resilient rail fastener (and new rail)

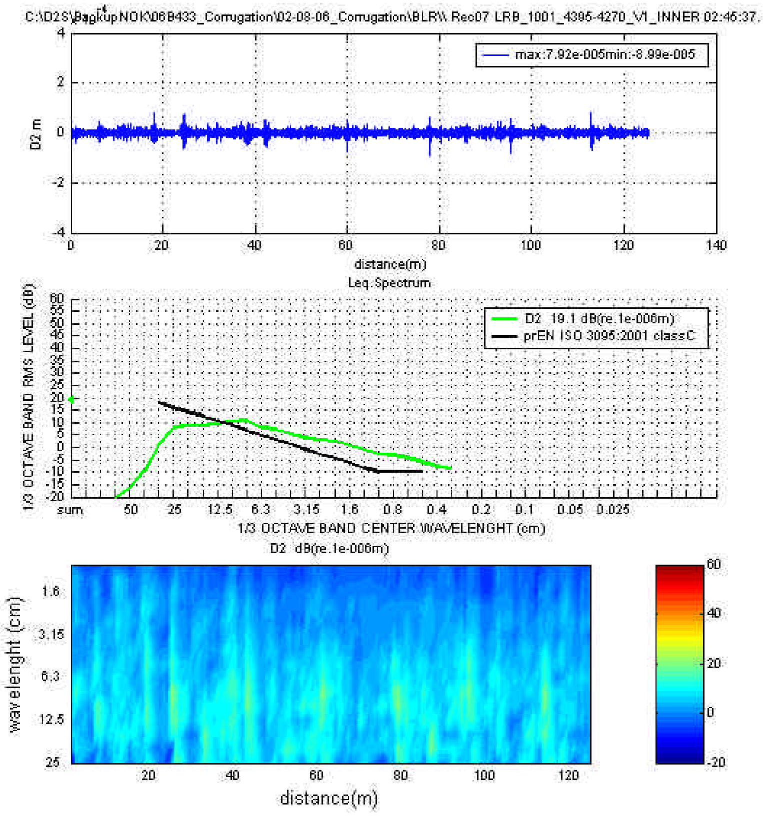

Figure 8: spectral analysis of the roughness spectra
14 months after installation of the resilient rail fastener

A detailed analysis of the measurement results shows that no corrugation can be found on the modified tracks, even after 14 months. The solution to use very resilient rail fasteners to avoid vertical anti-resonance in the low frequencies was validated to be effective for Brussels Metro.

CONCLUSION

The aim of the European Research Project “CORRUGATION” was the design and validation of efficient and cost effective solutions to reduce or eliminate the corrugation problem. Today, almost all railway administrations experience some kind of corrugation problem. Not only can it lead to urgent safety measures and increased maintenance costs but it can be responsible for a significant increase in noise and vibration levels, often causing community reaction. On site measurements at STIB’s tram network in Brussels demonstrated the relation between rail roughness and noise and vibration levels.

Within the scope of the project, an instrument to quantify corrugation in terms of its amplitude and wavelength was developed: Rail Surface Analyzer. This device was used to study the corrugation phenomenon and to evaluate the developed solutions. Issues regarding measurement precision and measurement autonomy, which came forward in the new EN ISO 3095, were addressed.

At an existing track, grinding is often the only way to deal with corrugation.

Research within the CORRUGATION project indicated the importance of high quality grinding. Insufficient grinding (remaining roughness) leads to an exponential increase of roughness levels (and noise & vibration levels as a consequence). Therefore it was recommended to verify the quality of the grinding process by measuring any remaining roughness with the Rail Surface Analyzer at each step of the grinding process. This results in an optimized maintenance strategy and in the long term decreased maintenance costs.

Further, it was found that in most cases, corrugation wavelengths correspond with vertical track anti resonances and/or with lateral track and wheelset resonance frequencies. Vertical track resonances can be avoided by using a highly damped embedded rail or a very soft rail fixation. Horizontal track resonances can be shifted outside the ‘dangerous‘ frequency band (corresponding with 20 mm - 200 mm wavelength) by using very rigid or very soft lateral rail fixation. These finding were demonstrated at several sites with specially designed track work. This papers describes the evaluation of very resilient rail fasteners (<10 kN/mm) at Brussels Metro: corrugation was prevented from reappearing even after 14 months of installation.

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