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Development and validation of a rail surface analyser for accurate quantification and evaluation of rail corrugation and track work acceptance after acoustic grinding

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ABSTRACT

An increased rail roughness and corrugation can have a significant influence on the generation of rolling noise originating from the wheel/rail contact area. In many cases, grinding or rail replacement is seen as the only solution for the noise annoyances caused by the increased roughness. Within the European Research Project "CORRUGATION" the importance of high quality grinding was stressed to avoid immediate reappearance of corrugation. It is suggested to measure rail roughness immediately after grinding to verify the quality of the grinding process. This paper describes the development of a portable, accurate and easy-to-use instrument to measure corrugation and rail roughness. During the development of the instrument, issues regarding measurement precision and measurement length, which came forward in the prEN ISO 3095, are addressed. The second part of this paper describes the results of an extensive corrugation measurement campaign at STIB (Brussels tram). The effect of rail roughness (and grinding) on noise and vibration levels is studied.

1 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 increased noise and vibration emissions caused by corrugation 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). Corrugation was considered with wavelengths from 20 mm to 200 mm.

The first part of this paper describes the development of a portable easy to use rail roughness measurement device, called Rail Surface Analyser (RSA). This device was developed to accurately quantify rail roughness and 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

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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 at Brussels tram network is 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 also used to conduct extensive measurement campaigns to evaluate the efficiency of these solutions.

2 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.

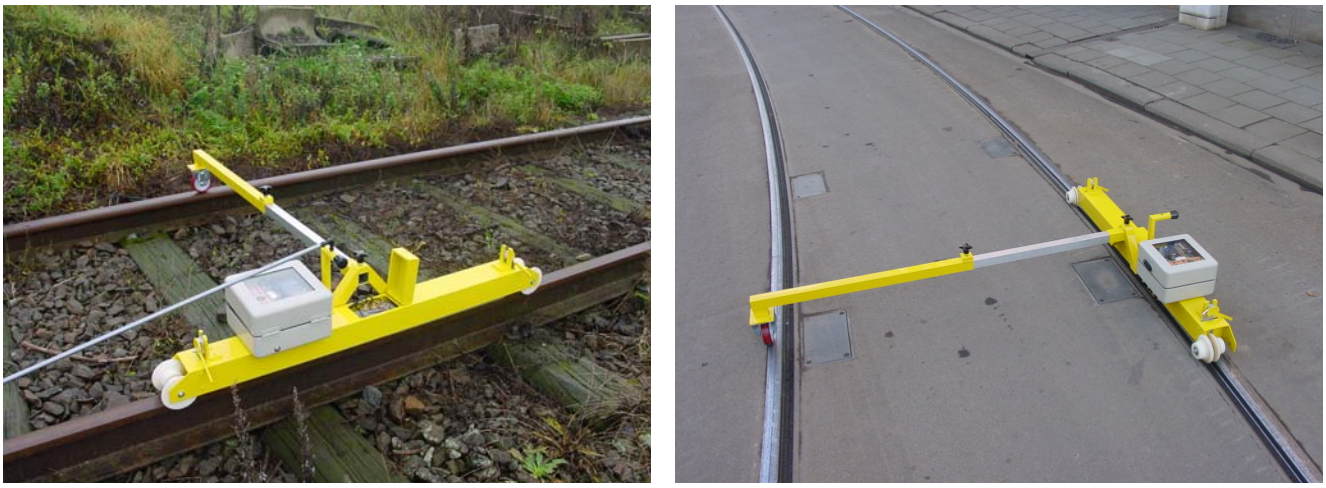

Figure 1: Rail Surface Analyser on embedded tracks and ballasted tracks

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).

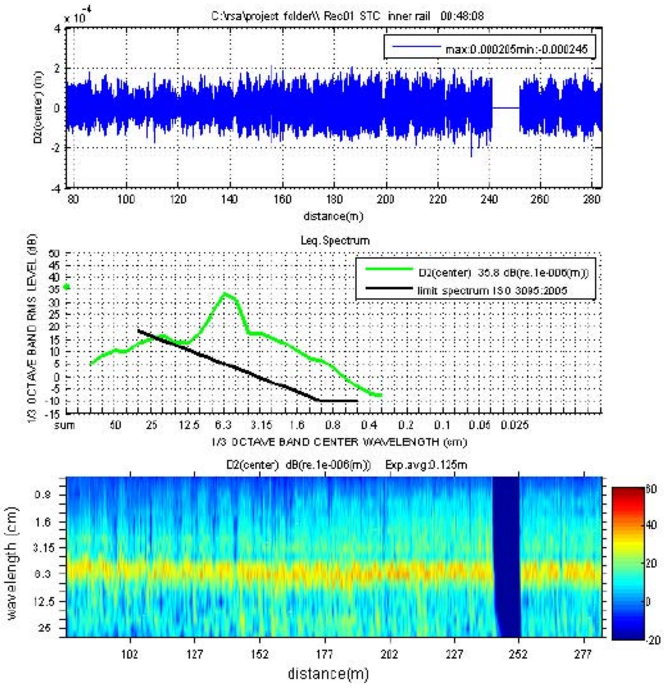

Figure 3: Typical measured roughness spectrum

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.

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

When a vehicle wheel runs over a track rolling noise is created. 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.

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 (7,5m; 20m; 25m).

The test (figure 4) site was easily accessible, tangent track with a low inclination. A dedicated test vehicle was made available and authorised 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 minimise to influence of road traffic on the test results.

Figure 4: Test site at Brussels tram network

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 15dB.

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

$$TEL = L_{eq,\,T} + 10\log\left(\frac{T}{T_P}\right)$$

With T_p the pass-by time of the vehicle, in seconds, which is the length of the vehicle divided by the vehicle speed; T the measurement time interval; Leq,T the equivalent noise or vibration level determined over the measurement time interval 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 and 58 km/h at 7,5m from the track centerline are plotted against the average measured roughness spectra (figures 5 and 6). 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.

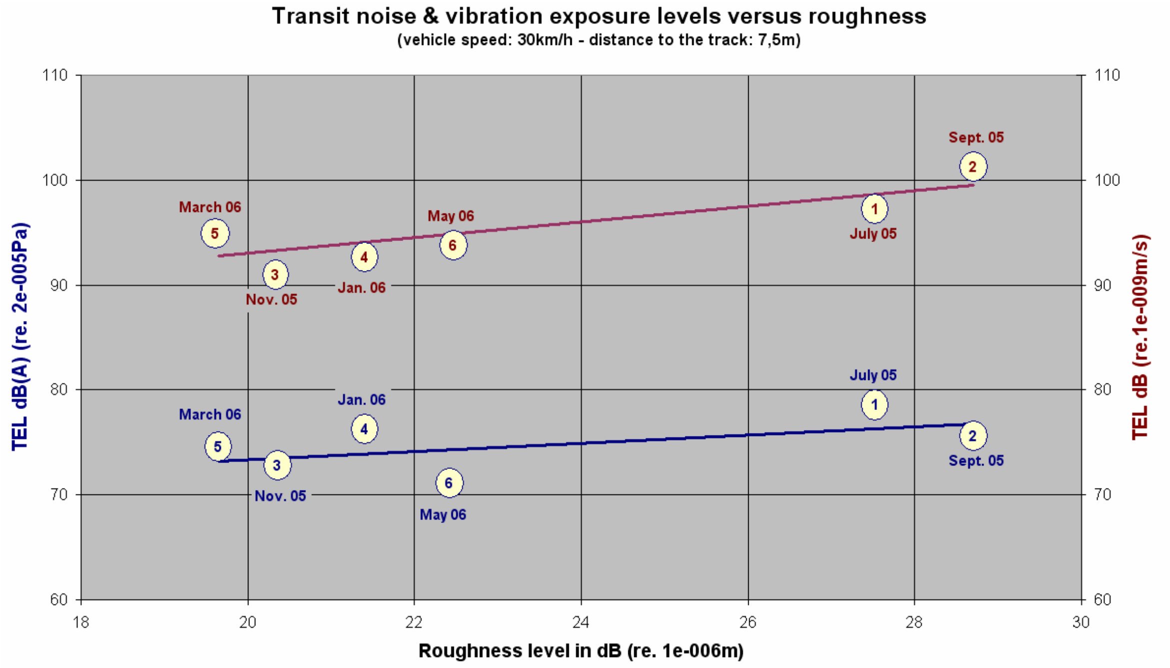

Figure 5: Transit noise and vibration exposure levels vs roughness at 7,5m from the track with a vehicle at 30 km/h.

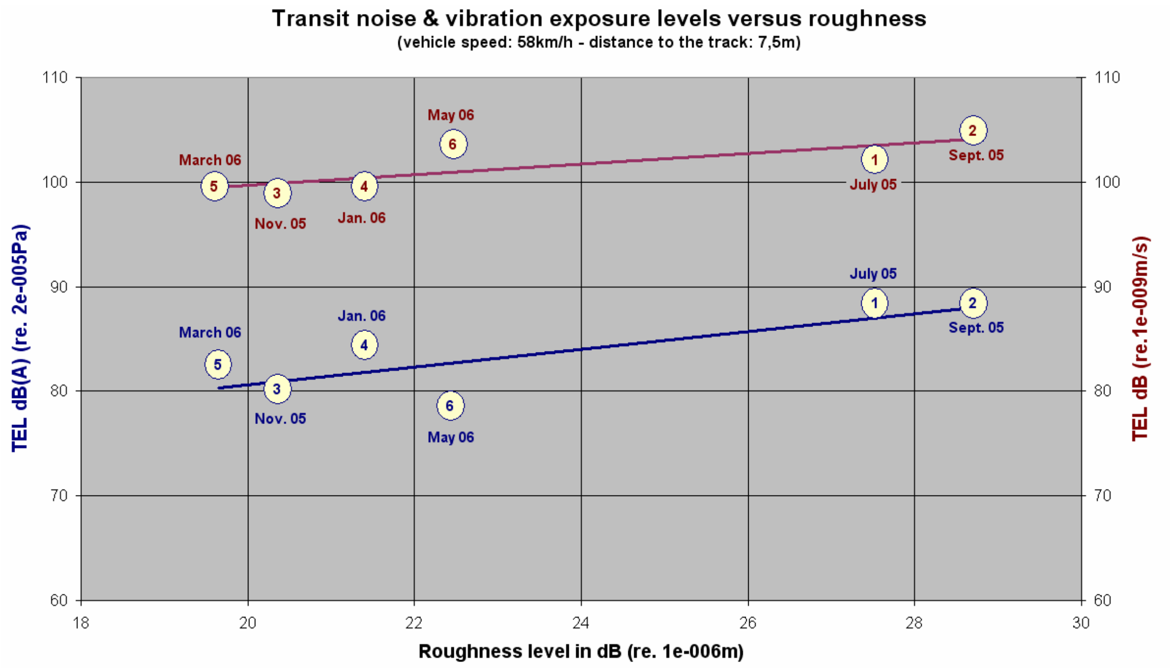

Figure 6: Transit noise and vibration exposure levels vs roughness at 7,5m from the track with a vehicle at 58 km/h.

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.

Research within the CORRUGATION project indicated the importance of high quality grinding. Other researchers also demonstrated that preventive grinding of new rails delays the development of corrugation (Frederick, 1983). Insufficient grinding (remaining roughness) leads to an exponential 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 at each step of the grinding process. This results in an optimized maintenance strategy and in the long term decreased maintenance costs.

4 CONCLUSIONS

The European Research Project "CORRUGATION", aimed at the design and validation of efficient and cost effective solutions to reduce or eliminate the corrugation problem. Corrugation is a serious and expensive problem experienced by transit systems around the world. Not only can it lead to urgent safety measures (such as rail replacements) 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 clearly 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 Analyser. 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 Analyser before and after the grinding process. This results in an optimized maintenance strategy and in the long term decreased maintenance costs.*

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