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Roughness measurements—Have the necessities changed?

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Abstract

Roughness of the running surfaces is the predominant source of noise of rail bound transport systems today. Reliable measurements of the roughness of rails and wheels are crucial for noise reduction purposes. In the past, the main purpose of measurements was the understanding of corrugation growth and rolling noise generation. Meanwhile, quantitative descriptions have gained considerable importance. Initiated by Deutsche Bahn, the RM1200E rail roughness measurement device became available in the early nineties of the last century and has since gained a good reputation in the scientific community.

Recently standards for measuring sound levels inside rail vehicles and pass-by levels of rail vehicles at a reference distance have been issued on a European level. They require that the level of roughness of the test track is known. Furthermore, Trans European rail networks have been defined, requiring technical specifications for interoperable, border-crossing vehicles, running in several countries. These specifications include noise limits, referring to the methods defined in the new standards. To allow for unambiguous results, the knowledge of the roughness of the rolling surfaces is essential.

In view of these developments in standards and specifications, the paper addresses the requirements for roughness measurements and for the data evaluation involved. It focuses on the scientific and practical experience of the past as well as on the present necessities, specifically those derived from regulations on a European scale and describes practical consequences for roughness measuring devices.

1. Introduction

It is well established that rolling noise is the predominant source of noise of tracked transport systems operating in the speed range from approximately 60–50 km/h. Below 60 km/h, machinery noise is dominant, and above 250 km/h, aerodynamic noise becomes prevalent for high speed trains. The excitation mechanisms have been studied and simulation models have been developed [1,2] which nowadays represent accepted tools in scientific and engineering work.

An important contribution to this research and development work of the late 1980s was the development of a device to measure the roughness of the running surfaces of wheels and rails in the range of magnitudes and wavelengths relevant for acoustics [3]. In addition to the requirements of noise research, the need for an advanced understanding of corrugation growth had been an incentive for German Federal Railways to support the development of a mechanical corrugation measurement recorder named RM1200E.

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2. Field experience with RM1200E and other devices

The device RM1200E is widely used in the railway acoustics community. It allows for the measurement of roughness over a length of 1200 mm of rail surface along one line at a time with a longitudinal discretization of 0.5 mm. The measurement principle is based on determining the distance between the rail surface and a reference surface by means of a straight edge with a relative displacement transducer. The resolution of the transducer is better than 1 μm resulting in a system noise level of approximately −20 dB re 1 μm in one-third-octave bands of wavelengths. Fig. 1 shows the influence of the measurement range of the transducer system on the noise floor determined by means of a polished calibration stone. For practical reasons it is desirable to use the setting with a higher displacement (similar to the dashed line in the graph) as otherwise a signal overload frequently occurs due to vertical misalignment of the instrument.

The evaluation algorithm comprises a correction derived from the calibration data which are obtained from a measurement on a calibration stone. Displacement data are Fourier transformed, windowed to wavenumbers and summed over one-third octave bands using at least three lines of the discrete Fourier spectrum. This results in a maximum wavelength of roughness of $(0.23/3) \times 1.2\,\mathrm{m} \approx 0.1\,\mathrm{m}$ for a 1.2 m long trace. Data for the wavelength of 1.2 m, although available in the FFT spectrum as a single line, are statistically too uncertain to be used.

Measurement experience showed that frequently raw data contains spikes or pits caused, for example, by surface irregularities of the rail or by dust build-up on the apex of the sensor. These spikes or pits are too small to be "seen" by a wheel but result in a broadband signal of the sensor hiding the desired results. To improve the situation, the measurement data have to be corrected to remove these effects. The concept was first published in Ref. [4]. Fig. 2 shows example spectra for two cases with and without correction for pits and spikes.

Meanwhile several "pits and spikes removal" algorithms are in use in the research community developed by different users of the instrument. A comparative benchmark test has been carried out in the AEIF/EC project NOEMIE, which showed that a reasonable comparability is achieved for low roughness rails, but not for those with high roughness. As the low roughness rails are the important ones for test sites, this was considered satisfactory. The underlying concepts vary greatly, from the practical approach of defining limits for certain geometric and derivative properties, including user intervention and manipulation, to the automatic model calculation based on an imaginary wheel checking the surface geometry and thus defining a filter for the suppression of the pits and spikes.

Based on the experience with the rail roughness device a wheel roughness measurement device was built, which uses the axle bearing as a reference point when revolving the wheel. Due to this fact the precision of the results is lower than that for the rail instrument, as the measured roughness includes the unroundness of the

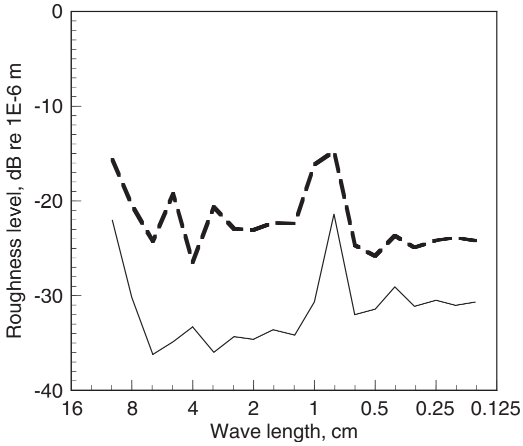

Fig. 1. One-third octave band system noise level versus band centre wavelength; parameter is the measurement range of the RM1200E: ±2.5 mm - - - and ±0.1 mm —.

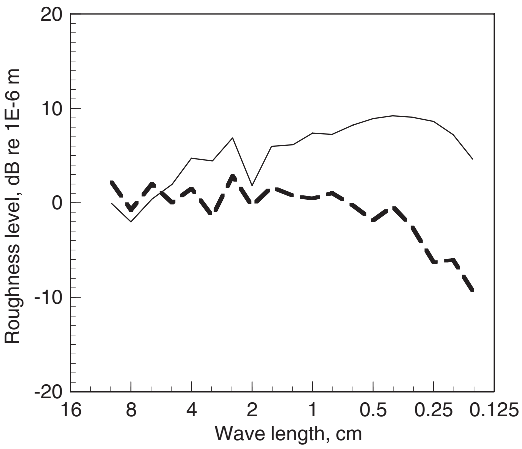

Fig. 2. One-third octave band roughness level versus wavelength: smooth rail - - -, smooth rail with a single spike —.

bearing and axle construction. The data evaluation algorithm is similar to that for rail roughness; in addition to the one-third octave spectra the so-called wheel harmonics are extracted from the FFT spectra, attributing a value to the unroundness (first FFT line) and the following *n*th order polygonization of the wheels.

An early trolley system for rail roughness measurements, which is based on acceleration measurements, was further advanced. The advantage of the system is the ability to measure unlimited length sections. The drawback is the need for double integration from acceleration to displacement to arrive at the desired quantity in terms of one-third octave roughness spectra.

3. Necessities

Fifteen years ago roughness measurements on rails were done only for research purposes. Today the importance of the source quantity "roughness of the running surfaces" is widely accepted in the industry. The roughness of rail and wheel running surfaces used to be acknowledged as influential on the sound creation, but had nevertheless only been verbally described with attributes like "very smooth", "not corrugated", "heavily corrugated", etc. after subjective visual inspection by the responsible measurement team.

With growth of experience about roughness excitation, the necessity to establish values for the quantitative characterization of rail and wheel running surfaces, especially in the context of e.g. type testing, was acknowledged. Therefore the two draft ISO standards prEN ISO 3095 [5] and prEN ISO 3381 [6] included the measurement of rail roughness and specified a limit spectrum not to be exceeded for type testing (see Fig. 3). The measurement method described in these standards is based on the available 1200 mm straight edge devices and specifies measurement along one to three traces depending on the width of the running band at six positions defined by the distance of the microphone from the track as shown in Fig. 4.

The idea behind the limit spectrum is to ensure that the contribution of the track to the sound creation on interior and pass-by sound is small compared to the vehicle contribution. This approach ensures that the vehicle manufacturer is responsible for the noise creation. Thus, if the limit values described in technical specifications for the order of the vehicle are exceeded, the responsibility is clearly defined. Furthermore it facilitates the reduction of legal limits, as the trackside noise has to be treated independently of the networks.

Within the scope of the development of the European high-speed network the technical specifications for interoperability of systems were defined (TSI-HS [7–9]). For conventional traffic a proposal of the Noise Expert Group of the European Association for Railway Interoperability (AEIF) is currently being prepared (TSI-CR [10]). Concerning the roughness measuring method TSI-HS and TSI-CR refer to prEN ISO 3095. In the TSI-HS compliance with the limit curve labelled TSI in Fig. 3 is demanded, whereas in the TSI-CR the curve labelled ATSI was proposed. The definitions for the TSI-HS and CR limit curves are still under discussion and the latest proposal is a compromise of TSI and ATSI called TSI+ as shown in Fig. 3.

The definition of the limit curves poses demands on the measurement technology concerning the precision required and the wavelength range to be measured. The noise floor of the instrument should be 3 dB or more below the limit curve. A comparison with Fig. 1 shows that this is achievable with the available devices.

The wavelength range to be measured depends on the frequency range to be considered and the speed of the vehicles. Table 1 shows the evaluation of the formula $f = v/\lambda$ for relevant speeds v (converted to km/h), wavelengths λ (in cm) and corresponding frequencies f.

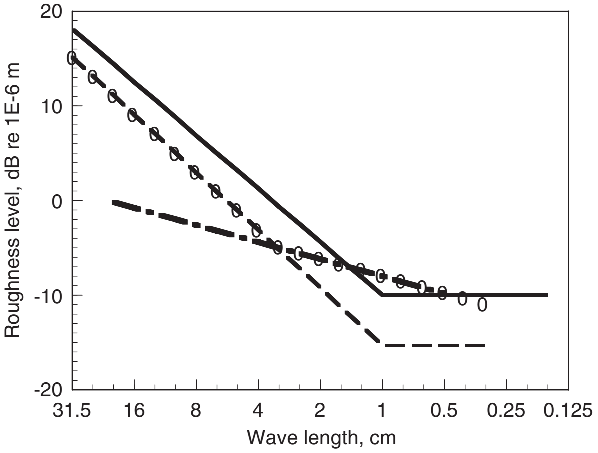

Fig. 3. Limit one-third octave band roughness spectra: according to prEN ISO 3095 — and the European technical specifications for interoperability TSI-HS -·-·-, alternative proposal ATSI - - - and latest proposal TSI+ ○ ○ ○.

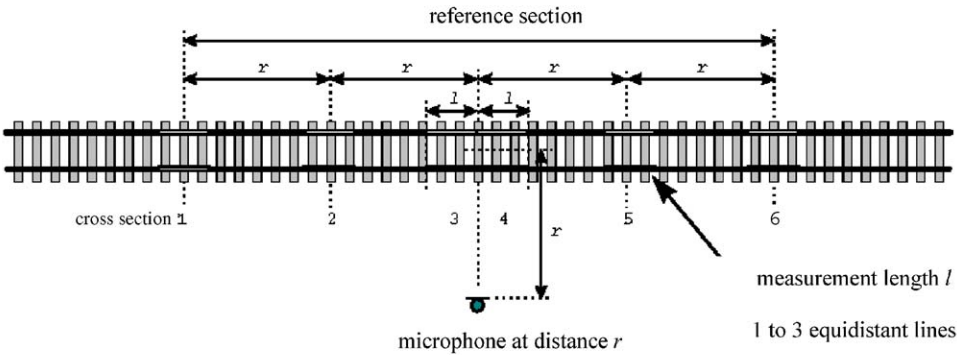

Fig. 4. Position of traces according to prEN ISO 3095 [5].

Table 1

Relation of frequency f for selected wavelength λ and train speed v

λ, cm	f, Hz at $v =$			
	80 km/h	160 km/h	240 km/h	320 km/h
25	89	178	267	356
12.5	178	356	533	711
6.3	356	711	1067	1420
3.1	711	1420	2133	2840
1.6	1420	2840	4270	5690
0.8	2840	5690		
0.4	5690			

As the measurement of longer wavelengths poses problems, at least with the straight edge instruments, thought should be given to the definition of the upper limit of the wavelength range for which the roughness of the test track is defined and thus has to be measured. A simple straightforward approach is to use available sound measurements and test for the sensitivity of the *A*-weighted overall sound pressure level for the lower frequency limit using the following relation:

$$\Delta(f_l) = 10\log_{10}\left(\sum_{f=20\,\mathrm{Hz}}^{10\,\mathrm{kHz}} 10^{L_{pA}(f)/10}\right) - 10\log_{10}\left(\sum_{f=f_l}^{10\,\mathrm{kHz}} 10^{L_{pA}(f)/10}\right), \tag{1}$$

with the difference $\Delta(f_l)$ for frequency f_l of the A-weighted one-third octave band sound pressure levels $L_{\mathrm{pA}}(f)$. For high-speed trains it was found that contributions from frequency bands below 500 Hz do typically add less than 0.5 dB to the overall level.

Additional information can be gained from a calculation based on the following roughness sensitivity definition: assume the roughness is not controlled above a certain wavelength, what will an increase of roughness (and, consequently, of sound) in a single one-third-octave band show for an effect in the overall A-weighted sound pressure level? For high speed trains it was found that a roughness in a single one-third octave band below 500 Hz that is 6 dB above the limit will typically result in a difference of less than 0.5 dB in the overall level; below 250 Hz for roughness that is 10 dB above the limit the overall level again shows a difference of less than 0.5 dB. It can therefore be deduced that for high-speed trains the knowledge of wavelengths up to 250 mm is desirable, whereas for conventional traffic wavelengths up to 100 mm are sufficient.

As already described above, the wavelength range covered by RM1200E is limited to 100 mm due to the length of the measurement device and the evaluation algorithm for the 1200 mm straight edges. To allow for longer wavelengths the RM1200E includes an angle sensor for measuring the inclination of the instrument's longitudinal axis. When measured data traces overlap by approximately 200 mm it is possible to concatenate these traces using correlation techniques and to estimate values for the longer wavelengths. Fig. 5 shows such data from the RIM validation campaign [2] for 20 concatenated traces together with the data evaluated using the standard method for shorter wavelengths. A comparison of the data derived in that way with data measured in a track measurement car for wavelengths around 5 m and more shows a satisfactory consistency.

Fig. 6 shows roughness data recently measured during the German NOEMIE measurement campaign [11]. The proposed new standard requires the measurements for wavelengths adequate for the higher speeds up to 320 km/h in the TSI regulations. Based on experience it was decided that roughness levels in the wavelength bands up to 315 mm are to be determined for the high-speed range up to 320 km/h.

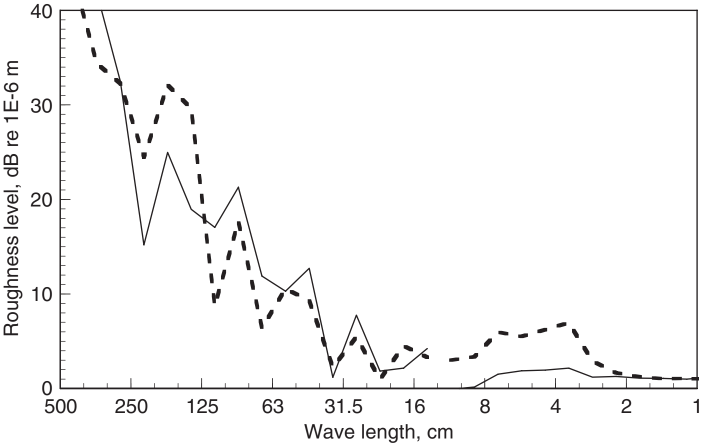

Fig. 5. One-third octave band roughness spectra measured on a smooth track — and on a corrugated track - - -, for wavelengths up to 10 cm evaluated with the standard procedure, above 12.5 cm evaluated using concatenation.

The rail roughness levels shown in Fig. 6 for the NOEMIE project on German track exhibit significantly lower values than at the older track sites, as shown in Fig. 5.

4. Standardization

The topic of roughness measurements on rail and wheel running surfaces is addressed in the proposed revisions of ISO 3095 [5] (and identically in 3381 [6]). In these standards, measuring positions relative to the microphone (see Fig. 4) are mentioned for the 1200 mm straight edge and a procedure allowing the limits to be exceeded somewhat for single result spectra. However, no description is given for the measurement method, for the evaluation method or for the calibration of the equipment. Requirements for standards concerning these issues are currently under discussion, the respective development of such standards is to be expected in the near future by CEN and should be used to advance certain issues.

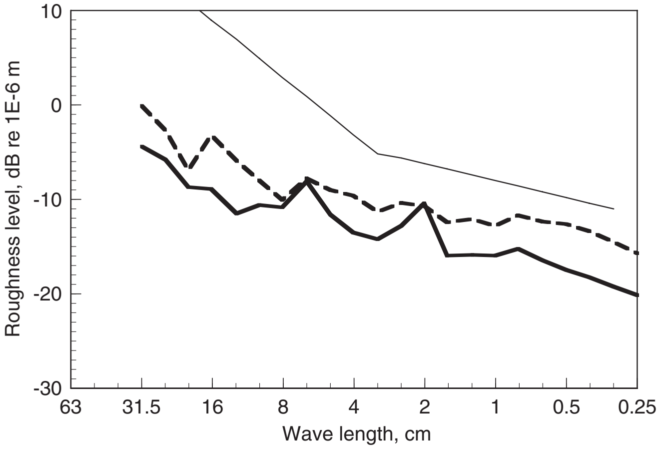

Fig. 6. Roughness spectra measured on the German NOEMIE track in autumn 2004 (thick —) and spring 2005 (- - -), comparing it with the TSI + limit curve (thin —).

Fig. 7. New mbbmRM1200 rail roughness measurement device on a test track.

5. New development mbbmRM1200

Based on the experience of more than 10 years of measurements with the RM1200E and the frequent need for more measurements a successor device to the RM1200E has been developed, see Fig. 7. Due to practical size and weight limitations the measurement length was kept at 1200 mm as well as the discretization at 0.5 mm. However, additional features have been added to facilitate the use of the new device called mbbmRM1200. The instrument is able to measure automatically a set of traces equidistantly spaced across the rail head in one clamping position. Due to the integration of a PC into the device it is possible during the measurement to display the resulting data in terms of the displacement trace and of one-third octave spectra on completion of all traces on the radio connected PDI panel. This is also used as system pad to control all activities of the device. For ease of positioning in the lateral direction a laser pointer has been added, as well as a tail wheel for longitudinal positioning. The controlling PDI panel and the device are self-contained including power supplies.

6. Conclusions

The measurement of roughness of running surfaces has become more important in the last decade outside of the scientific field as the standards for interior and pass-by sound measurements as well as the new European TSIs call for knowledge of the surface roughness. These demands can be satisfied by an improved device allowing easier handling and multi-trace measurements. The main wavelength range needed for conventional speed can be covered by the 1200 mm straight edges in use. For high-speed traffic, there is a necessity for the extension above 100 mm using a concatenation procedure which should be defined and used for high speed tracks.

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