Towards silent tracks and roads: beating the roughness

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Roughness lies at the basis of the rolling noise of both trains and cars. For trains, the roughness of wheel and rail are considered the excitation mechanism for wheel/rail noise. For cars, the processes and interactions involved are more complicated. But still the road roughness (often called texture) and the tyre roughness (or rather profile pattern) are the most important influencing factors for tyre/road noise. To understand and abate rolling noise from trains and cars, a thorough understanding of the noise generation processes and the influence of the roughness is essential. In this paper, all roughness related issues will be discussed: how roughness generates rolling noise, how roughness is handled in noise generation models, what systems and protocols are used to measure the roughness of the various system constituents, and finally how the roughness should be altered to accomplish noise reduction for both rail-bound and road vehicles.

1 Introduction

Rolling noise of rail and road vehicles is very similar in nature. The rolling noise of both is (mainly[1]) generated by roughness-induced vibrations. These roughness-induced vibrations are caused by irregularities of the running surfaces of the tread and of the surface the wheel rolls on.

But besides similarities between wheel/rail and tyre/road noise, there are also many differences between the excitation mechanisms, dynamic behaviors and radiation characteristics. In this article, the similarities and differences of roughness-induced rolling noise of railbound and roadbound vehicles will be presented. The aspects noise generation, modeling, measurement and mitigation will be discussed solely from the roughness viewpoint.

2 Noise generation and modelling

2.1 Wheel/rail noise

For rolling noise of railbound vehicles, roughness is considered the only excitation mechanism. The combined roughness of the surfaces in contact excites vibrations in both the wheel and the rail (see Figure 1). These vibrations partly radiate into airborne sound and are partly transmitted to the sleepers which in turn radiate sound. The vibration energy of the wheels is concentrated around the eigenmodes of the wheel, generally above 1500 Hz. The rail radiates broadband sound in the frequency region 250-1250 Hz.

In noise prediction models such as TWINS or RIM [1], the energetic sum of the roughness spectra of wheel and rail are taken as the input for a 2D-contact, vibration and radiation model. These models are linear: doubling the excitation will result in a doubling of the predicted noise levels. The linearity of the problem makes it possible to solve the modelling problem in the frequency/wavenumber domain.

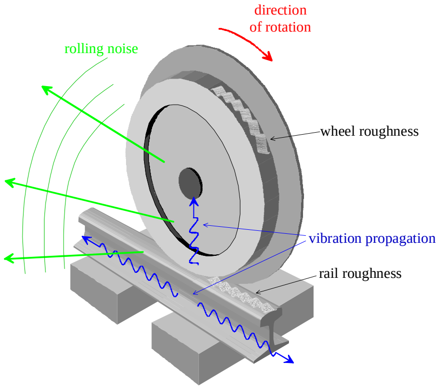

Figure 1: Wheel/rail noise generation

2.2 Tyre/road noise

Roughness induced rolling noise of tyres of roadbound vehicles is caused by the impact of road surface roughness on the tyre and/or tyre roughness (the tyre tread profile) on the road. These impacts cause vibrations in the tyre; the road is considered rigid. The roughness-induced vibrations propagate through the tyre and radiate air-borne sound.

In contrast with wheel/rail noise, there is no consensus on how to model the tyre/road interaction [2]. It seems that the phenomena involved in the generation of tyre/road noise are less well understood. But it is generally accepted that the contact between tyre and

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[1] Some researchers (in the field of tyre/road noise) assume that other mechanisms than roughness-induced vibrations (such as e.g. stick-slip and airpumping) also play an important role in the rolling noise generation. In this article, these mechanisms are not disputed nor confirmed. This article focuses on roughness as roughness-induced vibrations always play a (significant) role.

road is of a nonlinear nature. This means that the modeling has to be done in the time/space domain. It also means that in principle, the complete tyre and road profiles (possibly in 3D) are needed as an input to the noise prediction models.

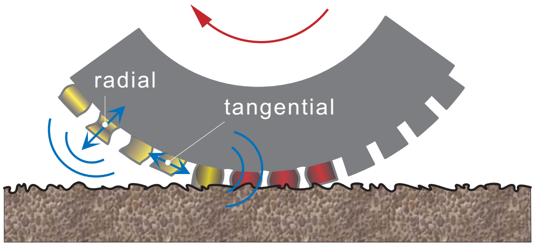

Figure 2: Radial and tangential tyre vibrations are the cause of tyre/road noise

3 Roughness measurement

Measuring roughness is characterizing and quantifying the excitation mechanism for rolling noise. Measurement of roughness can be done directly, by measuring the roughness profile, or indirectly, by measuring a derived quantity such as sound or vibration level. The rationale behind the indirect measurements is that the amplitude and frequency of the measured quantity are directly related to the roughness amplitude and wavelength.

A feature of the indirect method is that the roughness of wheel and rail or tyre and road cannot be separated directly: the roughness that is measured is always the combined (i.e. energetic sum of the) roughness. However, separation is possible when the roughness of one of the components is either well-known or very low.

3.1 Wheel/rail noise

Direct method Direct roughness measurements are done with a displacement sensor that is in contact with the wheel or rail running band. This sensor measures the displacement in the direction perpendicular to the running band. For rail measurements, this sensor is mounted on a subframe that is moved along a rigid beam along the rail (see Figure 3). For wheel roughness measurements, the wheel is rotated over a fixed sensor (see Figure 4). In both cases, the translation and perpendicular displacement are measured. This gives the (raw) roughness profile. Normally this roughness profile is post-processed to remove pits and spikes that are not “felt” by the wheel/rail contact and are thus irrelevant for the noise generation. The profiles are mostly presented as wavelength-amplitude spectra. Typically, roughness wavelengths between 1 and 250 mm are measured. Typical roughness energy level amplitudes range from -10 to +20 dB (re. 1 µm).

Figure 3: Direct rail roughness measurement with a Müller-BBM RM1200 rail roughness scanner

Figure 4: Direct wheel roughness measurement with a Müller-BBM RM1435 wheel roughness scanner

Indirect method For indirect rail roughness measurements, a microphone can be mounted on a bogie near a (low-roughness) wheel and the resultant noise can be registered. The registered noise level change is linearly dependent on the rail roughness level change[2]. For indirect wheel roughness measurements it is possible to position a microphone near a (low-roughness) track and the noise level changes are directly related to wheel roughness level changes[3].

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[2] Other rail/superstructure parameters such as railpad stiffness, sleeper type should be kept constant.

[3] All wheels that are compared should have similar dimensional and dynamic parameters: e.g. diameter and contact stiffness should be kept constant.

A good example of an indirect rail roughness measurement device is the German “Schallmeßwagen” (noise measurement car) where the rail roughness of ground rail is monitored by noise measurements near the bogie of a specially prepared measurement car [3].

Currently, there are no ISO standards that deal with wheel/rail roughness measurement devices and data processing.

3.2 Tyre/road noise

Direct method The principle of direct measurement of tyre and road roughness is very similar to the direct measurement of wheel and rail roughness. However, a laser distance sensor is normally used for tyre/road roughness instead of a mechanical transducer that is used for wheel/rail roughness measurements.

There are two types of road profile measurement systems: static and dynamic. In a static measurement system, the transducer is mounted on a subframe and moved along a rigid beam (Figure 5). In some systems, there is also a possibility to move the sensor in the direction perpendicular to the beam to be able to get a 3D road profile. The static method is comparable to the rail roughness measurement system. In a dynamic system, the laser is mounted on a driving vehicle. With a dynamic system it is possible to obtain the road profile over a larger measurement length, but the accuracy of such a system is generally less and it is not feasible to obtain a 3D road profile with a dynamic system.

Post-processing of the data is often necessary because the laser transducer sometimes produces invalid readings (called drop-outs). Further processing of road profiles is sometimes performed by determining the tyre-enveloped profile, i.e. the profile that is “felt” by the tyre that cannot penetrate in very narrow apertures in the road surface (which are for example present in porous road surfaces).

Figure 5: M+P static (3D) road surface roughness measurement system

After the post-processing step, the profiles are often presented as wavelength-amplitude spectra. However, this can be misleading since the contact between tyre and road is nonlinear and thus information about the profile and the noise generation potential is ignored by just presenting the spectra without any phase information (see explanation in Figure 6). Therefore, additional information about the texture orientation should be given. The problem with phase information is that it is not straightforward to interpret the phase information in terms of rolling noise production. For that reason, alternative texture orientation parameters have been suggested e.g. the shape factor [4].

Typically, roughness wavelengths between 2 and 500 mm are measured and the roughness energy level amplitudes range from +20 to +50 dB (re. 1 µm).

ISO standard 13473 deals with the measurement instrumentation and data processing for direct road roughness measurements.

Direct measurement of tyre profiles is not a standard procedure, but also possible in a way similar to train wheel roughness measurements [5].

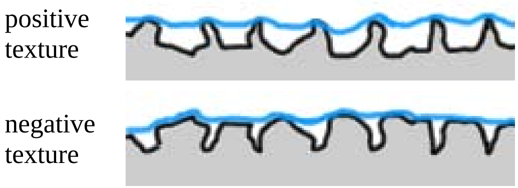

Figure 6: So-called positive and negative texture profiles that have the same spectral noise levels but with different phase information. The positive texture will produce higher noise levels. The blue line shows the envelopment by the tyre

Indirect method Indirect measurement of tyre and road profiles is possible in principle but not achievable in practice. This is due to a great amount of parameters besides roughness than influence rolling noise (e.g. tyre stiffness, tyre width, road surface porosity, etc.) and also because the variation in these parameters is rather large.

4 Roughness and lifetime

The development of roughness during the lifetime for wheel and rail is very different from the development of the roughness for tyre and road. This is something to consider when trying to optimize tracks and roads for low-noise.

Qualitatively, the roughness development of newly ground tracks and newly build roads is as depicted in Figure 7. For newly ground track, the roughness level will decrease very rapidly directly after grinding. After a certain period of time (depending on the traffic type and load) a minimum roughness level is reached. After that, the roughness will gradually increase.

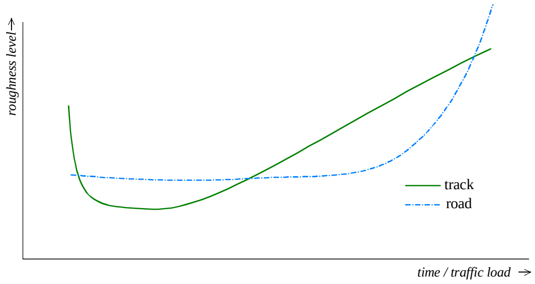

Figure 7: Development of the roughness level of tracks and roads as a function of time/traffic load

The rate of roughness development for the rail depends on the roughness level of the wheel and vice versa. A smooth rail with loaded with high roughness wheels will become rough at a higher rate than the same rail with smooth wheels. Another factor that influences the roughness growth rate is the stiffness variation in the track superstructure (due to the non-continuous/periodic support by the sleepers). For large stiffness variations, the roughness growth rate will be become larger (resulting in so-called corrugation).

The roughness level and growth of train wheels depends largely on the brake system. Cast-iron block brakes (on the wheels) give the highest roughness, disk brakes in combination with composite block brakes give the lowest roughness (see .Figure 8).

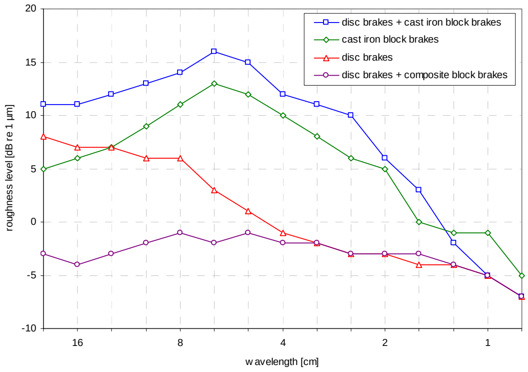

Figure 8: Standard wheel roughness spectra for train wheels with different brake systems (data taken from the Dutch Calculation Scheme)

For newly build roads, the roughness level is nearly constant in the first period of its lifetime. For roads with surface dressing, the roughness level will even decrease in the first period. A sharp increase in roughness level will occur when rutting takes place and stones will be removed from the surface. This will significantly increase the roughness level and hence the tyre/road noise. Rutting depends on the type and quality of asphalt, the traffic movements (think of the difference in tangential forces exerted on the road for inner-city versus highway traffic movements). In contrast with railways, the rate of roughness development for roads does not depend very much on the roughness of the tyres and vice versa.

5 Beating the roughness

The solution to obtain silent roads and tracks seems simple: remove the roughness and the rolling noise is significantly reduced. However, it is not easy to remove the roughness and sometimes the roughness is even vital for the transportation system to function correctly (think of a tyre without profile on a rainy smooth road). Therefore, a compromise has to be made between noise reduction, safety, costs and other boundary conditions.

5.1 Wheel/rail noise

Lowering the roughness of wheel and/or rail is an effective noise reduction measure for railway applications. The roughness is not needed to transmit the traction forces (not even in wet conditions). However, for railways it is important to beat the roughness on both the wheel and rail simultaneously since the actual roughness level of these components have a large mutual influence on their respective roughness growth rates. Furthermore, it is not effective to lower the roughness of one component (e.g. the rail) without treating the other component (e.g. the wheel) since the excitation mechanism of the rolling noise is the energetic sum of the wheel and rail roughness.

Rail To lower the roughness of the rail, the obvious measure is to grind the rail. In the railway world it becomes more customary to grind the rail to prevent or correct fatigue problems (such as head-checks). In addition to this maintenance grinding, the rail can be finished with a special grinding treatment to reduce the roughness in the wavelength range 0.1-25 cm. This results in a noise reduction of roughly 3 to5 dB(A) with respect to track with average roughness and a reduction of 10-15 dB(A) with respect to corrugated rail.

Wheel Since the brake system is very important for the roughness level of wheels, it is important to use disc braked wheels where possible. If this is not possible, the brake system could be adapted (e.g. exchange cast-iron block brakes for composite block brakes). To keep the wheel roughness of wheels at low levels it is important to regularly maintain the wheel's running surface. The running surface of the wheels can also be made more wear resistant by special surface treatments (e.g. laser cladding).

5.2 Tyre/road noise

For tyre/road noise, lowering the roughness is a very effective measure to reduce rolling noise. The lowest noise rolling levels are achieved for slicks (i.e. tyres without profile) on very smooth roads [4]. However, unlike for railways, the roughness is essential to transmit traction forces from tyre to road. So a certain amount of road roughness and a tyre profile are necessary for (wet) grip. Therefore, the optimal road and tyre roughness should be chosen within the safety boundary conditions.

Road The effect of lowering the road surface roughness to reduce the tyre/road noise. is illustrated in Figure 9. By comparing the roughness and noise spectra of passenger and truck tyres measured at Sperenberg [4] it was clearly shown that lowering the maximum stone size in the SMA mixture reduces the roughness levels and subsequently the noise levels. Note that the effect is much more pronounced for passenger car tyres than for truck tyres. This is probably caused by the fact that the profile spectra of the truck tyres have a higher amplitude than the car tyres and that thus the combined tyre/road roughness for passenger cars is lowered much more by changing the road surface roughness than in the case of the combination of road and truck tyres. However, this hypothesis has not been tested yet.

The noise reduction by lowering the roughness was achieved by lowering the maximum stone size and thus the long wavelength roughness levels. This resulted in a lower noise level for frequencies < 1250 Hz. In practice it is very difficult to change the noise levels above 1250 Hz by changing the roughness spectrum. This is because in that region, the small roughness wavelengths of the road are not “felt” by the tyre (the length of the contact patch is much larger than the wavelength size). Noise reduction (on the road) in that frequency region is normally achieved by introducing porosity in the road surface. However, porosity can only be introduced by making introducing accessible air ducts in the road surface and hence increasing the roughness level. Therefore, introducing porosity is a trade-off between optimal roughness and optimal porosity properties of a road surface.

Tyre Lowering the roughness amplitude of tyres is not a feasible noise reduction solution as a certain profile groove depth is essential for the car handling properties in wet conditions. An important noise reduction measure for tyres is the so-called profile randomization (see e.g. ref. [6]). Randomizing the length and position of the tread pattern blocks minimizes the variations in the impact force that is exerted on the tyre and hence the vibrations and noise radiation of the tyre. Nowadays, this randomization is applied by all major manufacturers of passenger car tyres, so the differences in tyre design from a roughness point-of-view are small [7]. This means that the possibilities for further optimization the roughness of passenger car tyres are expected to be limited. However, since the pattern design for truck tyres is less optimized, there are still possibilities for further noise reduction by a good profile pattern design.

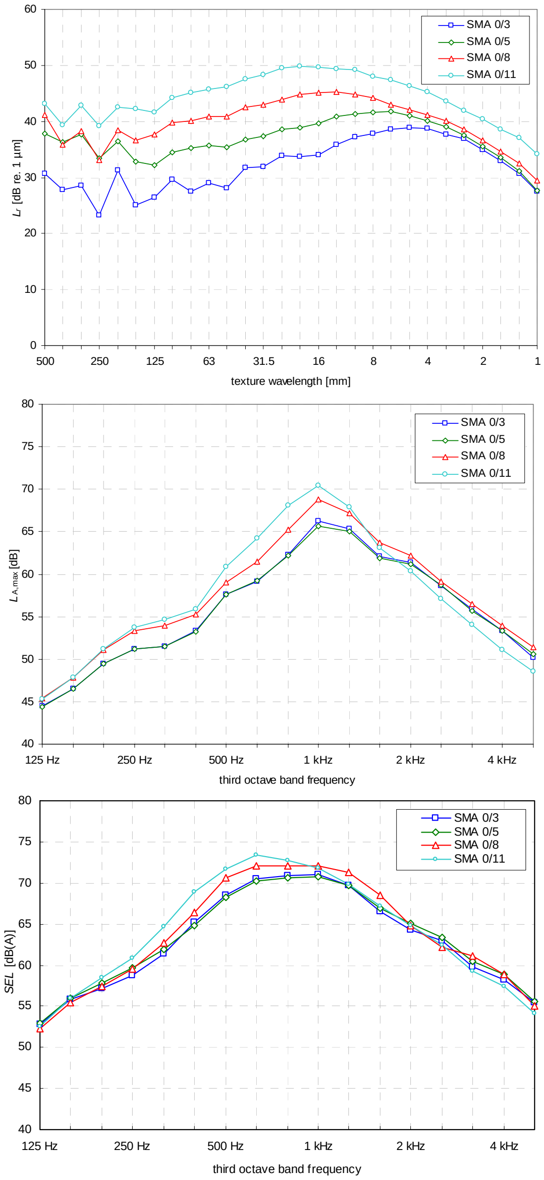

Figure 9: texture profile spectra (top graph) and pass-by noise spectra (middle graph for passenger car tyres, bottom graph for truck tyres) of 4 stone mastics asphalt (SMA) road surfaces with different max. stone sizes.

6 Conclusions

Roughness is the main excitation mechanism for both wheel/rail and tyre/road noise. The influence of roughness on rolling noise of rail and road vehicles was shown. For both transport fields, the similarities and differences were discussed of roughness-related noise models, measurement techniques, lifetime behavior and low-noise solutions.

In general roughness reduction leads to lower noise levels. However, roughness reduction is not always possible due to technical or economical restrictions. As often, a trade-off has to be made between these aspects to come to effective and affordable low-noise tracks and roads.

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