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Auralization of railway noise: Emission synthesis of rolling and impact noise

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ABSTRACT

Within the research project TAURA, a traffic noise auralization system was developed that covers road traffic and railway noise. This paper focuses on an emission synthesizer for railway noise and presents a concept for rolling and impact noise. The synthesis is based on a physical approach in which the noise generation mechanism is modeled in the time domain. As a starting point, equivalent roughness patterns of each wheel and the rail are generated. These spatial signals are used to implicitly model the mechanical excitation of the wheel/rail system. Transfer paths describing the vibrational behavior and the radiation of wheels and rail are implemented as digital filters. This approach features a high degree of flexibility but requires knowledge of the detailed model parameters.

1. Introduction

Auralization is the technique to artificially make a situation audible. By incorporating prediction models into the auralization process, this technique allows to listen to situations that do not exist yet. Auralization has a long tradition in architectural acoustics already, notably in room acoustics [1–3]. For instance concert halls and opera houses are typically auralized during the planing process. The application of auralization to environmental noise has been discovered only recently. Several studies on the auralization of road traffic noise [4–7], aircraft noise [8–11] and wind turbines [12,13] have been published.

To date, only a few studies have been related to the auralization of railway noise. In [14] the sound quality of traction noise of starting vehicles was assessed using synthesized sounds. In [15] train pass-bys have been auralized based on a combination of filtered and resynthesized binaural recordings. Within the SILENCE project, a software called VAMPPASS was developed which features audio synthesis capabilities for railway vehicle pass-bys [16–18]. The tool mainly uses recordings obtained by a microphone array and simulates physical acoustic sources on the vehicle by equivalent point sources [19]. Initial attempts to auralize train pass-bys are also indicated in [20]. In [21] beamforming was applied to obtain audio recordings of sub-sources during train pass-bys. These recordings may be used as input data to synthesize source signals [22].

Based on auralization, different acoustical scenarios may be compared in terms of their perception using e.g. listening test experiments. For railway noise where noise mitigation measures are diverse and costly, such an assessment of the effectiveness of different measures could be helpful. Measures at the source as well as on the propagation paths are viable options. Therefore an auralization model for railway noise should be able to simulate both intervention types independently, i.e. only measures at the source, on the propagation or on both. This suggests to use separate source and propagation modules which is in line with Vorländer's definition of the auralization process [2].

Auralization models are either based on audio recordings or include a synthesizer that artificially generates audible signals. In contrast to architectural acoustics where mainly speech or music signals are used, in environmental acoustics it is often desirable to synthesize the emission signals instead of relying on audio recordings. The latter only allows for little variation of different signal aspects. A more versatile method with a much higher degree of freedom, as well as full control of the influencing signal parameters is to synthesize the sounds.

Railway noise consists of different contributions which may dominate in dependence on the vehicle and track type, traveling speed, frequency and geometry. It consists of rolling and impact noise as well as noise from secondary sources such as the traction,

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aggregates and aerodynamic noise [23]. Today, in most noise exposure situations rolling and impact noise dominate the A-weighted sound pressure level. Rolling noise is generated by very small amplitude undulations of the wheel and the rail running surfaces. The resulting varying contact forces excite the wheel/rail structure which consequently vibrates and radiates sound waves. The three main parts contributing to the radiated noise of the wheel/rail interaction are the wheel, the rail and the track sleepers. Impact noise arises due to discrete irregularities on these surfaces [24]. These transient sounds occur notably in the context of wheel flats [25], insulated rail joints or switches [26]. The frequency content of rolling and impact noise is very wide and it covers almost the whole audible frequency range. The maximum sound pressure level lies in the mid frequencies, typically in the range of 500 Hz to 2 kHz [27,23]. Hence in an auralization, signals with a wide frequency content need to be utilized.

In the research project *TAURA: Traffic Noise Auralisator* (2014–2016) an auralization model for traffic noise was developed that covers road traffic [28,7] and railway noise [29]. It will form the basis for future listening test experiments to assess different noise mitigation measures. The objective of this article is to present an emission synthesizer for the rolling and impact noise components of railway noise. Section 2 shortly describes the railway noise measurement campaign that produced expedient data for the model development. In Section 3 the auralization model is established and presented.

2. Measurements

In the years 2007 and 2008 a large railway noise measurement campaign was carried out in Switzerland in the context of the sonRAIL project. It involved 15 measurement sites and, along with the regular rail traffic, a dedicated measurement train. At all sites, sound pressure and rail accelerations were synchronously measured and passing axles were detected using light barriers. The measurement sites typically consisted of two-track sections (see [30] for the set-up). For each track, sound pressure was measured on both sides at the reference position 'A' according to the standard ISO 3095 [31], that is at a distance of 7.5 m from the centerline of the track and 1.2 m above rail. Furthermore, direct rail roughnesses, track decay rates and propagation attenuations were determined. A vertical microphone array was used for sound source separation.

In Section 3, experimental data from one measurement point and the measurement train is shown (Figs. 3, 4 and 14). The site was located in Lussy (Swiss National coordinates [CH1903+] 2'56 2'275/1'173'600) on the route Lausanne-Fribourg. The southern track was built in 1994 and consists of concrete monobloc sleepers on ballast substructure and UIC60 rails. Direct roughness measurements from August 2007 yielded weighted roughness levels $L_{\lambda,CA}$ [32] of 7.4 and 9.4 dB for the two rails, respectively. On that basis, the rail roughness was classified as average [30].

The measurement train consisted of two locomotives, 7 passenger cars and 6 freight wagons and was composed as listed in Table 1. The train passed each measurement site six times in each direction at different speeds, i.e. 1×60 km/h, 3×80 km/h, 2×100 km/h. Subsequent to the pass-by measurements, direct roughness measurements of all 36 freight wagon wheels were conducted.

Parts of this measurement data set were used for the development and validation of the auralization model, which is described in the following section.

3. Model

Fig. 1 shows the structure of the auralization model which contains three separate modules. The first module provides the signals emitted by the sources. The emissions are synthesized based on source specifications. The second module is a series of filters that simulate the propagation effects of the sound waves traveling from the source to the virtual observer point. These propagation filters are generated as a function of the source-receiver-geometry, topography and weather conditions. Also propagation effects due to obstacles, such as buildings [33], barriers [34,13] or natural objects [35–37] may be considered here, e.g. reflections, scattering and shielding. The third module is a reproduction system, which adequately renders the received signals to headphones or a multi-channel loudspeaker system. By considering the sound incidence direction, a spatial impression can be created.

3.1. Point source model

To comply with the fundamentals of auralization [2], in particular the separation of sound generation and propagation, the proposed model follows the source-path-receiver concept and uses distributed point sources.

The train composition as an acoustical source is represented by a series of moving point sources. They all move at the same speed which is equivalent to the traveling speed V of the train. For most exposure situations, a train has to be viewed as an extended source as its total length is typically larger than or of similar magnitude as the distance to the receiver point. Therefore the point sources have to be horizontally spread across the train composition. To correctly model ground reflections and shielding, the source height is of importance. As railway noise consists of noise sources of different heights, the point sources in the model are thus horizontally and vertically distributed along the train.

Primary point sources, denoted as S_{tr} and S_{veh}, are used to represent rolling and impact noise. S_{tr} represents the contribution radiated by the track, and S_{veh} the contribution radiated by the vehicle. For each axle i two primary point sources, $S_{tr,i}$ and $S_{veh,i}$, are located at heights 0 and 0.5 m above rail. Secondary point sources, denoted as S_{sec}, are introduced for traction noise, aerodynamic noise, aggregates, etc. Secondary point sources are positioned at different heights, i.e. at 0.5, 2, 3, and 4 m above rail according to state-of-the art engineering models [38,39,30]. The sonRAIL model [30] describes the sound powers of secondary sources at these predefined heights for different vehicle types. The horizontal distribution of the secondary point sources along the wagons should be defined according to the physical positions

Table 1
Composition of the measurement train of the sonRAIL project.

Number of wagons	Type	Name	Number of axles per wagon	Wheel diameter [m]
1	Locomotive	SBB Re460	4	1.1
3	Passenger (D-brake)	SBB EWIV	4	0.92
4	Passenger (K-brake)	SBB RIC Bpm	4	0.92
3	Flat freight (Ci-brake)	SBB Slmmnps	4	0.92
3	Flat freight (Ci-brake)	SBB Kps	2	1.0
1	Locomotive	SBB Re420	4	1.23