Auralisation of Railway Noise: A Concept for the Emission Synthesis of Rolling and Impact Noise

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ABSTRACT
Within the research project TAURA[4], a traffic noise auralisator will be developed that covers road traffic and railway noise. This paper focuses on an emission synthesiser for railway noise and presents a synthesiser concept for rolling and impact noise. The synthesis is based on a physical approach in which the noise generation mechanism is modelled in the time domain. As a starting point, an equivalent roughness pattern 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 behaviour 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.

Keywords: Auralisation, Railway noise, Rolling noise, Sound synthesis
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1. INTRODUCTION

The application of auralisation to environmental noise has been discovered only recently. Several studies on the auralisation of road traffic noise [1–4], aircraft noise [5–8] and wind turbines [9, 10] have been published. To date, only a few studies have been related to the auralisation of railway noise. In [11] the sound quality of traction noise of starting vehicles was assessed using synthesised sounds. An auralisation model based on numerical simulations and measurements was reported in [12]. Initial attempts to auralise train pass-bys are also indicated in [13]. In [14] beamforming was applied to obtain audio recordings of sub-sources during train pass-bys.

The auralisation process generally consists of three modules [15]. The first module provides the signal emitted by the source. For environmental noise applications, it is often desirable to synthesise the emission signals instead of relying on audio recordings. The second module is a series of filters that simulate the propagation effects of the sound waves travelling from the source to the receiver. The third module is a reproduction system, which adequately renders the received signals to headphones or a multi-channel loudspeaker system.

In the ongoing research project *TAURA* a traffic noise auralisator is developed that covers road traffic and railway noise. It will form the basis for future listening test experiments to assess different noise mitigation measures. The objective of this paper is to detail a concept for the emission synthesis of railway noise.

2. MODEL

Auralisation models are either based on audio recordings or include a synthesiser that artificially generates audible signals. Relying on audio recordings 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

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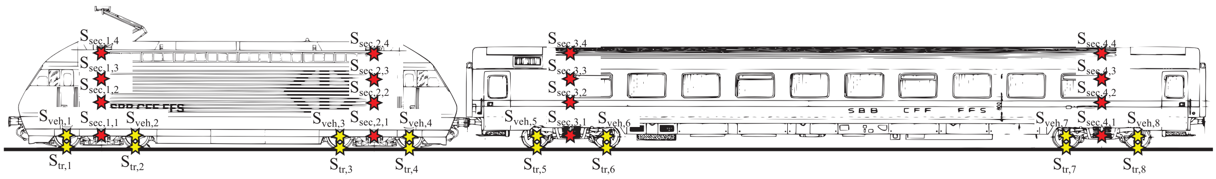

Figure 1: Point source locations marked by coloured stars along two Swiss rail vehicles of type SBB Re 460 and Bpm RIC.

parameters is to synthesise the sounds. Various techniques for digital sound synthesis exist [16]. In the context of sounds from aircraft, wind turbines and road traffic, a combination of additive and subtractive synthesis, referred to as *spectral modelling synthesis*, is commonly used [4, 5, 7–9]. For car engine sounds also a method based on granular synthesis was developed [3]. As implemented in [12], the most obvious approach is to also use spectral modelling synthesis for the emission synthesis of train pass-bys. However, our initial tests based on 1/3 octave band data failed. On the one hand impact noise could not be represented and on the other hand the sound characteristics (timbre) of rolling noise could not be reproduced. However, these subtle temporal and spectral patterns are important for realistic auralisations of railway noise.

Therefore we propose a more physical approach that includes modelling of the mechanical excitation of the wheel/rail system and the vibrational behaviour of the system. A physical approach on that basis has the advantage that it allows the extrapolation to situations for which no synthesizer parameters have been measured. This approach has already proved to be successful for the synthesis of transient sounds, specifically percussion and bells [17–19] or footstep sounds [20]. For railway noise, transient sounds occur notably in the context of wheel flats, insulated rail joints or switches. To comply with the fundamentals of auralisation [15], in particular the separation of sound generation and propagation, a point source model is proposed.

2.1 Point source model

The train composition as an acoustical source is represented by a series of moving point sources. 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. 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.

The point source locations are exemplified in Fig. 1. Primary point sources, denoted as $\mathrm{S_{tr}}$ and $\mathrm{S_{veh}}$, are used to represent rolling and impact noise. For each axle i two primary point sources, $\mathrm{S}_{\mathrm{tr},i}$ and $\mathrm{S}_{\mathrm{veh},i}$, are located at heights 0 and 0.5 m above track. $\mathrm{S_{tr}}$ represents the contribution radiated by the track, and $\mathrm{S_{veh}}$ the contribution radiated by the vehicle. Secondary point sources, denoted as $\mathrm{S_{sec}}$, are introduced for traction noise, aerodynamic noise, aggregates, etc. Secondary point sources are stacked at different heights, i.e. at 0.5, 2, 3, and 4 m above rail according to the sonRail model [21]. Their horizontal distribution along the wagons should be defined according to the positions of the real sources, i.e. individually for each vehicle type. As a default setting, one stack is placed on top of each boogie as shown in Fig. 1. However, it can be expected that in many cases fewer secondary sources suffice, e.g. at large distances or in unshielded cases. For a wagon with N_{ax} axles this yields a total of maximal $2N_{\mathrm{ax}} + 8$ point sources. Consequently, for a whole train composition the number of point sources typically lies well above 100.

2.2 Emission synthesis of rolling and impact noise

The signals attributed to the sources are artificially generated. As mentioned above, the synthesis of rolling and impact noise is based on a physical approach. The same approach is also reflected in theoretical models such as TWINS and state-of-the-art railway noise engineering models such as IMAGINE [22], sonRail [21] or CNOSSOS [23]. The basis of the proposed auralisation model is an estimate of the surface microstructure (i.e. the roughness) of the rail and the wheels. These roughness signals are then combined and processed to obtain the mechanical excitation of the track-wheel structure. Using the vehicle speed, a transformation from

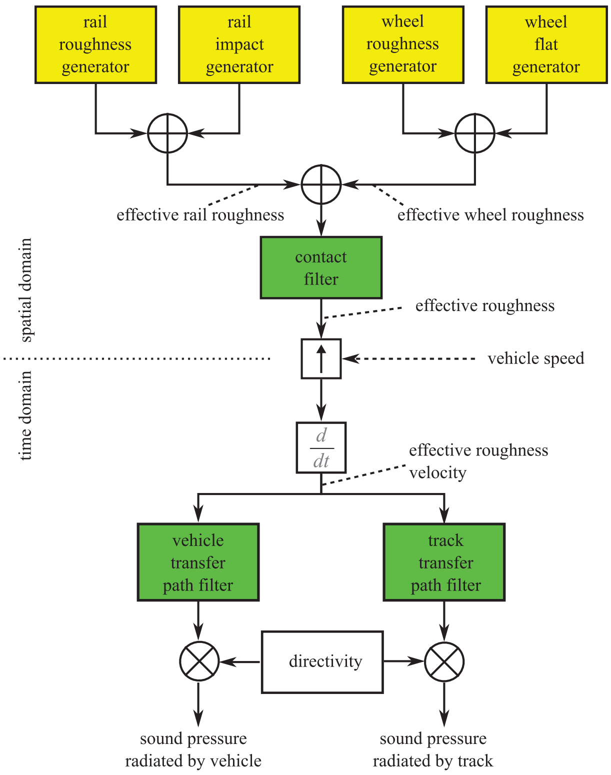

Figure 2: Signal flow of the auralisation model for rolling and impact noise source signals of a single wheel pass-by.

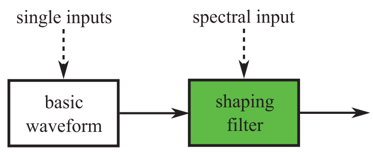

Figure 3. Signal flow of the generator modules (subtractive synthesis).

the spatial into the time domain is performed. Further, the modal behaviour of the structure and the radiation are simulated. These effects are characterised by transfer paths which are applied in the time domain using digital filters.

As an overview, Fig. 2 shows the signal flow of the proposed emission synthesiser for a pass-by of a single axle i. The yellow blocks represent generator modules which produce spatial signals. These spatial signals are summed up and modified by a contact filter. Subsequently, the resulting spatial signal is converted to the time domain by a vehicle speed dependent resampling. After a differentiation with respect to time, the resulting excitation time signal is then fed into two transfer filters. Their output is amplitude modulated by a directivity function representing the radiation pattern of the source. The resulting signals correspond to the free field sound pressure at a defined reference distance, as radiated by the track and the vehicle, respectively. Accordingly these signals are attributed to point sources $\mathrm{S}_{\mathrm{tr},i}$ and $\mathrm{S}_{\mathrm{veh},i}$.

The four generator modules in Fig. 2 produce signals as a function of the spatial coordinate x with a resolution of less than 1 mm. Measurement data indicate a strong wavenumber dependency of these signals with substantial low wavenumber content. The operating principle of the generators is depicted in Fig. 3. It is based on the subtractive synthesis technique but differs for each generator in terms of input and basic waveform. The rail roughness generator uses a rail roughness spectrum given in 1/3 octave bands as input. Based on that the rail roughness is modelled by white Gaussian noise (basic waveform) that is spectrally shaped using a digital FIR filter (shaping filter). On the other hand, the wheel roughness generator has to generate a periodic signal. A wheel roughness spectrum is needed as input and as a basic waveform a sequence of finite length white noise snippets with a period equal to the wheel perimeter is used. The rail impact generator uses a spatially shifted impulse as basic waveform, whereas the wheel flat generator uses an

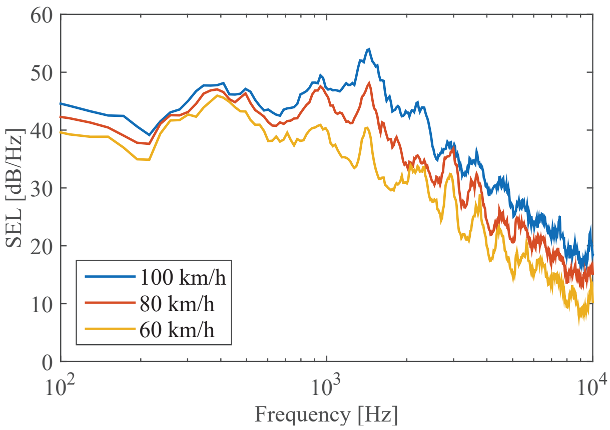

Figure 4: Measured sound exposure level of 12 axles with wheel diameter 920 mm of a Bpm RIC vehicle passing by at different speeds (see legend). The microphone was located at position A according to the standard ISO 3095 [25].

impulse train with a period equal to the wheel perimeter.

The contact filter models the effect of the contact zone of wheel and rail. This effect depends on the wheel diameter and the wheel load. The filter has a low-pass behaviour (in the spatial domain) and can be designed based on 1/3 octave band data. The output of this filter corresponds to the effective roughness $r_{\text{eff}}(x)$. Effective roughness spectra are commonly transformed between spatial and frequency domain using the relation $\lambda = V/f$ with the the wavelength λ in m, vehicle speed V in m/s and frequency f in Hz [21, 22]. This translates into $t = x/V$ where t denotes time. Applying this transformation to the spatial signal $r_{\text{eff}}(x)$ yields the deflection time signal $\zeta_i(t) = r_{\text{eff},i}(x = V(t - T_{\text{PB},i}))$ where $T_{\text{PB},i}$ denotes the pass-by time of axle i. This compression of the time axis corresponds to a stretching of the frequency axis as a function of V. In the digital domain this transformation is known as resampling. If the vehicle speed is constant, this process is known as synchronous resampling or sampling rate conversion. The conversion rate depends on V, the spatial sampling rate and the audio sampling rate. The subsequent differentiation of $\zeta_i(t)$ with respect to time t yields the effective roughness velocity time signal $v_i(t)$. This signal is the basis for the excitation of the dynamic wheel/rail system. Together with the frequency dependent mobilities of the track, wheel and the contact zone, the contact forces can be derived [24]. However, the derivation of the contact forces requires very detailed knowledge of the complex dynamic system and is thus very ambitious. Therefore in the proposed auralisation model, the contact forces are not explicitly identified but rather included in an integral way.

The two subsequently applied transfer path filters implicitly describe a series of effects: They incorporate the transformations from the velocity signal v_i to the contact forces which excite the wheel/rail structure. Further, they simulate the vibrational behaviour of the wheel and track and their radiation efficiencies. In today's engineering models, these effects are often summarised by two transfer functions, one for the vehicle and one the track superstructure [21, 22]; CNOSSOS even distinguishes three separate transfer functions for freight wagons [23]. Their magnitude responses are typically given in 1/3 octave bands [21–23]. The published spectra feature a high-pass behaviour as they also include to the above stated differentiation which corresponds to a ω-proportionality in frequency domain. In a first attempt, the transfer path filters were designed with linear phase and a smooth magnitude response based on 1/3 octave band data. However, listening tests revealed that different filter types with a more subtle frequency response are needed.

Fig. 4 shows measured narrowband spectra of sound pressure signals recorded close to the passing of axles of the same type. Notably above 1 kHz the fluctuating frequency dependency of rolling noise can be observed clearly. Fig. 4 further illustrates that the distinct peaks do not depend on the vehicle speed. Thus it appears that they are not linked to the spatial domain or roughness. For higher speeds the peaks are still present but somewhat less pronounced due to the Doppler effect. We conclude that the narrowband level variations as shown in Fig. 4 are most probably attributed to the modal behaviour of the structure. Consequently, within the model structure depicted in Fig. 2 this effect has to be incorporated in the transfer path filters.

The separation into excitation and structural vibration is typical for physical modelling synthesis. To describe the vibration we propose to use the modal synthesis technique where a resonating structure is described in terms of its modes [18, 26]. The modal resonators can be modelled by second order oscillators (also known as damped harmonic oscillators) for an underdamped system. They can be realised by M digital filters that are connected in parallel [18, 19]. Each filter is designed using the resonance frequency f_m and the decay rate α_m of the respective mode m. The decay rate is related to the structural reverberation time T for a 60 dB drop by $\alpha = 3\ln(10)/T$, and to the bandwidth B of the resonance by $B = \alpha/\pi$. The total impulse response y of a transfer path filter may be approximated by

$$y(t) = \sum_{m=1}^{M} A_m e^{-\alpha_m(t-\tau_m)} \sin(2\pi f_m(t-\tau_m))H(t-\tau_m) \quad (1)$$

with the Heaviside function H, delays τ and amplitudes A. The main challenge is to find an appropriate setting of the parameters f_m, α_m, A_m and τ_m. To do so, detailed information about the dynamic behaviour is required. The required parameters cannot be determined separately for a single wheel or a track, as they differ for the combined coupled dynamic system. The interaction adds further resonances and damping [24]. It is also known that the rolling of the wheel affects these parameters. For instance, compared to a wheel at rest a rolling wheel possesses additional resonances [24]. Consequently, as isolated measurements or simulations are not expedient and data from current literature is not sufficient, the estimation of the model parameters in Eq. (1) may be taken as solving the inverse problem. We propose to use suitable pass-by measurements to fit the required parameters.

The final amplitude modulation to describe the radiation pattern is performed based on the horizontal directivity function proposed in CNOSSOS [23]. Converted to sound pressure, the modulation function reads

$$\delta_i(t) = \sqrt{0.01 + 0.99\sin^2(\varphi_i(t))} \quad (2)$$

with the the horizontal emission angle φ_i being equal to $\pi/2$ on the axis of rotation of axle i.

3. CONCLUSIONS

Our study showed that for a realistic synthesis of rolling noise it is insufficient to only rely on 1/3 octave band data. In addition, modal data of the wheel/rail system has to be included to create the required timbre and thus realistic sounds. Further typical audible railway noise characteristics such as squeal would even demand more complexity and subtlety. A synthesiser concept is presented that is based on a physical model, allowing for auralising the effect of varying wheel and rail roughness and different noise mitigation measures without the need of elaborate measurements.

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