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ROAD TRAFFIC AURALIZATION: MODELING AND SYNTHESIS OF ELECTRIC DRIVES

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ABSTRACT

Nowadays, road traffic emissions are dominating urban sound. Beyond the scope of objective noise assessments based on weighted sound pressure levels, the consideration of the sound generation and propagation from different traffic noise sources is a future-oriented research aspect in the urban planning process. Auralizations can be used to simulate spatial sound fields in virtual environments and thus enables an assessment of perception-related environmental noise aspects. To achieve physically meaningful and perceptually plausible auralizations, individual sound sources must be precisely characterized and modeled. At the example of the increasingly important sound emission from electric drives to the urban soundscape, this paper presents a combined method for modeling and synthesizing electric drive sound radiation. A particular focus of this work is a computationally efficient implementation using C++ and its integration to a real-time road traffic sound synthesis tool.

Key words — Auralization, noise research, source characterization

1. INTRODUCTION

The importance of acoustics for the urban planning process is constantly growing. In its key publication Guidelines for community noise [1], the World Health Organization addressed the impact of noise on health based on a comprehensive systematic review. With primary focus on noise reduction in cities the approaches are manifold. They reach from emission reductions at the sound sources, the geometrical outline of urban development plans, and noise masking techniques (e.g. by installation of fountains). For the subjective evaluation of soundscapes already during the planning process, auralization in combination with visualization is a promising approach [2]. Compared to the sound emission from vehicles equipped with conventional combustion engines, electrical powertrains will seriously change the soundscape of urban environments since their acoustical characteristics significantly differ (Table 1). Most important, the drivetrain emission reduces to a purely harmonic source spectrum and due to increased torque of electric drives, the load dependency decreases. Furthermore, the sound radiation from the electric engine's vibrating surface reduces its spatial distribution to a single source point.

Table 1: Acoustical characteristics of combustion and electrical engine drives.

Engine type	**Combustion**	**Electric**
Components	Harmonics + stochastic noise	Harmonics
Dependency	Rotational speed + Load (strong)	Rotational speed + Load (weak)
Radiation locations	Multiple, spatially distributed partial sound sources 1) Intake 2) Exhaust 3) Structural vibration	Single source

For the auralization of road traffic sound sources, the authors presented a C++-based and real-time capable synthesizer in a VST plugin format [3] by using a procedural synthesis approach. The synthesizer contains submodules for spatially distributed partial sound sources of both, combustion engines and electrical drives. Further details have been presented with focus on the inverse modeling method based on recorded vehicle pass-by sounds [4]. The sound sources are accompanied by according directivity data for according reproduction of the spatial variations of the sound emissions. Several techniques for the rendering of combustion engine sounds were proposed, e.g. by using other synthesis techniques, e.g. wavetables [5] or combined additive/subtractive synthesis approaches [6]. The change to electrical drives has led to considerable effort in research and industry to develop tools for the prediction of sound emissions based on numerical simulations along the whole

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simulation chain. It comprises from the electrical, mechanical and structural-dynamic properties of the permanent magnet synchronous machine (PMSM) over the sound-radiating surface vibrations of the engine's housing to a binaural auralization for subjective evaluation considering the indoor (rooms) or outdoor sound propagation [7]. Generally, different techniques for modelling sound source signals exist, each exhibiting certain advantages and disadvantages. Notable techniques are additive, subtractive, wavetable, granular synthesis or physical modeling [8]. Technically, they can be distinguished regarding their computational load, parameterization and generalizability.

2. SIGNAL PROCESSING CHAIN

A PMSM uses permanent magnets in the rotor and a variable frequency current traveling through the stator to generate torque. As the rotor turns, the stator uses electric currents to generate a magnetic field that follows the speed of rotation of the rotor to generate a consistent torque. The electromagnetic forces generated during its operation generate vibrations not only at the frequency of excitation but also at higher frequencies or harmonics. These variations, called higher-order harmonics, appear at multiples of the first harmonic. Since the electric engine is a periodically rotating machine its spectrogram is composed of multiple sinusoidal harmonics (Fig.3). In consequence, the sound synthesis can be achieved by using the additive synthesis technique by means of a low computational load, parameterization of the rotational speed and the possibility to modularly adapt the tool to data a specific electric engine. As shown in Fig. 1, the signal processing chain consists of an analysis step (chapter 2.1) that transforms the electric engine's sound emission signal $\mathbf{s(n)}$ into a set of coefficients by means of discrete, rotational speed-dependent amplitude values $\hat{\mathbf{A}}_{\mathbf{p}}$. Based on these coefficients, the synthesis step (chapter 2.2) produces audible sound by using additive synthesis.

Figure 1: Block diagram of the analysis-and-synthesis procedure based on the sinusoidal model.

2.1. Analysis

The input is a time-discrete (digital) signal $\mathbf{s(n)}$ of an electrical drive's run up (Fig.2) – which can be a microphone recording or numerically simulated. The synthesis step (cf. chapter 2.2) either can be based on synchronized information on the rotational speed (e.g. from CAN bus data) or information on the PMSM geometry by means of its number of pole pairs.

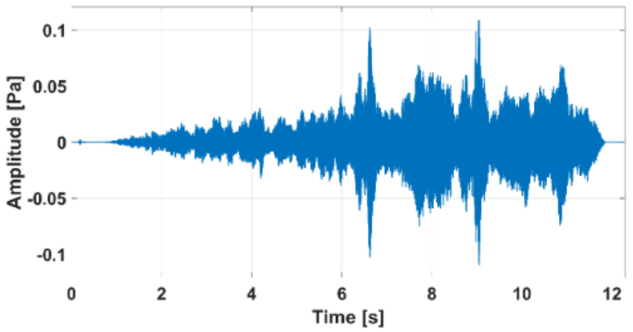


Figure 2: Time signal of the electric engine's run-up.

The Campbell plot (Fig.3) of the run-up signal is showing the main harmonics contributing to the acoustic response of the PMSM at various speeds of rotation (rpm). Using the Fast Fourier Transform (FFT), peak amplitude values $\hat{\mathbf{A}}_{\mathbf{p}}$ are computed at discrete frequencies $\hat{\boldsymbol{\omega}}_{\mathbf{p}}$. For the given run-up signal, the plot reveals the signal to be composed by 15 dominant harmonics.

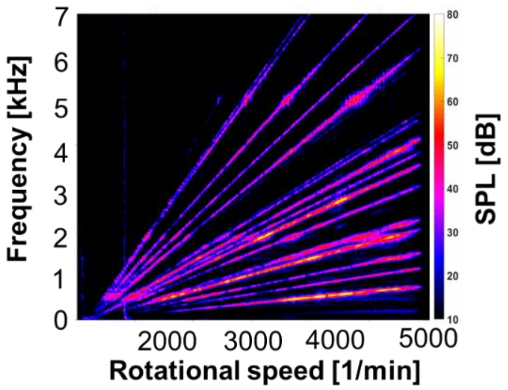


Figure 3: Characteristic spectrogram of the electric engine's sound emission showing multiple sinusoidal harmonics.

Furthermore, it can be observed that each individual oscillator has a unique amplitude envelope. From a perception-related view, this specific pattern is responsible for the characteristic sound of an electric engine. From the time-frequency representation, only the amplitude magnitude $|\hat{\mathbf{A}}_{\mathbf{p,N}}|$ from each of the N harmonic oscillators is used for the synthesizer programming (Fig.4).

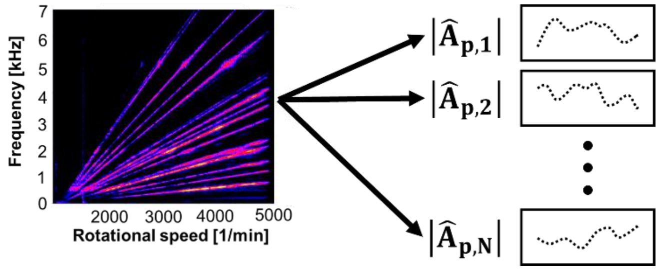


Figure 4: Peak detection and extraction of discrete amplitude envelopes (right, dotted lines) for harmonic oscillators (right) from the time-frequency representation (left).

The amplitude magnitudes (Fig.5) are extracted from the overall spectrogram by using peak detection [9].

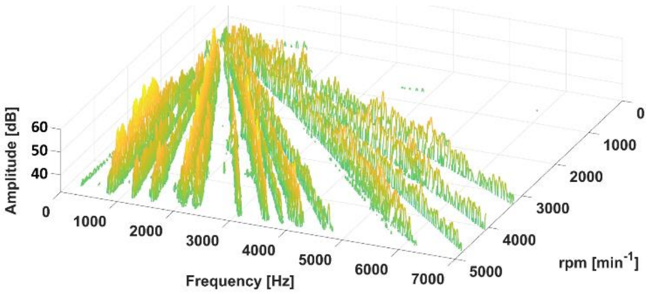


Figure 5: Logarithmically scaled amplitude magnitudes of the run-up signal in dependency of its variables, rotational speed and frequency.

For implementation of the electric engine sound synthesizer, the discretized harmonic oscillator's amplitude values for different rotational speeds are stored by using look-up tables (LUT) in a matrix form (Fig.6).

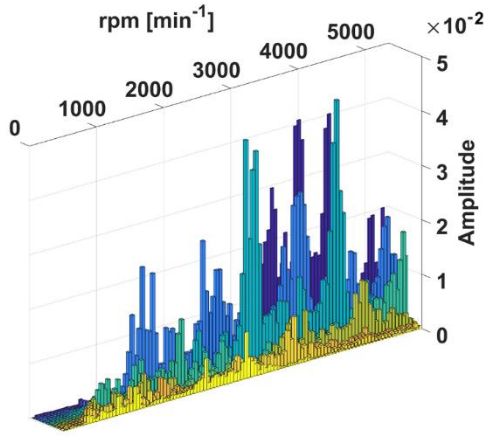


Figure 6: Discretized, linearly scaled amplitude values of the run-up signal. Each data point is stored in the LUT.

2.2. Synthesis

For auralization, the actual source signal of the electric engine must be a 1-channel audio stream format (mono). With regard to the decomposition ending up in multi-channel output information (c.f. chapter 2.1), additive synthesis is used in this work (Fig.7). Each discretized amplitude magnitude $|\hat{\mathbf{A}}_{\mathbf{p},\mathbf{N}}|$– that is stored in the LUT – individually scales the amplitude of the according harmonic oscillator $\boldsymbol{\omega}_{\mathbf{N}}$ where N denotes an integer multiple of the elementary sinusoidal oscillator's frequency $\boldsymbol{\omega}_{\mathbf{1}}$.

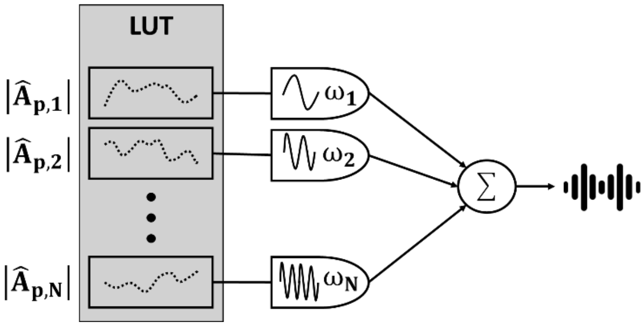
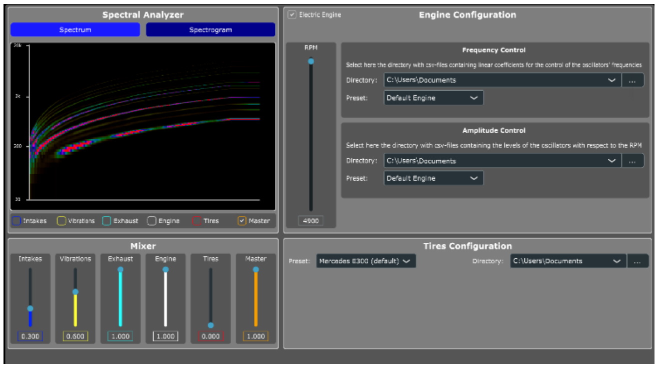


Figure 7: Block diagram of the synthesis step by superposition of N discretized amplitude magnitudes (left) and N sinusoidal oscillators (right).

Auralization of dynamic driving behavior needs continuous control of the electric engine's rotational speed (cf. Table 1). Therefore, the LUT data are interpolated using cubic splines for intermediate rpm values. Moreover, the frequency of each harmonic oscillators linearly scales with the rpm control.

3. RESULTS

The algorithm presented in the previous chapter has been implemented using C++ and added to a VST plugin for synthesis of different road-traffic sound sources [3]. The tool has controls that can be automated in any host Digital Audio Workstation (DAW) or by using the VST plugin host in MATLAB. As shown in Fig. 8, the result of the automated synthesis can be visually monitored in the real-time spectrogram of the graphical user interface (GUI). The resulting 1-channel source signal can be rendered in the DAW and exported as audio file or directly be applied by streaming to auralization software, such as Virtual Acoustics [10].



Select here the directory with csv-files containing linear coefficients for the control of the oscillators' frequencies

Directory: C:\Users\Documents

Preset: Default Engine

Select here the directory with csv-files containing the levels of the oscillators with respect to the RPM

Directory: C:\Users\Documents

Preset: Default Engine

Preset: Mercedes E300 (default)

Directory: C:\Users\Documents

Figure 8: GUI of the electric engine module for synthesizing vehicle sound emissions. The real-time spectrogram window shows the result of a run-up scenario (top, left).

4. CONCLUSIONS

Urban sound simulation and auralization tools can be helpful to better understand the origin of noise effects and the efficiency of mitigation measures. With implementation of synthesizers for various sound sources, here in the example of electric vehicles, prediction towards future environments can be tested, checked by expert panels but also by the population living in the city quarters. The combined method for modeling and synthesizing electric drive sound radiation was proven to create realistic sounds. Further work will focus on integration of the synthesizer in soundscape research by using Virtual Reality to simulate urban environments in a larger context.

5. REFERENCES

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